Interreg NEXT Black Sea Basin

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EfxINNOs

EfxINNOs

Establishing and Operating an Innovative Marine Technology Transfer Network for Enhancing the Transition to a Sustainable Blue Economy in the Black Sea Basin

Process physicochemical data collected by surface buoy, apply ML and AI for short-term forecasts, and validate satellite data

8/2026

https://envrio.eu/efxinnos/

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1. Introduction

The purpose of this deliverable is to present a framework for short-term forecasting of environmental and physicochemical conditions in Georgian waters using advanced data-driven methods. The scope includes the collection, processing, and integration of both in-situ and satellite-based observations to support timely decision-making for marine and maritime stakeholders. By combining high-frequency measurements from surface buoys with remote sensing data, the system aims to provide early warnings for extreme events and environmentally harmful conditions, such as eutrophication, harmful algal blooms (HABs), and anoxia.

Surface buoys play a critical role in this framework by providing continuous, high-resolution measurements of key water quality variables, including temperature, oxygen concentration, and chlorophyll-a levels. These in-situ data serve as the foundation for training machine learning (ML) and deep learning (DL) models, enabling accurate short-term forecasts. Complementing these measurements, Sentinel-2 satellite imagery is collected over the Georgian study area to assess spatial patterns of eutrophication and turbidity. Image processing techniques are applied to estimate chlorophyll-a concentrations, an indicator of algal biomass and overall eutrophication, and to quantify turbidity, reflecting water clarity based on light scattering and absorption in the water column.

By integrating buoy and satellite data, EfxINNOs can gain detailed insights into both the spatial distribution and temporal evolution of eutrophication and turbidity. This combined approach allows the estimation of the probability of extreme events and high-turbidity incidents, supporting the assessment of human impacts on water quality, identification of critical areas, and development of targeted mitigation strategies. Furthermore, the in-situ measurements provide essential reference data for calibrating Sentinel-2 observations. This calibration improves the accuracy of satellite-derived data not only for the Georgian study area but also across the wider Black Sea Basin, enhancing the reliability of regional environmental monitoring and management.

Neuro-fuzzy, ML, and DL algorithms will leverage this integrated dataset to produce short-term forecasts that are both actionable and scientifically robust. The resulting predictions will inform stakeholders, facilitate proactive management, and contribute to the sustainable monitoring and protection of the Black Sea ecosystem.

SECTION A – Data Collection

2. Data Collection from the Online Buoy

Marine coastal ecosystems are among the most productive and environmentally valuable natural systems in the world. They support high biological diversity, provide numerous ecosystem services, and play an essential role in regional economies through fisheries, maritime transport, tourism, and other activities associated with the Blue Economy. At the same time, coastal environments are exposed to multiple natural and anthropogenic pressures, including climate change, river discharge, urbanization, maritime activities, nutrient enrichment, and pollution. Continuous observation of environmental conditions is therefore fundamental for understanding ecosystem functioning, detecting environmental change, and supporting sustainable coastal management.

The Black Sea represents one of the most distinctive semi-enclosed marine basins in Europe. Its hydrography, restricted water exchange with the Mediterranean Sea, and extensive river catchment create unique environmental conditions that differ considerably from those of the open ocean. Coastal waters are particularly dynamic because they respond simultaneously to atmospheric forcing, river inflow, seasonal biological productivity, and human activities. These interacting processes generate substantial temporal variability, making long-term environmental monitoring essential for distinguishing natural seasonal fluctuations from emerging environmental pressures.

Traditional marine monitoring programs are often based on periodic field sampling carried out at weekly or monthly intervals. Although such surveys provide valuable information, they may fail to capture rapid environmental changes associated with storms, phytoplankton blooms, rainfall events, or short-term oxygen fluctuations. High-frequency autonomous monitoring systems overcome this limitation by providing continuous observations that capture both seasonal trends and short-lived environmental events. The increasing availability of smart marine sensors and autonomous observation platforms has therefore transformed environmental monitoring from periodic assessment to continuous ecosystem observation.

The EfxINNOs project was established to strengthen marine observation capacity in the Black Sea Basin by applying innovative environmental monitoring technologies and enhancing scientific cooperation among participating countries. One of the major objectives of the project is to demonstrate how continuous in situ observations can improve understanding of coastal ecosystem dynamics while supporting evidence-based environmental management and the transition towards a sustainable Blue Economy.

Within this framework, a smart marine buoy equipped with multiple environmental sensors was deployed in the coastal waters near Poti, on the Georgian Black Sea coast. The monitoring station continuously measured six key environmental parameters: water temperature, conductivity, dissolved oxygen, oxygen saturation, turbidity, and chlorophyll a. Together, these variables provide complementary information describing the physical, chemical, and biological state of the marine environment and allow integrated assessment of ecosystem functioning.

Unlike short-term monitoring campaigns, the present program covers the full annual cycle from 20 July 2025 to 20 July 2026, enabling detailed evaluation of seasonal variability across a wide range of environmental conditions. Continuous measurements enable identification of both gradual seasonal changes and rapid responses to storms, rainfall, river discharge, and biological processes. Following quality control, the resulting dataset represents one of the first comprehensive year-long autonomous marine observation records collected along the Georgian Black Sea coast within the EfxINNOs project.

The monitoring program also demonstrates the importance of quality assurance in long-term environmental observations. Continuous datasets inevitably include occasional sensor artifacts

or temporary measurement anomalies; therefore, systematic quality control procedures were applied before scientific interpretation. The quality-controlled data set serves as the basis for all analyses presented in this report and provides confidence that the observed environmental patterns reflect natural ecosystem processes rather than measurement errors.

This report presents the results of the first annual monitoring cycle and provides an integrated assessment of environmental conditions in the investigated coastal area. Rather than considering each parameter independently, the report examines the relationships among physical, chemical, and biological processes that together regulate ecosystem behavior throughout the year. Attention is given to seasonal dynamics, interactions among monitored variables, short-term environmental events, and the overall ecological status of the monitored waters.

The findings presented here establish an important environmental baseline for future long-term monitoring programs in Georgia and contribute to the broader regional effort to improve marine observation throughout the Black Sea Basin. Beyond the scientific value of the dataset itself, the experience gained during deployment, maintenance, and interpretation of the smart buoy observations demonstrates the practical benefits of continuous autonomous monitoring for environmental assessment, climate adaptation, and evidence-based coastal management. The results also provide a valuable foundation for integrating buoy observations with satellite remote sensing, laboratory analyses, and future predictive modeling approaches, thereby supporting the continued development of innovative marine observation systems across the region.

2.1. Study Area

The monitoring program was conducted in the coastal waters of **Poti Port**, located on the eastern coast of the Black Sea in western Georgia. The study area represents one of the country's most important coastal zones, where natural marine processes interact with riverine inputs, port activities, and regional meteorological conditions. Owing to its strategic geographical position, the area is environmentally and economically significant, serving as a major maritime gateway while supporting valuable coastal ecosystems (Figure 1).

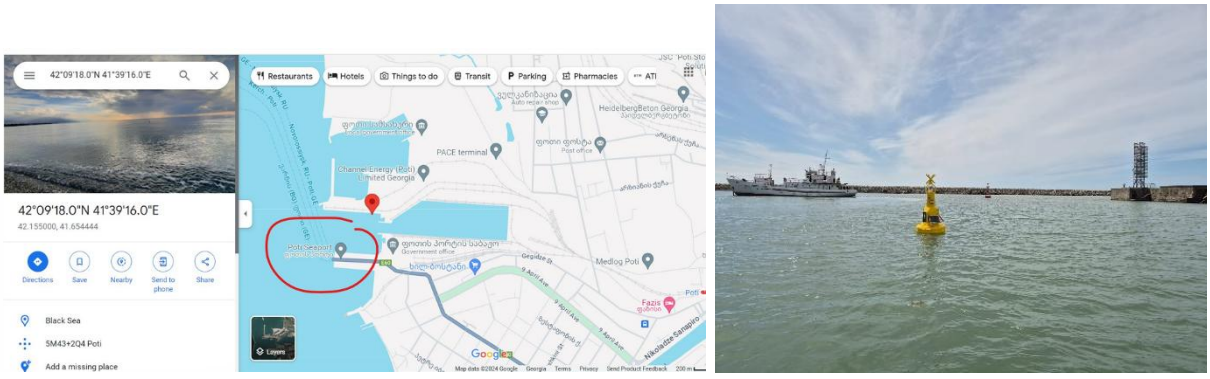


***Figure 1**. Location of the EfxINNOs monitoring station in the coastal waters of Poti, Georgian Black Sea coast.*

The buoy continuously recorded environmental conditions throughout the one-year observation period, enabling high-frequency measurements under a wide range of meteorological and oceanographic conditions.

The study area is periodically influenced by freshwater inflow originating from river discharge and surface runoff following heavy precipitation. These processes temporarily modify conductivity, turbidity, and suspended sediment concentrations in the coastal zone. At the same time, wave action and coastal currents promote continuous water exchange with the adjacent Black Sea, preventing prolonged stagnation and supporting favorable oxygen conditions.

Biological productivity within the monitored area follows a typical seasonal pattern of temperate coastal ecosystems. During spring and summer, increasing solar radiation and higher water temperatures stimulate phytoplankton development, resulting in elevated chlorophyll concentrations and enhanced primary production. During autumn and winter, lower temperatures and reduced daylight decrease biological activity while improving oxygen solubility.

Because the monitoring station remained operational throughout all seasons, the dataset captures both gradual seasonal transitions and short-term environmental events. Storms, intense rainfall, and river discharge episodes were recorded together with periods of relatively stable hydrological conditions, providing a comprehensive representation of the annual environmental variability of the coastal ecosystem.

The monitoring site was selected to provide representative observations of the Georgian coastal environment while ensuring the safe long-term deployment of the autonomous buoy. Continuous measurements collected at this location constitute one of the first uninterrupted annual high-frequency marine environmental datasets obtained along the Georgian Black Sea coast within the EfxINNOs project. The resulting observations provide a valuable baseline for future environmental assessments, climate-change studies, and the development of integrated coastal monitoring systems.

The location is also well-suited for evaluating the combined influence of natural environmental processes and human activities. Seasonal warming, atmospheric forcing, freshwater inflow, sediment transport, and biological production interact continuously within the monitored area, making it an ideal site for studying ecosystem dynamics through integrated multiparameter observations. These characteristics enhance the scientific value of the dataset and strengthen its relevance for regional environmental management and future international research initiatives (Figure 2).



***Figure 2**. Deployment of the EfxINNOs monitoring buoy during field installation.*

2.2. Monitoring Platform

The environmental monitoring program was conducted using an autonomous **smart marine buoy** equipped with a multiparameter water-quality monitoring system. The buoy was designed for continuous long-term operation under coastal marine conditions and provided uninterrupted high-frequency observations throughout the one-year monitoring period.

The monitoring platform continuously measured six key environmental parameters describing the physical, chemical, and biological characteristics of the coastal ecosystem: water temperature, conductivity, dissolved oxygen, oxygen saturation, turbidity, and chlorophyll-*a*. Measurements were automatically transmitted and stored in the project database, enabling near-real-time environmental observation and long-term data archiving.

The autonomous monitoring system operated continuously between **20 July 2025 and 20 July 2026**, providing one of the first uninterrupted annual marine environmental datasets collected along the Georgian Black Sea coast within the EfxINNOs project. The high temporal resolution of the observations allowed the detection of both seasonal environmental variability and short-term events that are often missed by conventional sampling programs.

2.3. Measured Environmental Parameters

Six environmental variables were continuously monitored throughout the study period:

- **Water temperature (°C)** – indicator of seasonal thermal variability and one of the principal controls of marine physical and biological processes.
- **Conductivity (mS/cm)** – used as an indicator of seawater salinity and freshwater influence.
- **Dissolved oxygen (mg/L)** – essential indicator of ecosystem health, aerobic biological activity, and water quality.
- **Oxygen saturation (%)** – describes the balance between oxygen production, atmospheric exchange, and oxygen consumption.
- **Turbidity (NTU)** – reflects suspended sediments, river inflow, storm impacts, and water transparency.
- **Chlorophyll-a (ppb)** – proxy for phytoplankton biomass and primary productivity.

Together, these parameters provide an integrated description of the physical, chemical and biological status of coastal marine waters and allow evaluation of seasonal ecosystem dynamics (Table 1).

__Table 1__. Environmental parameters monitored during the EfxINNOs annual observation program.

Parameter	Unit	Environmental significance
Water Temperature	°C	Seasonal thermal regime
Conductivity	mS/cm	Salinity and freshwater influence
Dissolved Oxygen	mg/L	Ecosystem health
Oxygen Saturation	%	Oxygen balance
Turbidity	NTU	Suspended particles
Chlorophyll-*a*	ppb	Phytoplankton biomass

2.4. Data Acquisition

Environmental measurements were collected automatically at regular time intervals throughout the monitoring period. Sensor observations were transmitted electronically and stored within the project database, creating a continuous high-frequency record of environmental conditions.

The resulting dataset covers an entire annual cycle and captures environmental variability across all seasons. Continuous monitoring enabled the identification of gradual seasonal trends alongside rapid environmental events, including storm responses, rainfall, sediment resuspension, and periods of increased phytoplankton productivity.

For scientific interpretation, the high-frequency observations were aggregated into daily, weekly, and monthly summaries, while the complete dataset was retained for detailed statistical analysis and graphical visualization. The final dataset serves as the basis for the annual graphs, seasonal analyses, correlation studies, and ecological interpretations presented in this report.

2.5. Quality Control

Quality assurance constituted an essential component of the monitoring program. Before analysis, the complete dataset underwent systematic quality-control procedures to identify missing observations, sensor artifacts, and temporary measurement anomalies.

Quality-control procedures included visual inspection of time-series data, identification of unrealistic values, consistency checks among related environmental parameters, and evaluation of sensor performance throughout the deployment period. Temporary anomalies associated with sensor maintenance or instrument malfunction were identified and excluded from further interpretation.

Only the **quality-controlled (QC-clean)** dataset was used for statistical analysis, graphical presentation, and ecological assessment presented in this report. This approach ensured that the observed environmental patterns reflected genuine ecosystem behavior rather than measurement artifacts.

Regular maintenance and cleaning of the monitoring equipment further contributed to maintaining high data quality throughout the one-year observation period.

2.6. Statistical Analysis

Statistical analyses were performed using the quality-controlled annual dataset to characterize temporal variability and relationships among monitored environmental parameters.

For each parameter, descriptive statistics including minimum, maximum, mean, median, and standard deviation were calculated. Annual time-series plots, monthly, weekly, and rolling averages, and seasonal box plots were generated to visualize temporal patterns.

Relationships among environmental variables were evaluated using **Pearson correlation analysis**, enabling the assessment of interactions among physical, chemical, and biological processes within the coastal ecosystem. Scatter plots and correlation matrices were used to illustrate the strength and direction of these relationships.

The statistical outputs were integrated with graphical analyses to support the interpretation of seasonal dynamics, the identification of short-term environmental events, and the assessment of the overall ecological status of the monitored coastal waters. The figures and statistical summaries presented throughout this report are based on the quality-controlled annual dataset and provide the scientific foundation for the monitoring program's conclusions (Figure 38).

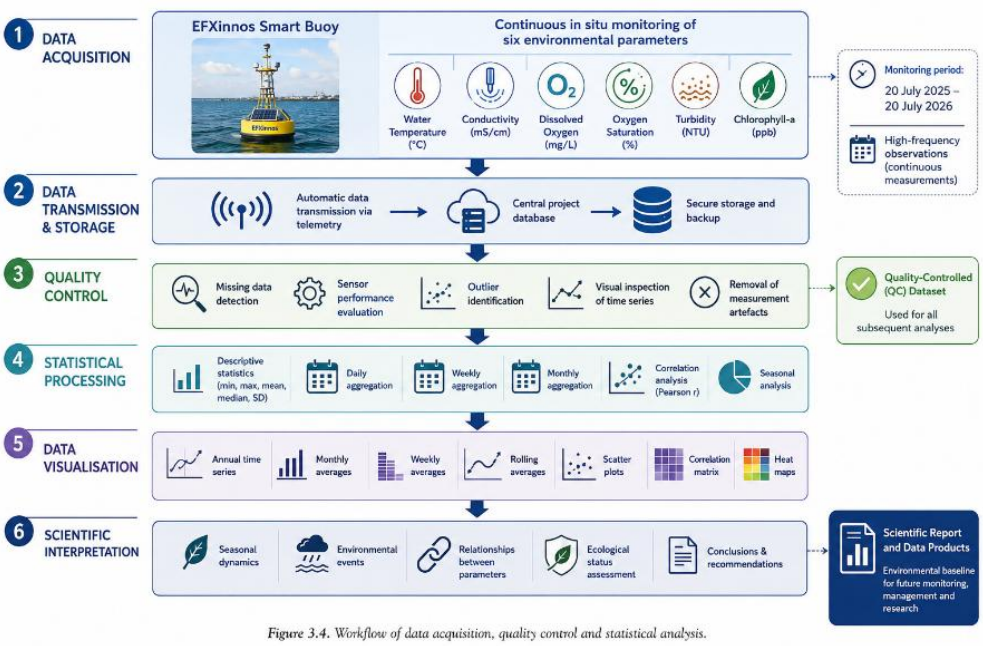


Figure 3.4. Workflow of data acquisition, quality control and statistical analysis.

***Figure 3**. Workflow of data acquisition, quality control, and statistical analysis.*

3. Results

3.1. Annual Overview

The one-year monitoring program provided a comprehensive high-frequency dataset describing the annual evolution of environmental conditions in the coastal waters of Poti Port, Georgia. Continuous observations collected between **20 July 2025 and 20 July 2026** revealed clear seasonal patterns across all monitored parameters and captured numerous short-term environmental events associated with meteorological and hydrological processes.

Water temperature displayed the most pronounced annual cycle among all monitored variables. Surface waters gradually cooled from late summer towards winter, reaching minimum values during the coldest months before increasing steadily during spring and early summer. This seasonal thermal cycle strongly influenced the behavior of several other environmental parameters, particularly dissolved oxygen, oxygen saturation, and biological productivity.

Conductivity remained comparatively stable throughout most of the monitoring period, reflecting the predominantly marine character of the study area. Short-term decreases occurred intermittently and were consistent with temporary freshwater influence following precipitation and river discharge events. However, no long-term changes indicative of altered salinity conditions were detected during the observation period.

Dissolved oxygen concentrations remained within ranges typical of healthy coastal marine waters. Seasonal reductions during the warmest months corresponded closely with increasing water temperature and reduced oxygen solubility, whereas winter mixing promoted elevated oxygen concentrations. Importantly, the monitoring program detected no persistent hypoxic conditions, suggesting that the investigated coastal waters maintained adequate oxygen availability throughout the annual cycle.

Oxygen saturation followed seasonal changes similar to those observed for dissolved oxygen while also reflecting variations in biological activity and atmospheric gas exchange. Periods of elevated oxygen saturation coincided with enhanced photosynthetic activity, whereas temporary decreases were associated primarily with seasonal warming rather than ecosystem degradation.

Turbidity demonstrated greater short-term variability than most other parameters. Several distinct peaks occurred during the monitoring period, reflecting episodic sediment resuspension, wave activity, and freshwater inflow. These events were generally short-lived, after which turbidity rapidly returned to background levels, indicating efficient hydrodynamic recovery within the monitored coastal area.

Chlorophyll-*a* concentrations showed clear seasonal variability consistent with natural phytoplankton dynamics. Higher values generally occurred during periods favorable for primary production, while lower concentrations characterized colder months when biological productivity decreased. Although several temporary chlorophyll peaks were recorded, their duration and magnitude were consistent with natural seasonal variability rather than persistent eutrophication.

The integrated dataset also highlighted the strong coupling between physical, chemical and biological processes within the coastal ecosystem. Correlation analysis demonstrated that water temperature was negatively associated with dissolved oxygen and positively associated with chlorophyll-*a*, illustrating the important role of seasonal warming in regulating oxygen availability and biological productivity. These relationships provide valuable insight into the functioning of the monitored coastal environment and form the basis for the more detailed

analyses presented in the following sections.

From an ecological perspective, the monitoring program indicates that the investigated coastal waters remained in **good environmental condition** throughout the study period. Natural seasonal fluctuations dominated the observed variability, while no evidence of persistent oxygen depletion, long-term salinity disturbance, or chronic deterioration of water quality was identified. The continuous observations, therefore, establish a robust environmental baseline against which future monitoring results can be compared.

The following sections present a detailed analysis of each monitored environmental parameter, including annual behavior, seasonal variability, statistical characteristics, and ecological interpretation. Together, these analyses provide a comprehensive assessment of the environmental dynamics observed during the first annual monitoring cycle of the EfxINNOs smart buoy program.

3.2. Water Temperature

Water temperature is one of the most influential environmental variables in marine ecosystems, controlling a wide range of physical, chemical, and biological processes. Seasonal temperature fluctuations regulate water density, vertical mixing, oxygen solubility, nutrient cycling, and the metabolic activity of marine organisms. Consequently, continuous monitoring of water temperature provides essential information for understanding ecosystem dynamics and interpreting changes observed in other environmental parameters.

During the monitoring period from **20 July 2025 to 20 July 2026**, water temperature exhibited a well-defined annual cycle characteristic of the temperate eastern Black Sea. The quality-controlled dataset showed temperatures ranging from **7.43 °C** to **30.80 °C**, with an annual mean of **17.75 °C**. These values are consistent with the expected seasonal thermal regime of the Georgian Black Sea coast and indicate that the monitoring program successfully captured the complete annual variability of the coastal environment (Figure 4).

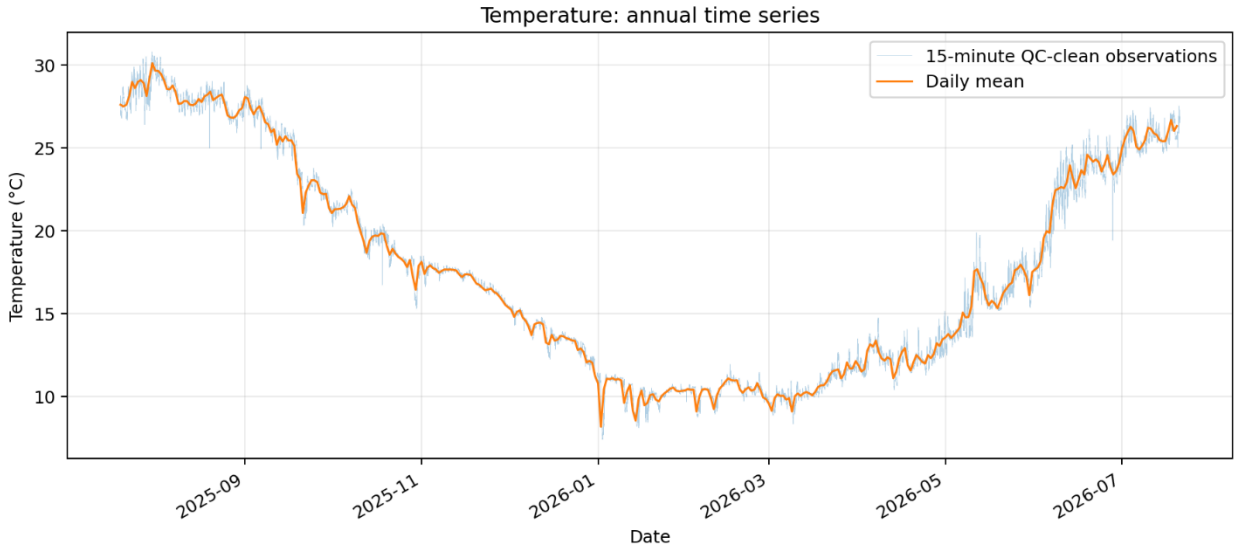


***Figure 4**. Annual water temperature time series recorded by the EfxINNOs smart buoy between July 2025 and July 2026.*

The annual time series illustrates a gradual transition between seasons rather than abrupt

temperature shifts. During late summer, water temperatures remained relatively high, reflecting the accumulated heat stored within the upper water column. A progressive cooling phase followed throughout autumn as decreasing solar radiation and lower air temperatures reduced surface heating. Cooling continued during winter, when the lowest temperatures of the monitoring period were recorded.

Beginning in early spring, the thermal regime changed direction as increasing solar radiation and longer daylight hours promoted gradual warming of the surface waters. Temperature increased steadily throughout spring and early summer, reaching maximum values in July. The smooth seasonal progression observed in the annual record suggests that thermal variability was primarily driven by natural climatic forcing rather than by short-term anthropogenic disturbances.

The seasonal behavior becomes even more evident when monthly averages are considered (Figure 5).

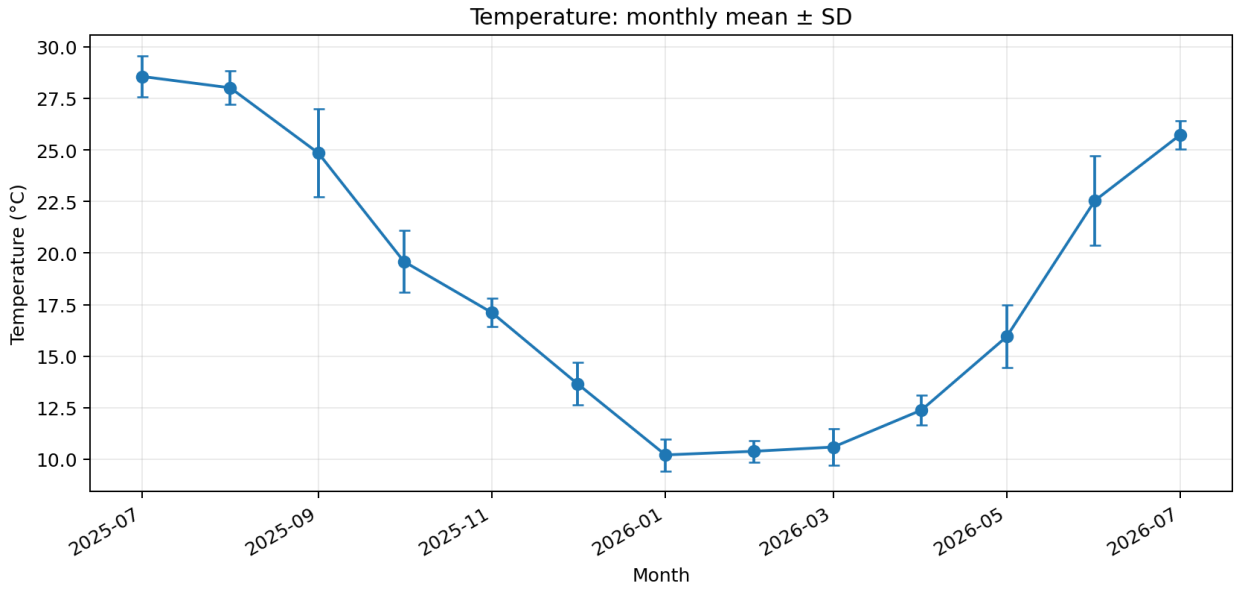


***Figure 5**. Monthly mean water temperature during the monitoring period.*

Monthly averages demonstrate the characteristic annual thermal cycle of the study area. The winter months were associated with the lowest average temperatures, whereas late spring and summer exhibited progressively higher values. The absence of abrupt month-to-month fluctuations indicates a relatively stable seasonal transition typical of coastal marine environments influenced predominantly by regional climatic conditions.

Weekly averages provide additional insight into shorter-term environmental variability (Figure 6).

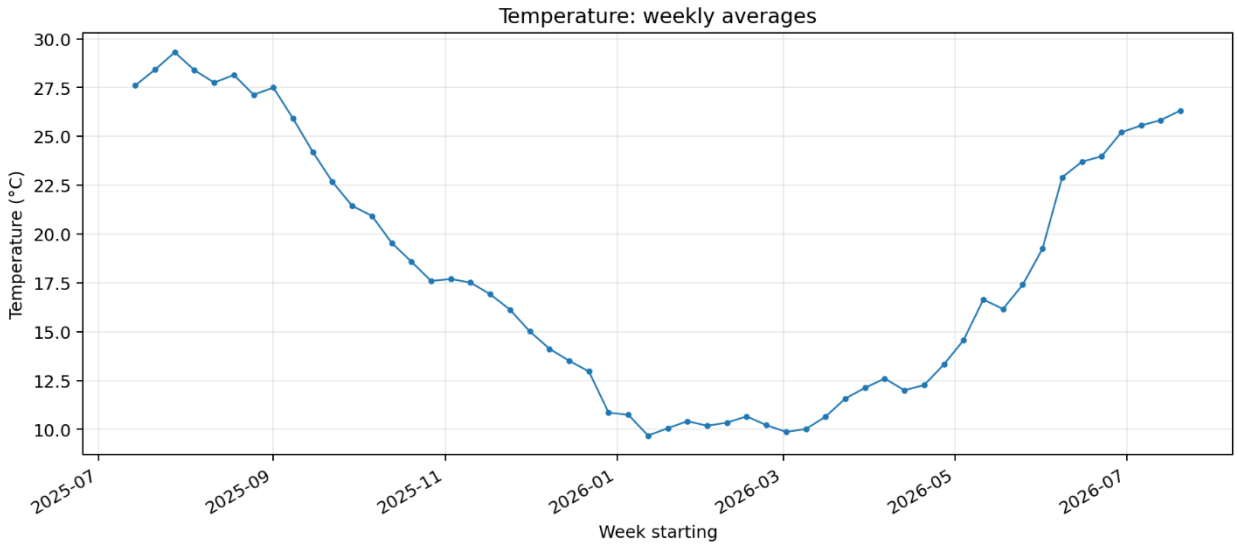


Figure 6. Weekly average water temperature.

Compared with monthly averages, weekly values reveal temporary fluctuations superimposed upon the overall seasonal trend. These short-term variations most likely reflect changes in meteorological conditions, including wind-driven mixing, rainfall events, and transient atmospheric temperature fluctuations. Nevertheless, the general seasonal trajectory remained clearly identifiable throughout the observation period. To further illustrate long-term thermal evolution, rolling-average analysis was performed (Figure 7).

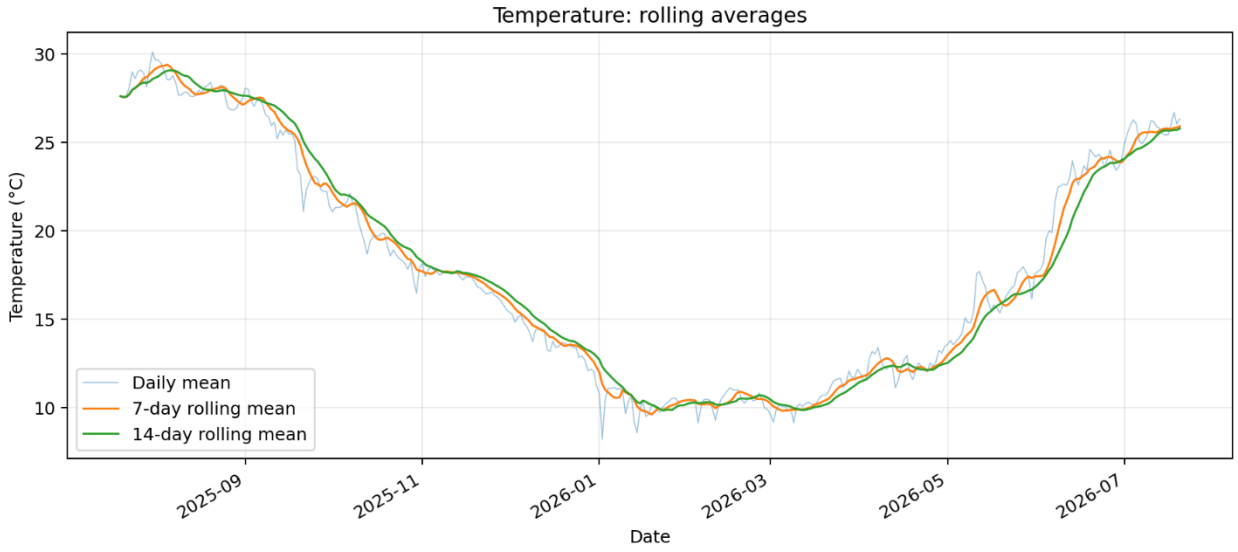


Figure 7. Rolling average of water temperature.

The rolling-average curve effectively removes high-frequency variability while emphasising the long-term seasonal signal. The smoothed profile clearly demonstrates the gradual cooling from late summer to winter followed by continuous warming during spring and early summer. This representation confirms that the observed annual cycle was highly coherent and governed

primarily by seasonal climatic forcing.

Temperature is also closely linked with the behavior of several other monitored environmental variables. Correlation analysis revealed a **moderate negative relationship** between water temperature and dissolved oxygen (**r = -0.325**), consistent with the well-established decrease in oxygen solubility with increasing water temperature. Conversely, a **moderate positive correlation** was observed between temperature and chlorophyll a (r = 0.464), indicating that warmer conditions generally favored higher biological productivity within the monitored coastal waters.

From an ecological perspective, the observed thermal regime is consistent with normal seasonal behavior in the eastern Black Sea and provides no evidence of prolonged thermal anomalies during the monitoring period. Although short-term fluctuations occurred in response to changing weather conditions, these events remained within the expected natural range and did not disrupt the overall seasonal pattern. The continuous dataset, therefore, establishes a valuable thermal baseline against which future observations may be compared to evaluate potential long-term climatic trends.

Overall, water temperature acted as one of the principal drivers of seasonal ecosystem dynamics throughout the study period. Its influence on dissolved oxygen availability, biological productivity, and other environmental variables demonstrates the importance of continuous temperature monitoring within integrated coastal observation programs. The annual record obtained through the EfxINNOs monitoring platform provides a robust foundation for future assessments of climate variability and environmental change along the Georgian Black Sea coast.

3.3. Conductivity

Electrical conductivity is one of the principal indicators of the physical characteristics of coastal marine waters. Because conductivity is closely related to salinity, it provides valuable information on the balance between seawater and freshwater inputs and helps identify changes associated with river discharge, precipitation, evaporation, and coastal mixing processes. Continuous conductivity monitoring, therefore, contributes to understanding hydrological variability and provides important context for interpreting changes observed in other environmental parameters.

During the monitoring period from **20 July 2025 to 20 July 2026**, conductivity exhibited a generally stable annual pattern with relatively limited long-term variability. This behavior reflects the predominantly marine nature of the monitoring site, where coastal waters remain under the continuous influence of the Black Sea while experiencing only temporary freshwater inputs. The annual dataset indicates that the hydrological regime remained stable throughout the observation period, with no evidence of prolonged salinity disturbances or major shifts in water mass characteristics (Figure 8).

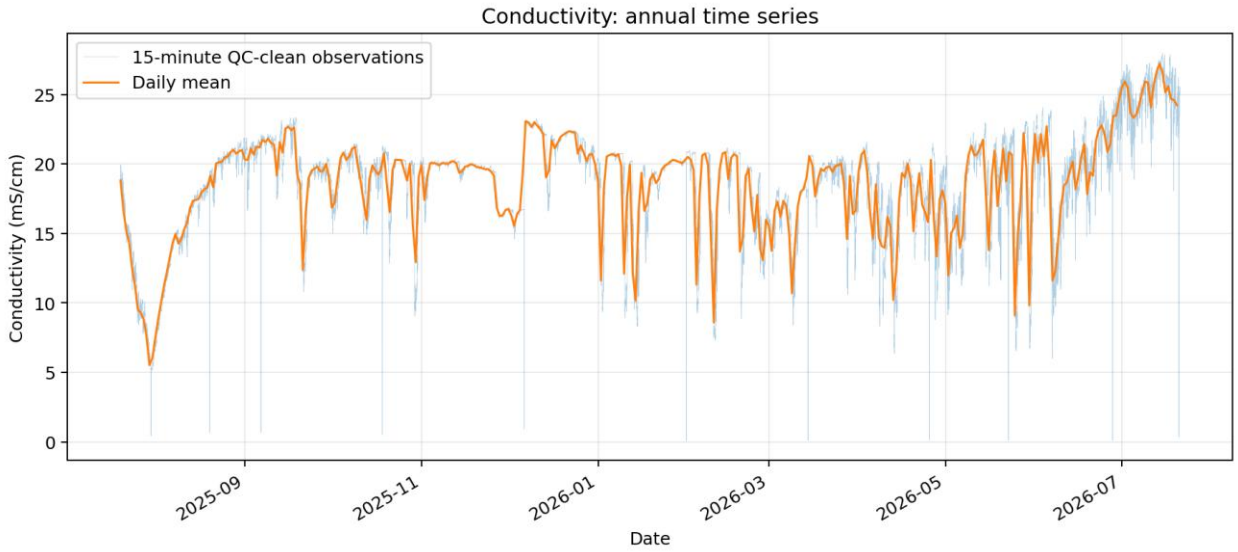


***Figure 8**. Annual conductivity time series recorded by the EfxINNOs smart buoy between July 2025 and July 2026.*

The annual time series demonstrates that conductivity remained relatively constant during most of the monitoring period. Unlike water temperature, which followed a pronounced seasonal cycle, conductivity varied within a comparatively narrow range. Short-term decreases were observed at several points during the year and are consistent with temporary dilution of coastal waters following rainfall events or increased river discharge. These episodes were generally brief, after which conductivity rapidly returned to its typical marine values, indicating efficient mixing and water exchange within the coastal zone. Monthly averages further illustrate the overall stability of conductivity throughout the monitoring period (Figure 9).

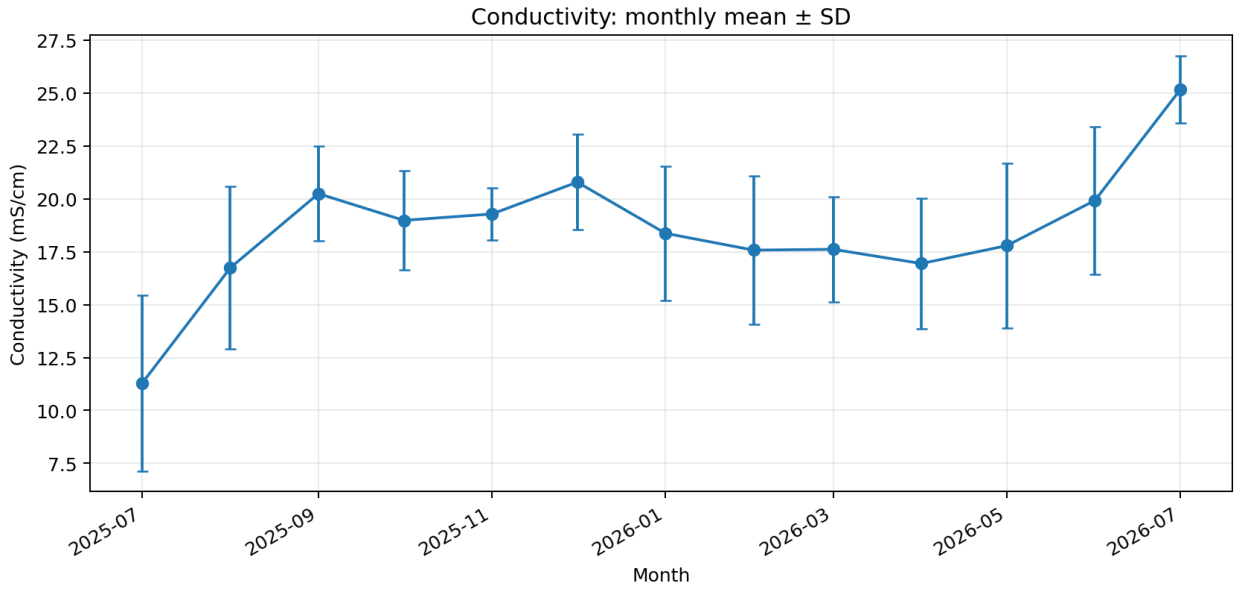


***Figure 9**. Monthly mean conductivity during the monitoring period.*

The monthly averages show only moderate seasonal variability. Slightly lower values observed during periods of increased precipitation are consistent with enhanced freshwater influence, whereas relatively higher conductivity during drier periods reflects the dominance of marine waters. Overall, the monthly pattern indicates that seasonal hydrological processes exerted only a limited influence on the salinity characteristics of the monitored coastal environment.

Weekly averages reveal the short-term fluctuations that are largely masked in monthly summaries (Figure 10).

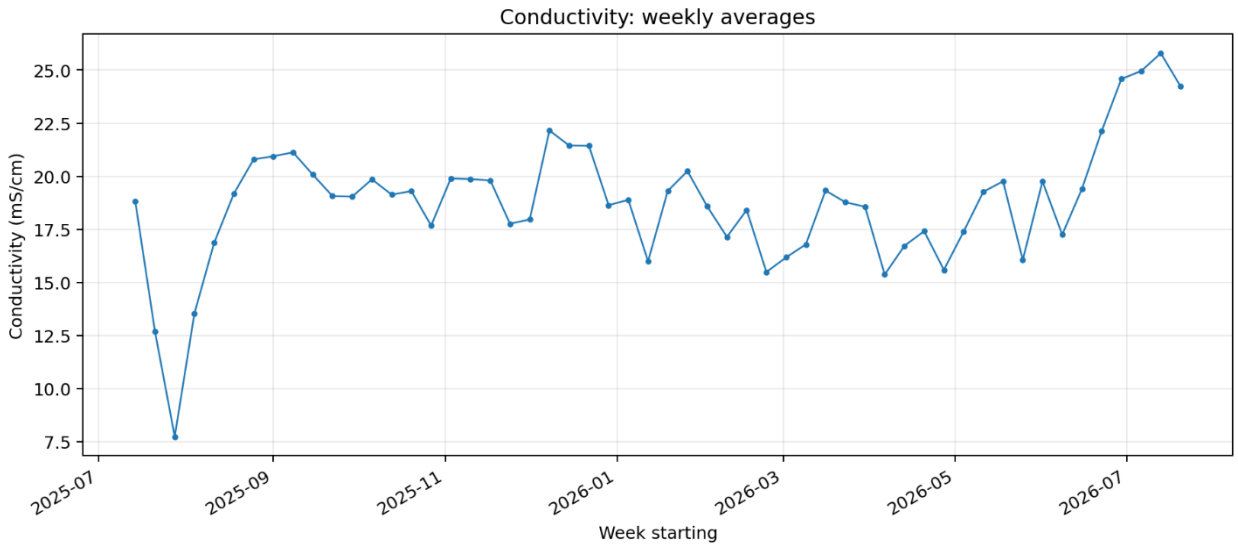


***Figure 10**. Weekly average conductivity.*

Several brief conductivity decreases are evident in the weekly record. These events most likely correspond to periods of rainfall, river inflow or local hydrological disturbances. However, the rapid recovery following each event demonstrates the coastal system's resilience and the effectiveness of natural water exchange processes in restoring typical marine conditions.

The rolling-average analysis highlights the long-term behavior of conductivity over the annual cycle (Figure 11).

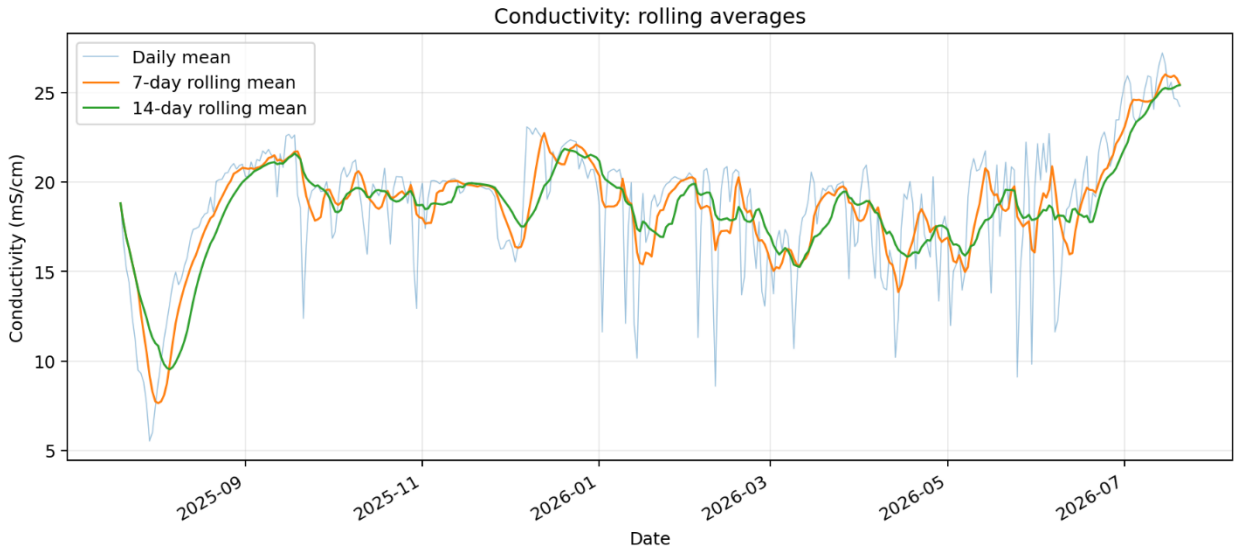


***Figure 11**. Rolling average conductivity.*

The rolling-average curve confirms that conductivity remained remarkably stable throughout the year, with only minor long-term variation. This stability indicates that the monitoring site was not subjected to sustained freshwater intrusion or long-lasting hydrological disturbances during the observation period.

From an ecological perspective, the observed conductivity regime reflects favorable environmental conditions. Stable salinity conditions are essential for maintaining healthy coastal marine ecosystems because many marine organisms are adapted to relatively narrow salinity ranges. Frequent or prolonged reductions in conductivity may indicate significant freshwater intrusion or other hydrological disturbances that can affect biological communities. In contrast, the present observations suggest that such disturbances were temporary and limited in extent.

The conductivity record also provides valuable context for interpreting variations in turbidity and chlorophyll-*a*. Several short-lived reductions in conductivity coincided with periods of increased turbidity, suggesting that freshwater inflow transported suspended particles into the coastal zone. These episodic events represent normal hydrological responses within coastal environments and do not indicate persistent degradation of water quality. Instead, they demonstrate the dynamic interaction between terrestrial and marine processes that characterizes the eastern Black Sea coastal ecosystem.

Overall, conductivity remained one of the most stable environmental parameters measured during the monitoring program. The observations indicate that the investigated coastal waters preserved their characteristic marine properties throughout the annual cycle while responding naturally to short-term meteorological and hydrological events. Consequently, the conductivity dataset provides an important hydrological baseline for future monitoring and strengthens confidence that the observed variations in other environmental parameters primarily reflect seasonal ecosystem dynamics rather than major changes in water mass composition.

3.4. Dissolved Oxygen

Dissolved oxygen (DO) is one of the most important indicators of marine water quality and ecosystem health. Oxygen availability directly influences the survival, growth and distribution

of aquatic organisms, while also regulating numerous biological and biogeochemical processes. Variations in dissolved oxygen reflect the combined effects of water temperature, atmospheric exchange, vertical mixing, photosynthetic activity and microbial respiration. Continuous monitoring of dissolved oxygen is therefore essential for assessing ecological status and identifying potential environmental stress within coastal ecosystems.

During the monitoring period from **20 July 2025 to 20 July 2026**, dissolved oxygen concentrations exhibited a clear seasonal pattern closely associated with changes in water temperature and hydrodynamic conditions. The annual observations demonstrated that oxygen concentrations remained within the range expected for healthy coastal marine waters, with no evidence of prolonged oxygen depletion or persistent hypoxic conditions. This finding indicates that the monitored ecosystem maintained favourable conditions for marine organisms throughout the annual cycle (Figure 12).

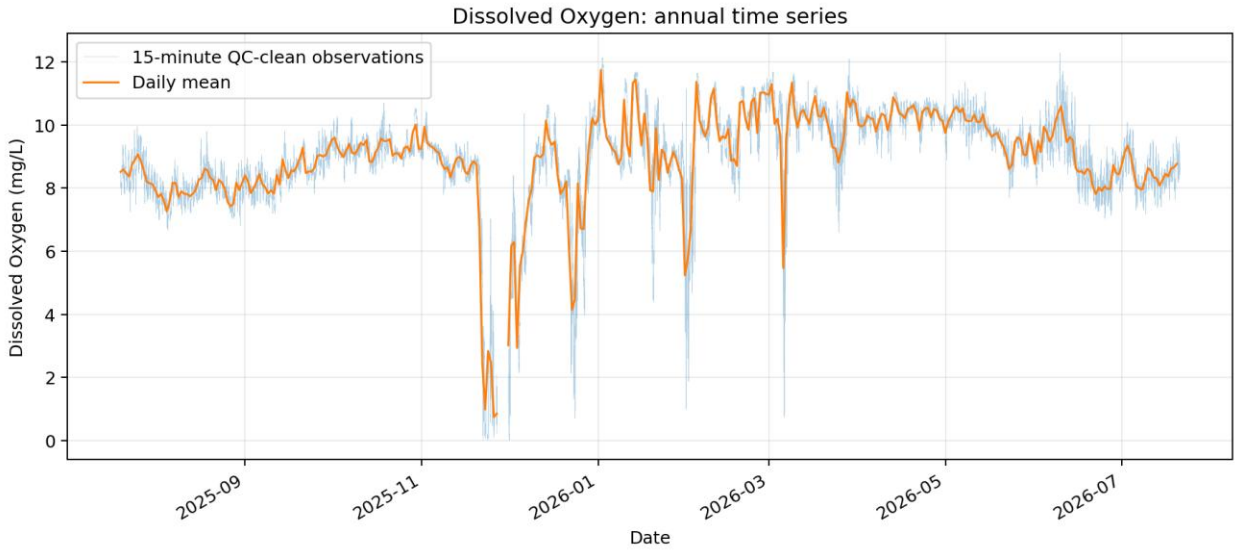


***Figure 12**. Annual dissolved oxygen time series recorded by the EfxINNOs smart buoy between July 2025 and July 2026.*

The annual time series illustrates a well-defined inverse seasonal relationship between dissolved oxygen and water temperature. Oxygen concentrations gradually declined during late spring and summer as increasing water temperatures reduced oxygen solubility and enhanced biological oxygen consumption. Conversely, concentrations increased throughout autumn and winter when cooler conditions promoted greater oxygen solubility and more effective vertical mixing of the water column. This seasonal pattern is characteristic of temperate marine ecosystems and reflects normal environmental processes rather than ecological deterioration. Monthly averages clearly illustrate these seasonal trends (Figure 13).

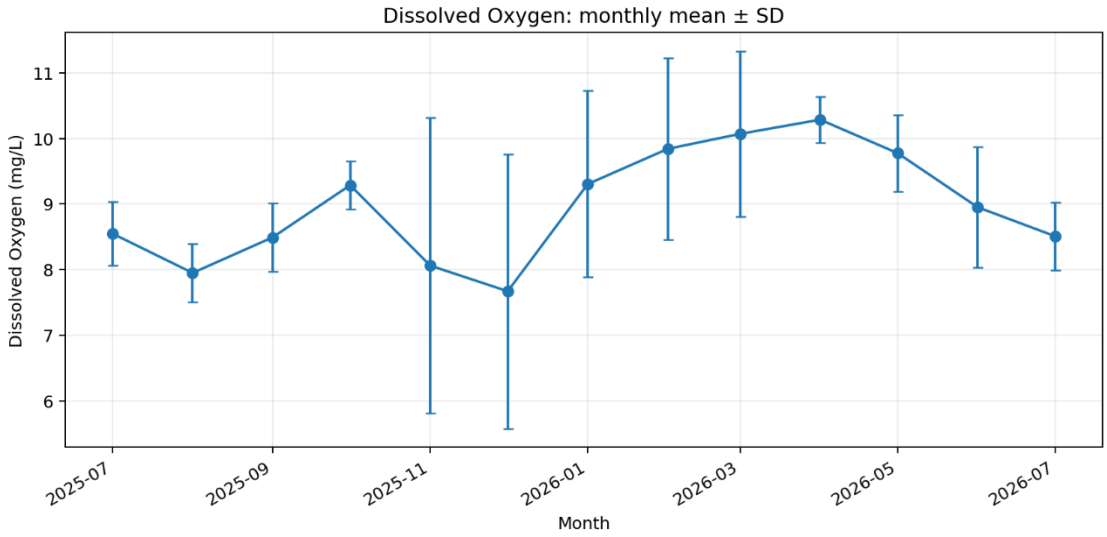


***Figure 13**. Monthly mean dissolved oxygen concentrations during the monitoring period.*

The monthly record shows that the highest dissolved oxygen concentrations occurred during the colder months, when lower water temperatures and increased mixing enhanced oxygen availability. In contrast, the lowest average concentrations were observed during the warmest part of the year. Importantly, even during summer, dissolved oxygen remained well above levels generally associated with ecological stress or hypoxic conditions, indicating that the coastal environment retained sufficient oxygen to support normal biological functioning.

Weekly averages provide a more detailed view of short-term variability (Figure 14).

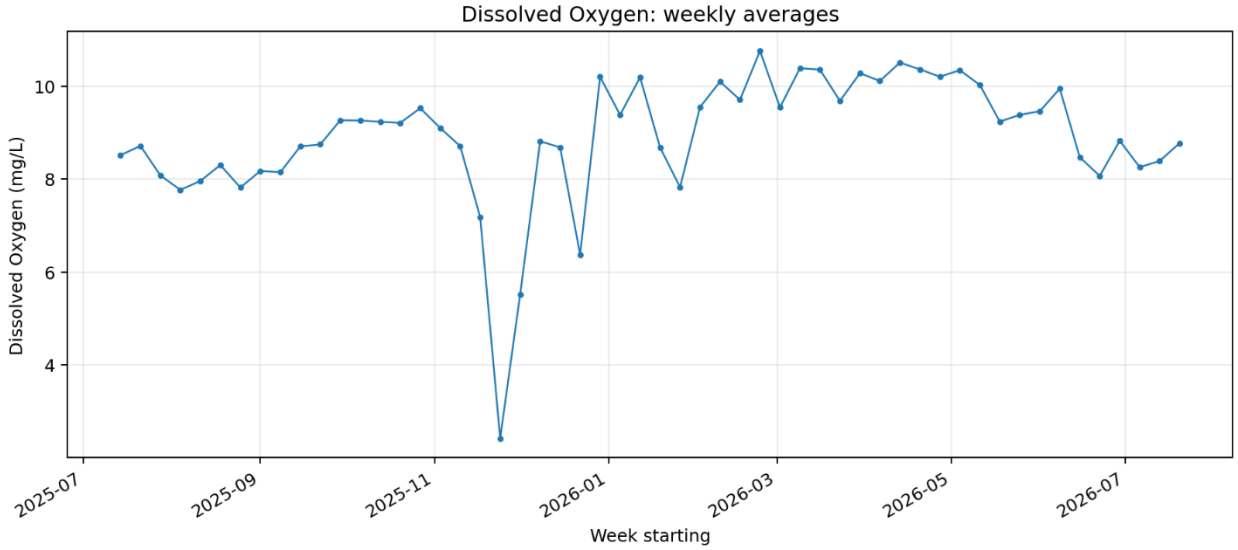


***Figure 14**. Weekly average dissolved oxygen concentrations.*

The weekly record reveals several short-lived fluctuations that likely resulted from changes in meteorological conditions, wave-induced mixing and variations in biological activity. Although these fluctuations temporarily altered oxygen concentrations, they did not interrupt the overall

seasonal pattern. The rapid recovery following individual events demonstrates the dynamic nature of oxygen exchange within the monitored coastal waters and highlights the resilience of the ecosystem.

Long-term seasonal behaviour is further emphasised by the rolling-average analysis (Figure 15).

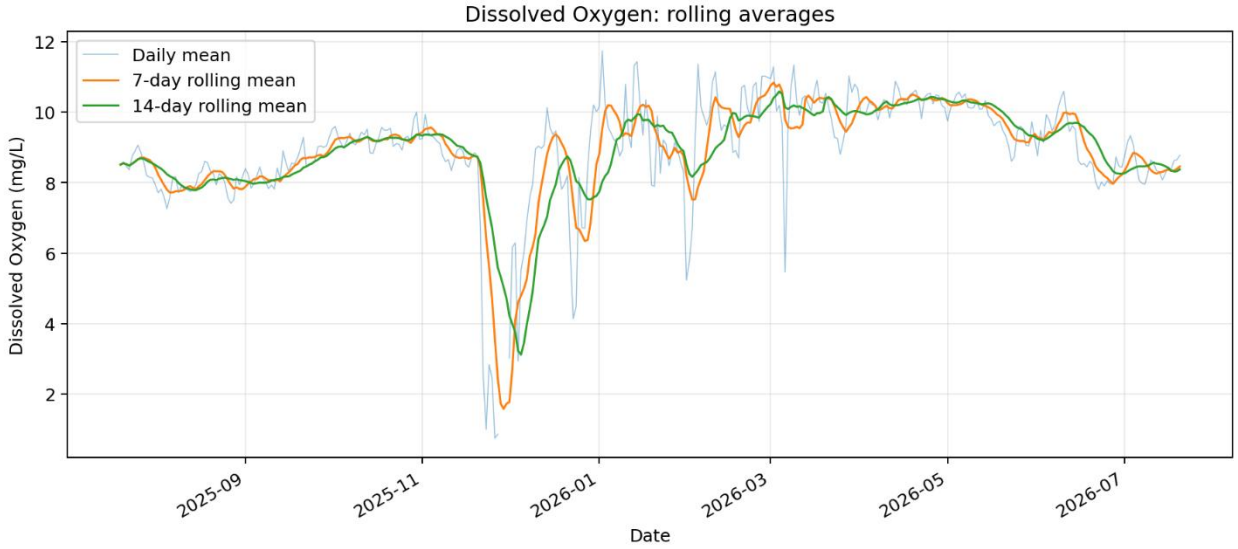


***Figure 15**. Rolling average dissolved oxygen concentrations.*

The rolling-average curve highlights the gradual seasonal evolution of dissolved oxygen throughout the monitoring period. A steady decline from late summer into the warm season is followed by progressive recovery during autumn and winter, illustrating the dominant influence of seasonal climatic conditions on oxygen availability.

The relationship between dissolved oxygen and water temperature is one of the most prominent features of the annual dataset. Correlation analysis showed a moderate negative correlation ($r = -0.325$) between these two parameters, confirming the expected decrease in oxygen solubility with increasing water temperature. This relationship represents a fundamental physical process governing oxygen dynamics in aquatic environments and explains much of the observed seasonal variability.

Biological processes also contributed to short-term fluctuations in oxygen levels. Periods of increased phytoplankton activity, reflected by elevated chlorophyll-*a* concentrations, occasionally enhanced oxygen production through photosynthesis during daylight hours. Conversely, respiration and organic matter decomposition contributed to temporary decreases in oxygen concentrations. However, these biological influences were superimposed upon the much stronger seasonal control exerted by temperature and water-column mixing.

From an ecological perspective, the dissolved oxygen record indicates that the monitored coastal ecosystem remained in **good environmental condition** throughout the observation period. The absence of persistent oxygen depletion suggests effective hydrodynamic exchange with adjacent Black Sea waters and the lack of excessive organic loading or severe eutrophication. Temporary fluctuations observed during individual environmental events remained within the range expected for healthy coastal ecosystems and did not indicate sustained ecological stress.

The continuous dissolved oxygen dataset also provides an important reference for future long-term monitoring. As climate change is expected to increase water temperatures and potentially reduce oxygen availability in marine environments, the present observations establish a valuable baseline against which future changes can be evaluated. Continued monitoring will therefore be essential for detecting long-term trends and assessing the resilience of the Georgian Black Sea coastal ecosystem under changing climatic conditions.

Overall, dissolved oxygen measurements confirmed that the monitored waters maintained favorable ecological conditions throughout the annual cycle. Seasonal variability was primarily driven by natural environmental processes, and no evidence of chronic oxygen stress or ecosystem degradation was identified. The high-quality continuous observations obtained through the EfxINNOs monitoring platform therefore provide a robust scientific foundation for future environmental assessment and coastal management.

3.5. Oxygen Saturation

Oxygen saturation is a key indicator of the balance between oxygen supply and oxygen demand in aquatic ecosystems. Unlike dissolved oxygen concentration, which represents the absolute amount of oxygen dissolved in water, oxygen saturation expresses the percentage of oxygen present relative to the theoretical equilibrium concentration at prevailing temperature and atmospheric pressure. Consequently, oxygen saturation provides valuable information on the combined effects of physical processes, atmospheric exchange, and biological activity within the marine environment.

Throughout the monitoring period from **20 July 2025 to 20 July 2026**, oxygen saturation exhibited a clear seasonal pattern that closely followed changes in water temperature and dissolved oxygen dynamics. The annual observations demonstrated that oxygen saturation remained within the range expected for a healthy coastal marine ecosystem, with no evidence of persistent oxygen deficits. Temporary increases above equilibrium conditions and short-term decreases occurred during the monitoring period, reflecting natural biological and hydrodynamic processes rather than environmental degradation (Figure 16).

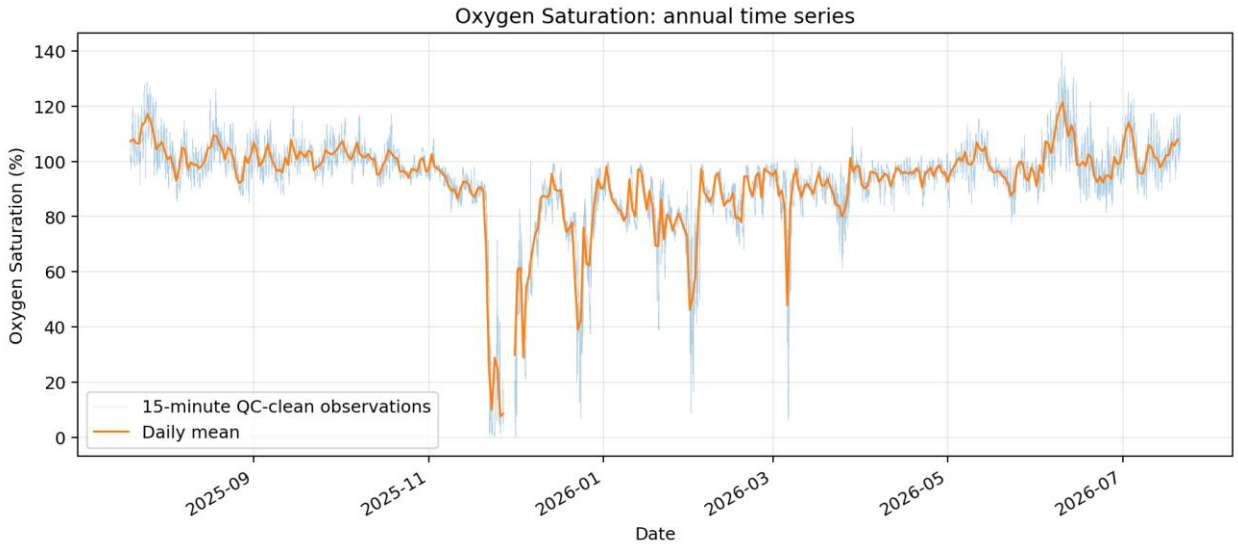


Figure 16. Annual oxygen saturation time series recorded by the EfxINNOs smart buoy between July 2025 and July 2026.

The annual time series illustrates gradual seasonal transitions superimposed by several short-lived fluctuations. During colder months, lower water temperatures increased oxygen solubility and promoted more efficient vertical mixing, contributing to relatively high oxygen saturation values. Conversely, during late spring and summer, increasing water temperature reduced oxygen solubility, resulting in lower saturation values. Despite these seasonal changes, oxygen saturation remained within environmentally acceptable limits throughout the monitoring period.

Monthly averages further emphasize the annual seasonal cycle (Figure 17).

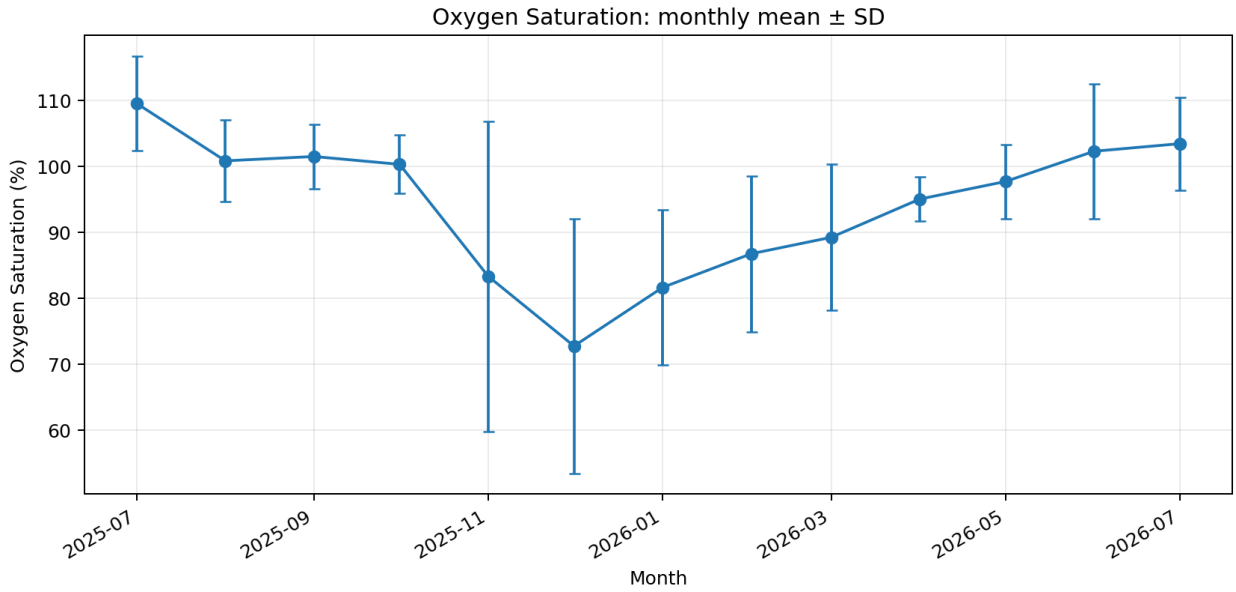


***Figure 17**. Monthly mean oxygen saturation during the monitoring period.*

The monthly averages show relatively stable seasonal behavior, with higher oxygen saturation in autumn and winter and lower values during the warmest months. This pattern closely matches the seasonal evolution of dissolved oxygen and confirms the dominant influence of temperature on oxygen dynamics in the monitored coastal waters.

Weekly averages reveal additional short-term variability associated with rapidly changing environmental conditions (Figure 18).

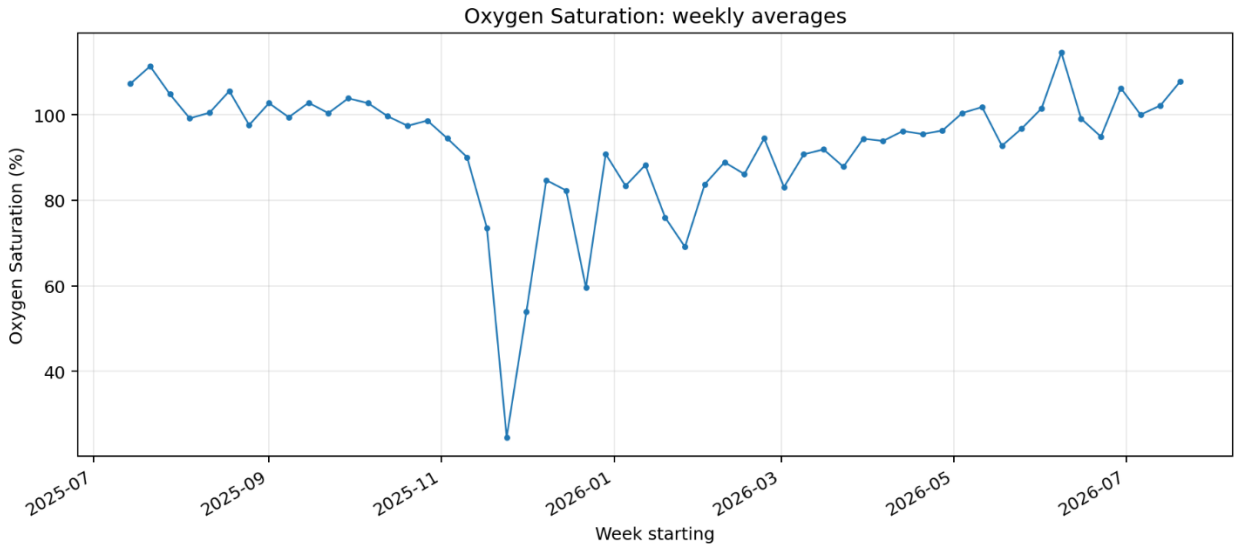


Figure 18. Weekly average oxygen saturation.

Several temporary increases and decreases are evident in the weekly record. These short-duration fluctuations most likely reflect variations in wind-induced mixing, wave activity and biological productivity. Strong wind events enhance atmospheric oxygen exchange and vertical mixing, whereas periods of intense phytoplankton photosynthesis may temporarily elevate oxygen saturation during daylight hours. Conversely, calm weather, respiration and organic matter decomposition may contribute to short-term decreases.

The long-term seasonal pattern becomes particularly evident in the rolling-average analysis (Figure 19).

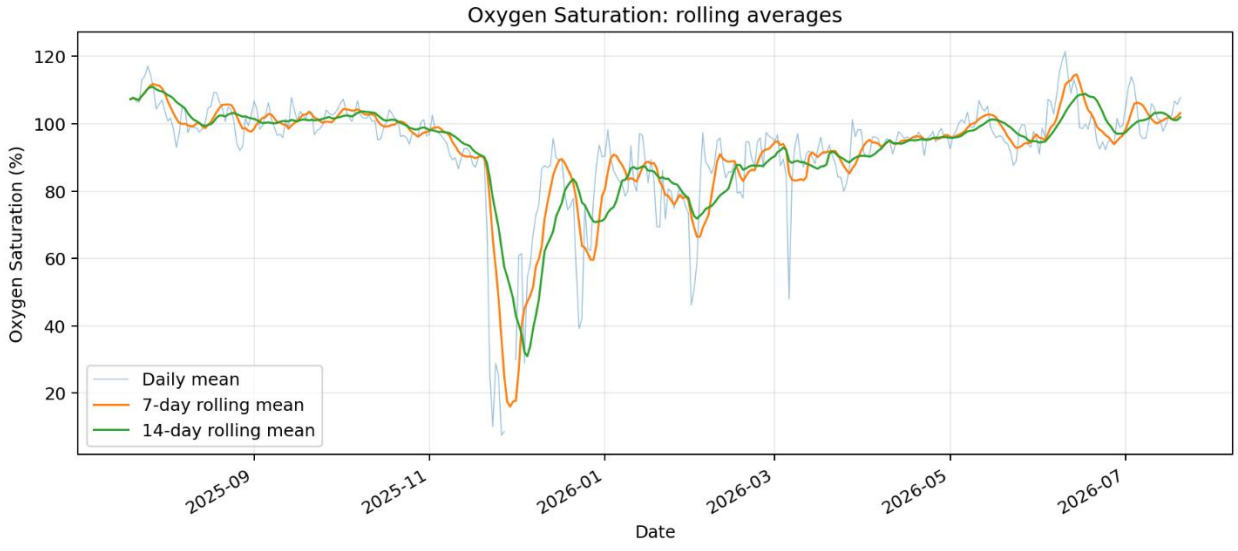


Figure 19. Rolling average oxygen saturation.

The rolling-average curve demonstrates a smooth annual progression closely following seasonal climatic conditions. The absence of abrupt long-term shifts indicates that oxygen exchange

processes remained stable throughout the observation period and that no prolonged ecological disturbances affected the oxygen balance of the monitored coastal waters.

Comparison with dissolved oxygen concentrations shows that both parameters exhibit remarkably similar seasonal behavior. However, oxygen saturation provides additional insight by accounting for temperature-dependent oxygen solubility. Consequently, the combined interpretation of dissolved oxygen concentration and oxygen saturation allows a more comprehensive assessment of ecosystem functioning than either parameter alone.

Several short-lived periods of elevated oxygen saturation were observed during the monitoring program. These episodes are consistent with increased daytime photosynthetic activity by phytoplankton and represent normal seasonal biological processes rather than evidence of ecological imbalance. Likewise, temporary reductions in oxygen saturation corresponded primarily to seasonal warming and changes in hydrodynamic conditions, without indicating persistent oxygen stress.

From an ecological perspective, the oxygen saturation record confirms the favorable environmental status of the monitored coastal ecosystem. The absence of prolonged undersaturation suggests efficient atmospheric oxygen exchange, effective water circulation, and no excessive oxygen consumption associated with severe organic pollution or eutrophication. These findings are fully consistent with the dissolved oxygen observations and support the conclusion that the monitored waters remained in **good ecological condition** throughout the annual cycle.

The continuous oxygen saturation dataset also highlights the value of autonomous high-frequency monitoring. While periodic field surveys may overlook transient supersaturation or undersaturation events, continuous observations capture both short-term biological responses and seasonal environmental trends, providing a more complete understanding of coastal ecosystem dynamics.

Overall, oxygen saturation proved to be a highly informative parameter for evaluating ecosystem health and interpreting interactions between physical and biological processes. Together with dissolved oxygen concentration, it provides a robust basis for assessing oxygen dynamics and establishes an important reference dataset for future environmental monitoring along the Georgian Black Sea coast.

3.6. Turbidity

Turbidity is an important indicator of water clarity and suspended particulate matter in aquatic environments. In coastal marine ecosystems, turbidity is influenced by a combination of natural and anthropogenic processes, including river discharge, wave-induced sediment resuspension, coastal erosion, phytoplankton blooms, and human activities. Continuous turbidity monitoring, therefore, provides valuable information on hydrodynamic processes, sediment transport, and short-term environmental disturbances that may affect water quality and ecosystem functioning.

Throughout the monitoring period from **20 July 2025 to 20 July 2026**, turbidity exhibited substantially greater short-term variability than the other monitored physical parameters. Unlike water temperature or conductivity, which followed relatively smooth seasonal patterns, turbidity showed episodic peaks separated by periods of comparatively low, stable values. This behavior is typical of dynamic coastal environments, where suspended particle concentrations respond rapidly to changing meteorological and hydrological conditions (Figure 20).

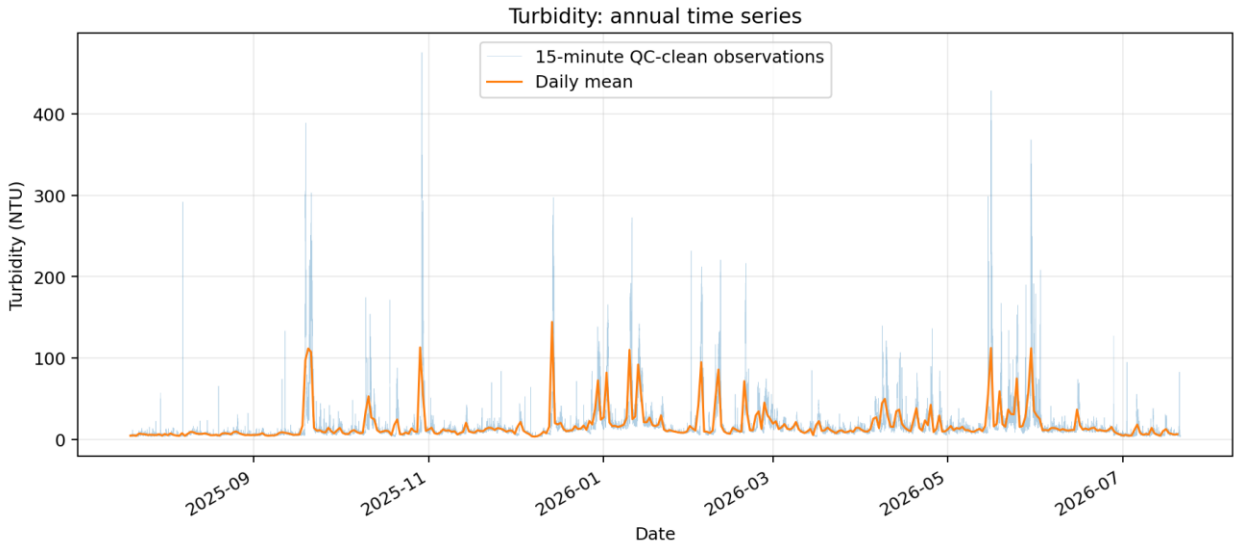


***Figure 20**. Annual turbidity time series recorded by the EfxINNOs smart buoy between July 2025 and July 2026.*

The annual time series shows that most of the monitoring period was characterized by relatively low turbidity, indicating good water transparency and low suspended material concentrations. However, several distinct turbidity peaks occurred during the year. These episodes were generally short-lived and were followed by rapid returns to background conditions, suggesting efficient sediment settling and effective water exchange within the coastal zone.

The observed turbidity peaks are most likely associated with a combination of environmental processes. Storm events increase wave energy and resuspend bottom sediments, while heavy precipitation and river discharge transport suspended particles from terrestrial catchments into the coastal waters. In addition, periods of increased biological productivity may contribute to elevated turbidity by increasing phytoplankton and other suspended organic material concentrations. These mechanisms often operate simultaneously and collectively explain the episodic nature of turbidity observed during the monitoring program. Monthly averages illustrate the broader seasonal behavior of turbidity (Figure 21).

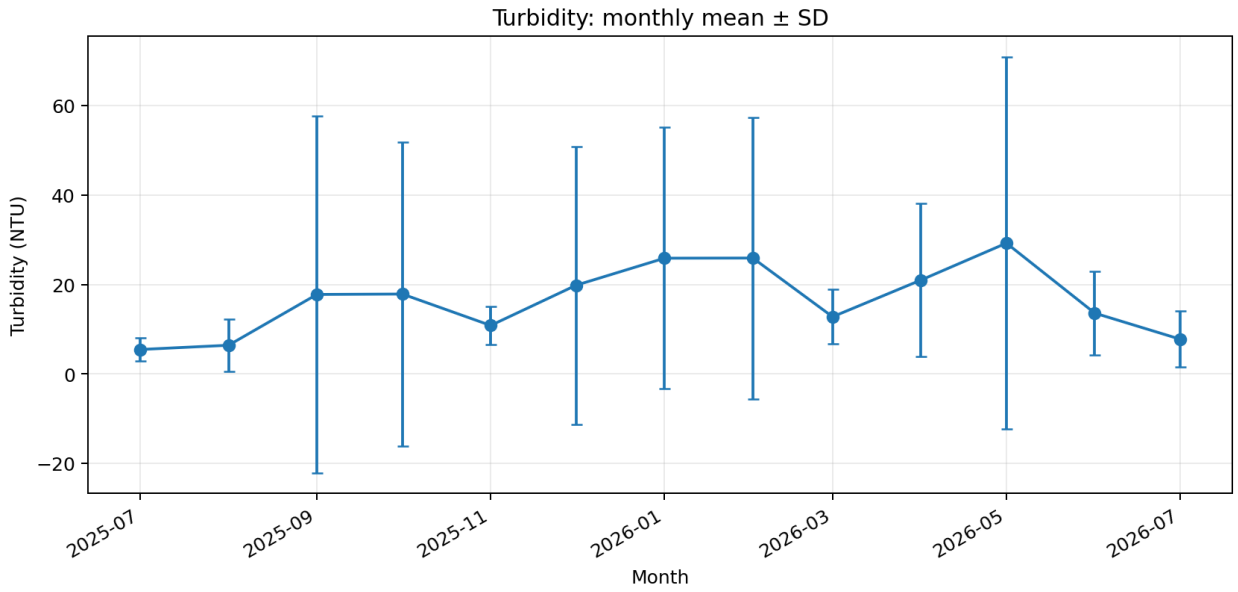


Figure 21. Monthly mean turbidity during the monitoring period.

Unlike temperature and dissolved oxygen, monthly turbidity averages display relatively modest seasonal differences because the parameter is primarily controlled by short-duration environmental events rather than gradual seasonal forcing. Nevertheless, months with repeated rainfall or storm activity exhibit slightly elevated average turbidity, reflecting the cumulative effect of multiple short-term episodes.

Weekly averages provide a more detailed perspective on these transient events (Figure 22).

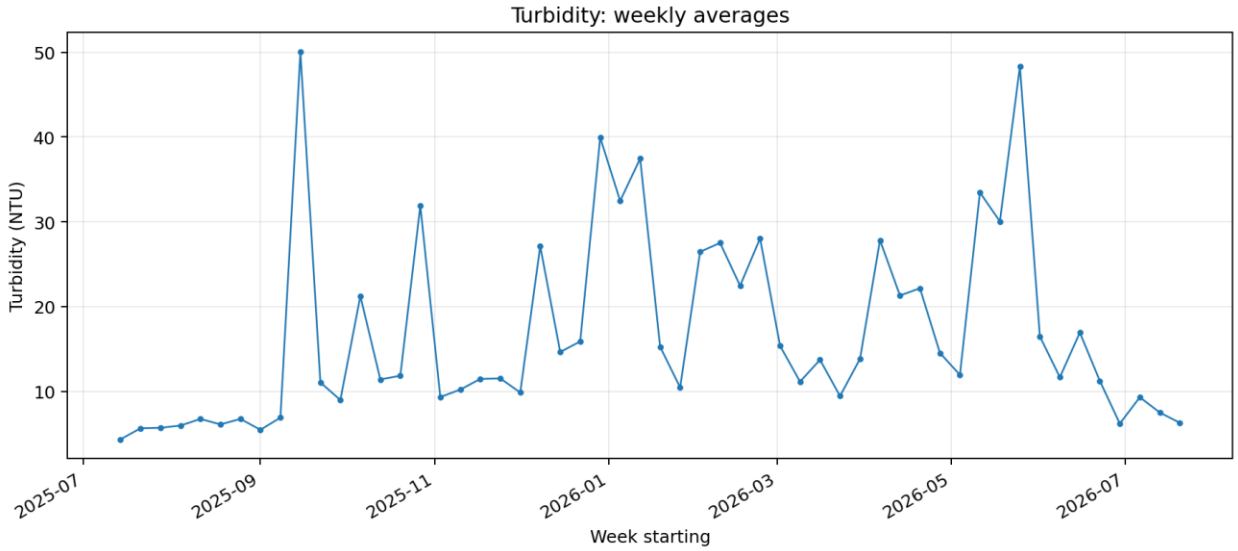


Figure 22. Weekly average turbidity.

The weekly record clearly demonstrates the episodic character of turbidity fluctuations. Individual peaks generally lasted only a few days before declining rapidly to baseline conditions.

This rapid recovery indicates that suspended particles were efficiently dispersed or settled following each disturbance, highlighting the dynamic hydrodynamic conditions of the monitored coastal environment.

The rolling-average analysis further illustrates the absence of long-term deterioration in water transparency (Figure 23).

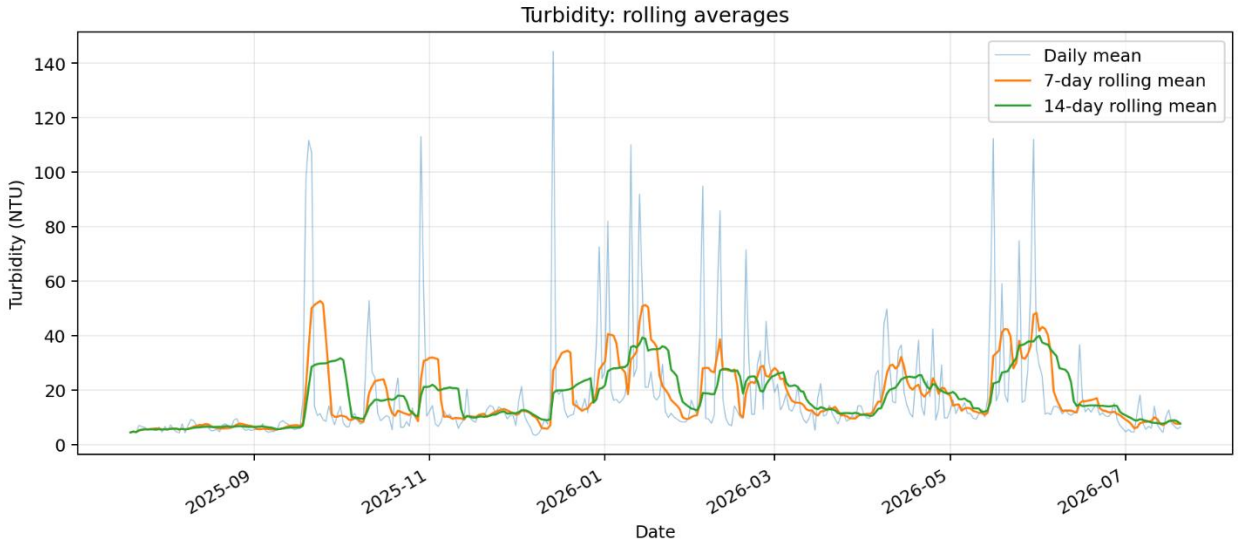


***Figure 23**. Rolling average turbidity.*

The rolling-average curve remained relatively stable throughout the monitoring period, despite several pronounced short-term peaks. This observation confirms that turbidity events were temporary rather than persistent and did not result in sustained degradation of water clarity.

Interpretation of turbidity should also consider its relationship with other monitored environmental variables. Several periods of elevated turbidity coincided with temporary decreases in conductivity, suggesting that rainfall and freshwater inflow introduced suspended sediments into the coastal zone. In addition, certain turbidity peaks occurred simultaneously with increases in chlorophyll-*a*, indicating that biological production may have contributed to suspended particle concentrations during periods of enhanced phytoplankton growth. These interactions emphasize the complex coupling between hydrological and biological processes in coastal marine ecosystems.

The continuous monitoring program also demonstrated the importance of high-frequency observations for interpreting turbidity dynamics. Many of the observed peaks developed and disappeared within a relatively short period. Such transient events would likely have been missed by conventional monthly sampling programs, illustrating one of the principal advantages of autonomous monitoring platforms for coastal environmental assessment.

From an ecological perspective, the turbidity record indicates that the monitored waters generally maintained good optical conditions throughout the annual cycle. Although several temporary increases in suspended particles were observed, these episodes were consistent with natural coastal processes and recovered rapidly. No evidence of persistently elevated turbidity or chronic sediment loading was detected during the monitoring period, supporting the conclusion that the coastal ecosystem remained in a favorable environmental condition.

Overall, turbidity proved to be one of the most responsive indicators of short-term environmental change within the monitored coastal waters. While temperature and dissolved oxygen primarily reflected seasonal climatic forcing, turbidity provided immediate evidence of episodic hydrological and meteorological events. Together with the other monitored parameters, the turbidity dataset contributes to a comprehensive understanding of the annual environmental dynamics of the Georgian Black Sea coast.

3.7. Chlorophyll-*a*

Chlorophyll-*a* is widely recognized as one of the most important indicators of phytoplankton biomass and primary productivity in aquatic ecosystems. As the principal photosynthetic pigment present in algae and phytoplankton, its concentration provides valuable information on biological activity, nutrient availability, and ecosystem functioning. Continuous chlorophyll-*a* monitoring is particularly important in coastal waters because changes in phytoplankton abundance directly influence oxygen production, water transparency and nutrient cycling. Moreover, long-term observations help distinguish natural seasonal productivity from conditions that may indicate eutrophication.

During the monitoring period from **20 July 2025 to 20 July 2026**, chlorophyll-*a* concentrations displayed clear temporal variability, reflecting the natural seasonal dynamics of phytoplankton communities within the monitored coastal waters. Although several distinct peaks were observed during the annual cycle, these events were generally short-lived and were followed by rapid recovery to background levels. The overall behavior of chlorophyll-*a* indicates a biologically active but environmentally balanced coastal ecosystem without evidence of persistent algal overgrowth or chronic eutrophication (Figure 24).

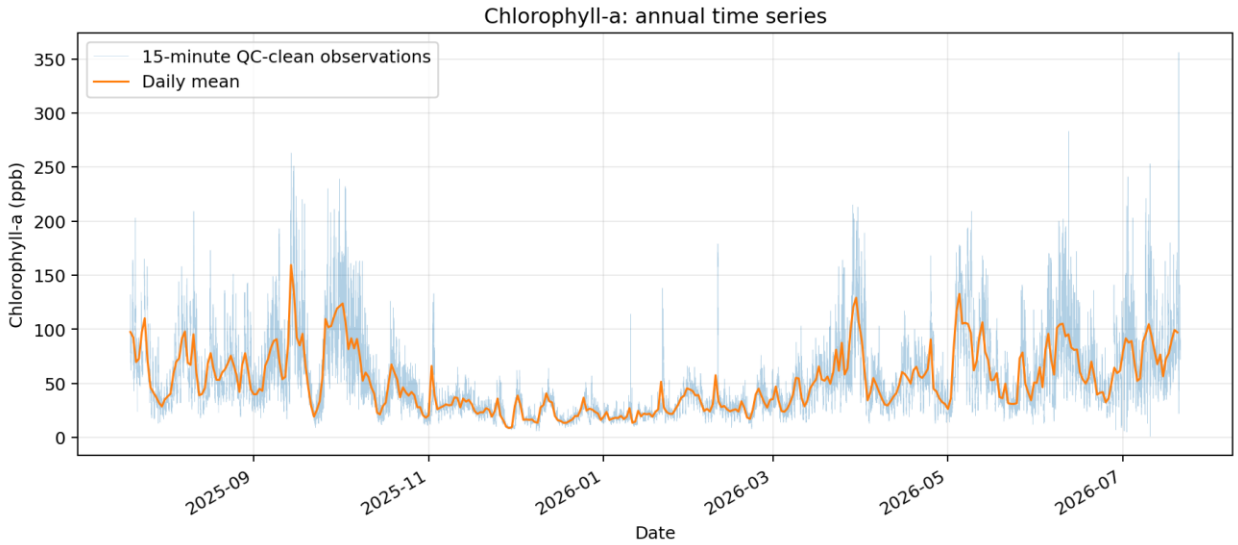


***Figure 24**. Annual chlorophyll-a time series recorded by the EfxINNOs smart buoy between July 2025 and July 2026.*

The annual time series demonstrates that chlorophyll-*a* concentrations fluctuated considerably throughout the monitoring period. Rather than following a perfectly smooth seasonal pattern, phytoplankton biomass responded dynamically to changing environmental conditions, including water temperature, light availability, nutrient supply, and hydrodynamic mixing. Several pronounced peaks occurred during the year, representing temporary periods of enhanced

biological productivity. However, none of these events persisted for extended periods, indicating that phytoplankton growth remained under natural ecological control.

Monthly averages provide a broader perspective on seasonal biological productivity (Figure 25).

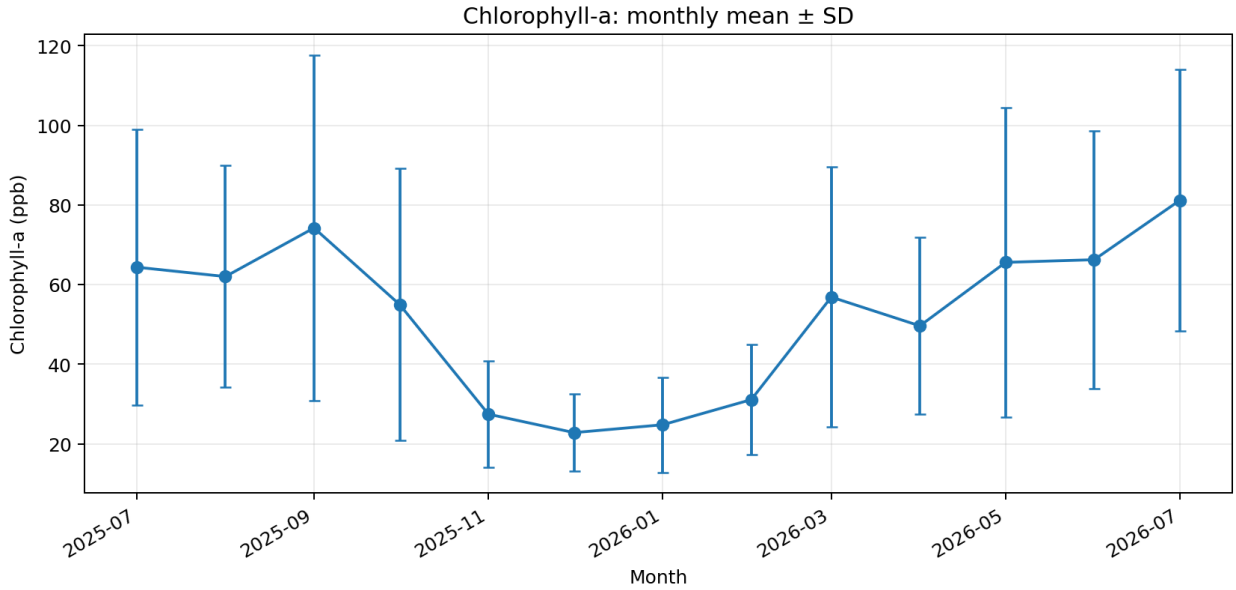


***Figure 25**. Monthly mean chlorophyll-a concentrations during the monitoring period.*

The monthly averages reveal a gradual seasonal pattern, with relatively lower chlorophyll a concentrations during colder months and increased biological productivity during warmer months. This behavior is consistent with seasonal increases in solar radiation, water temperature, and day length, all of which promote phytoplankton growth. Nevertheless, the seasonal pattern also reflects the influence of nutrient availability and hydrodynamic conditions, demonstrating that phytoplankton development is regulated by multiple interacting environmental factors.

Weekly averages illustrate the short-term biological variability captured by continuous monitoring (Figure 26).

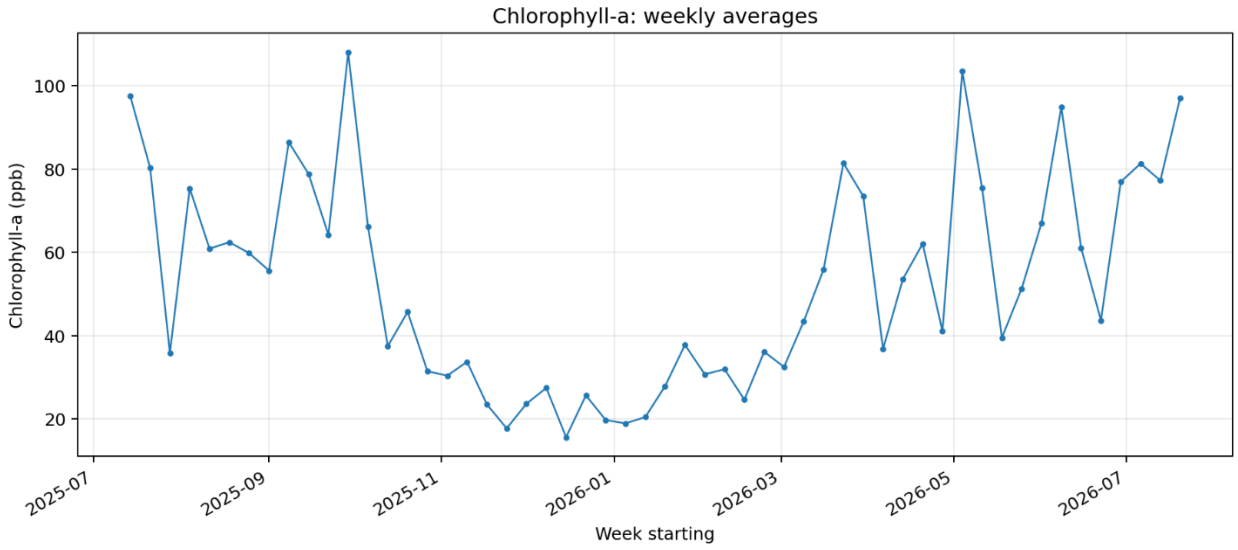


***Figure 26**. Weekly average chlorophyll-a concentrations.*

Compared with monthly averages, the weekly record highlights several rapid increases and decreases in chlorophyll-*a*. These fluctuations likely represent short-lived phytoplankton growth events associated with favorable environmental conditions, followed by natural declines resulting from nutrient limitation, grazing, water mixing, or changes in meteorological conditions. Such transient biological responses are characteristic of coastal marine ecosystems and demonstrate the value of continuous observations for detecting events that would likely remain unnoticed during conventional periodic sampling.

The rolling-average analysis further emphasizes long-term biological trends (Figure 27).

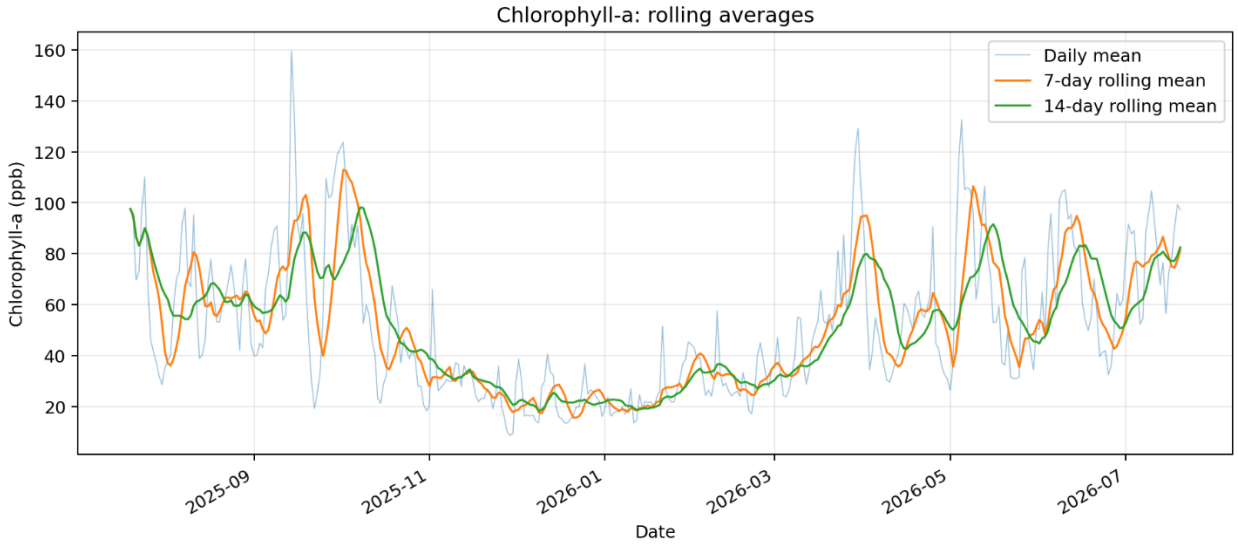


***Figure 27**. Rolling average chlorophyll-a concentrations.*

The rolling-average curve smooths short-term fluctuations and reveals the overall seasonal evolution of phytoplankton productivity. The analysis confirms that biological activity gradually

increased during warmer months before declining as environmental conditions became less favorable. Importantly, no sustained upward trend indicative of progressive eutrophication was observed during the monitoring period.

The chlorophyll-*a* dataset also demonstrates strong interactions with other monitored environmental parameters. Correlation analysis revealed a **moderate positive relationship** between water temperature and chlorophyll a (r = 0.464), indicating that increasing temperatures generally favored higher biological productivity. This relationship reflects the influence of seasonal warming on phytoplankton growth and represents one of the most significant biological patterns observed during the monitoring program.

Several chlorophyll-*a* peaks also coincided with temporary increases in turbidity. This association suggests that periods of elevated suspended particles may partly reflect increased phytoplankton biomass in addition to inorganic sediment inputs. Such simultaneous increases are common in productive coastal waters, where biological and hydrological processes frequently interact. However, the absence of prolonged chlorophyll-*a* enrichment, together with the rapid recovery following individual peaks, indicates that these events were part of the normal seasonal functioning of the ecosystem rather than manifestations of harmful algal blooms or persistent nutrient enrichment.

From an ecological perspective, the chlorophyll-*a* observations indicate a healthy balance between biological productivity and environmental stability. Moderate seasonal increases in phytoplankton biomass are expected and play a fundamental role in supporting marine food webs and oxygen production. The monitoring program detected no evidence of sustained phytoplankton accumulation or chronic eutrophic conditions, supporting the conclusion that the investigated coastal waters remained in **good ecological condition** throughout the annual cycle.

The continuous chlorophyll-*a* record provides an important biological baseline for future environmental monitoring. As coastal productivity may respond sensitively to climate change, nutrient inputs, and alterations in hydrological conditions, long-term observations will be essential for distinguishing natural interannual variability from emerging environmental trends. Integration of chlorophyll-*a* measurements with satellite remote sensing and complementary water-quality observations will further strengthen ecosystem assessment and improve regional environmental monitoring within the Black Sea Basin.

Overall, chlorophyll a proved to be an effective indicator of biological activity and ecosystem productivity during the monitoring program. Together with measurements of temperature, dissolved oxygen, oxygen saturation and turbidity, it contributes to a comprehensive understanding of the physical, chemical and biological processes governing the annual dynamics of the Georgian Black Sea coastal ecosystem.

3.8. Relationships Between Environmental Parameters

Understanding the interactions among environmental parameters is essential for interpreting the functioning of coastal marine ecosystems. Although each variable provides valuable information individually, their combined analysis offers a more comprehensive understanding of the physical, chemical, and biological processes governing ecosystem dynamics. The continuous multiparameter observations obtained during the EfxINNOs monitoring program made it possible to investigate these interactions throughout a complete annual cycle and to distinguish seasonal environmental responses from short-term variability.

Correlation analysis demonstrated that the monitored parameters were closely interconnected through well-established environmental processes. Most observed relationships were consistent

with the expected behaviour of temperate coastal marine ecosystems, indicating that the annual variability of the monitored waters was primarily driven by natural climatic and hydrodynamic processes rather than by persistent environmental disturbance.

3.8.1. Relationship Between Water Temperature and Dissolved Oxygen

Among all observed relationships, the strongest ecological significance was the inverse association between water temperature and dissolved oxygen. Correlation analysis produced a **moderate negative correlation (r = -0.325)**, confirming that oxygen availability decreased as water temperature increased (Figure 28).

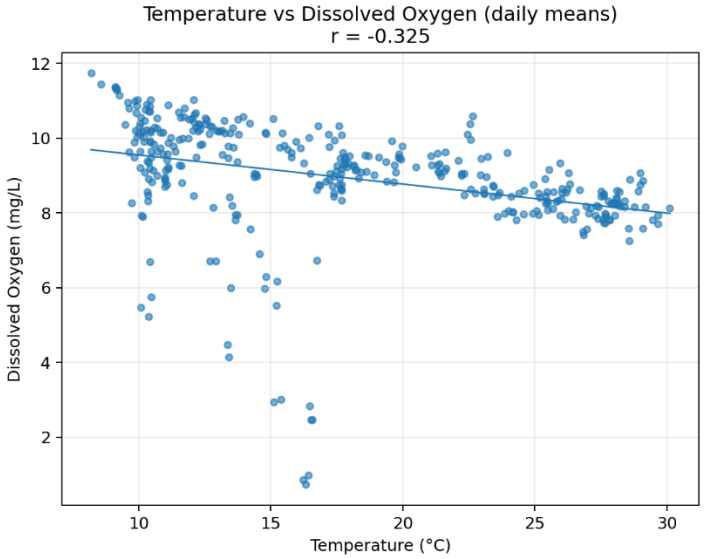


***Figure 28**. Scatter plot showing the relationship between water temperature and dissolved oxygen.*

This relationship reflects one of the most fundamental physical principles governing aquatic ecosystems. As water temperature increases, the solubility of oxygen decreases, reducing the maximum amount of oxygen that can remain dissolved in seawater. During summer, increased biological respiration further contributes to lower oxygen concentrations, whereas winter cooling enhances oxygen solubility and promotes vertical mixing, resulting in higher dissolved oxygen levels. Despite this seasonal decline, dissolved oxygen concentrations remained within environmentally acceptable limits throughout the monitoring period, demonstrating that the ecosystem maintained favourable oxygen conditions even during the warmest months.

3.8.2. Relationship Between Water Temperature and Chlorophyll-a

Correlation analysis also revealed a **moderate positive relationship (r = 0.464)** between water temperature and chlorophyll-*a* concentrations (Figure 29).

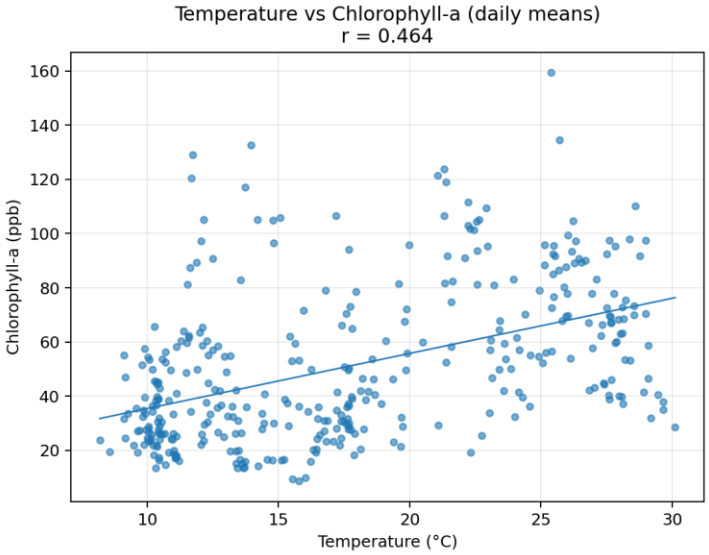


***Figure 29**. Scatter plot showing the relationship between water temperature and chlorophyll-a.*

This relationship reflects the strong influence of seasonal climatic conditions on phytoplankton productivity. Increasing water temperature during spring and summer coincided with longer daylight periods and enhanced solar radiation, creating favourable conditions for phytoplankton growth and primary production. However, temperature alone did not determine chlorophyll-*a* concentrations. Nutrient availability, water-column stability, hydrodynamic mixing and freshwater inputs also contributed to phytoplankton variability. Consequently, although higher temperatures generally favoured increased biological productivity, chlorophyll-*a* remained highly dynamic throughout the year.

3.8.3. Relationship Between Conductivity and Turbidity

The combined interpretation of conductivity and turbidity provides valuable information regarding freshwater influence on coastal waters (Figure 30).

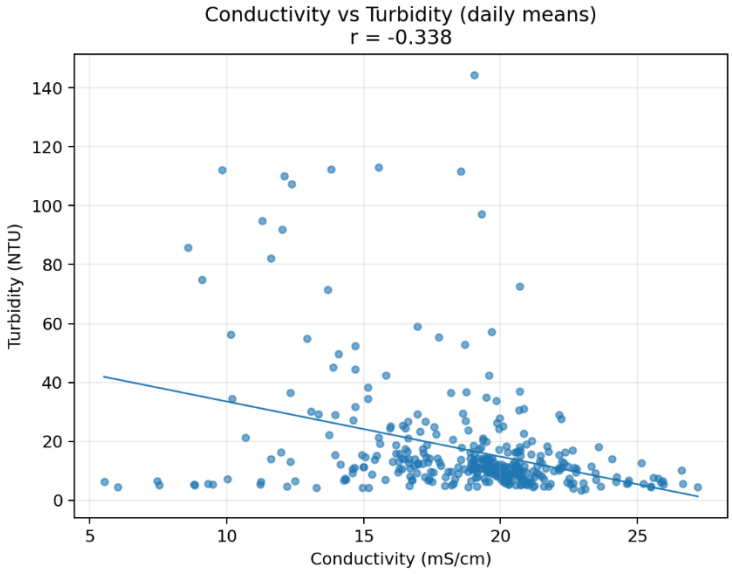


***Figure 30**. Scatter plot showing the relationship between conductivity and turbidity during selected monitoring periods.*

Several short-lived decreases in conductivity coincided with temporary increases in turbidity. This pattern suggests that rainfall and river discharge introduced suspended sediments together with lower-salinity freshwater into the monitored coastal zone. These hydrological responses were typically short-lived, and both parameters returned rapidly to baseline values after each event. Such behavior is characteristic of naturally functioning coastal environments influenced by episodic freshwater inflow rather than chronic hydrological disturbance.

3.8.4. Relationship Between Turbidity and Chlorophyll-a

The annual observations indicate that turbidity and chlorophyll-*a* occasionally increased simultaneously during certain periods of the monitoring programme (Figure 31).

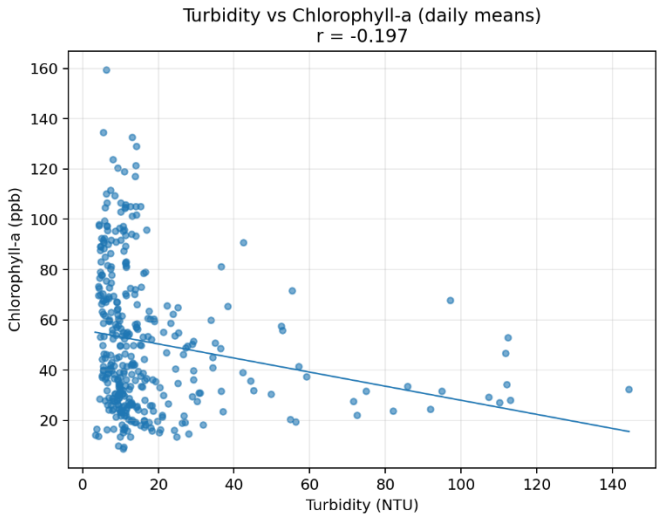


***Figure 31**. Temporal comparison of turbidity and chlorophyll-a.*

This relationship demonstrates that suspended material within coastal waters originates from multiple sources. While storm events and river inflow transport inorganic sediments into the coastal zone, periods of enhanced phytoplankton productivity increase the concentration of suspended biological particles. Consequently, elevated turbidity does not necessarily indicate deteriorating water quality but may instead reflect increased biological productivity or natural hydrological events.

The continuous observations enabled discrimination between these processes by simultaneously monitoring both parameters throughout the annual cycle.

3.8.5. Integrated Seasonal Relationships

When interpreted collectively, the monitored parameters reveal a coherent seasonal progression governed by climate-driven environmental processes. The annual observations indicate the following sequence:

1. Winter cooling increases oxygen solubility and promotes vertical mixing.

2. Spring warming stimulates phytoplankton growth through increasing solar radiation and favorable temperatures.
3. Summer conditions support maximum biological productivity while reducing oxygen solubility.
4. Autumn cooling restores higher oxygen concentrations as biological activity gradually declines.

Superimposed upon this seasonal cycle are short-duration hydrological events, including storms and freshwater inflow, which temporarily modify conductivity and turbidity without substantially altering the long-term environmental behavior of the ecosystem.

3.8.6. Correlation Matrix

The overall relationships among environmental parameters are summarized by the correlation matrix (Figure 32).

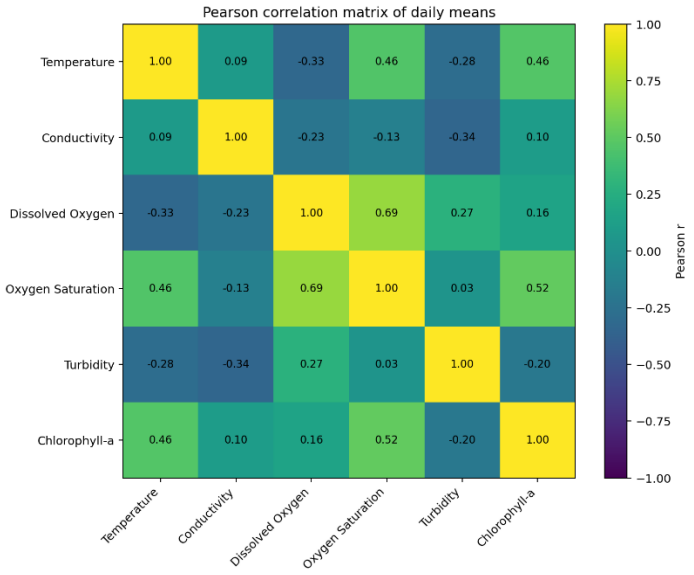


***Figure 32**. Pearson correlation matrix for the monitored environmental parameters.*

The correlation matrix provides a concise visual summary of the interactions among all measured variables. Most correlations were weak to moderate, reflecting the complexity of coastal marine ecosystems where multiple physical, chemical and biological processes operate simultaneously. Importantly, none of the observed relationships suggested abnormal ecosystem behaviour or persistent environmental degradation. Instead, the annual dataset demonstrates that seasonal climatic forcing remained the dominant control of environmental variability throughout the monitoring period.

3.8.7. Overall Interpretation

The multiparameter approach adopted in the EfxINNOs monitoring program proved essential for understanding ecosystem functioning. Individual environmental variables provide only partial information, whereas their combined interpretation reveals the mechanisms controlling seasonal ecosystem dynamics. The observed relationships demonstrate a well-balanced coastal

ecosystem in which physical forcing, hydrodynamic processes and biological productivity remain closely coupled. Seasonal changes in temperature regulate oxygen dynamics and primary production, while episodic hydrological events temporarily influence conductivity and turbidity without causing long-term environmental deterioration. Taken together, the correlation analysis supports the conclusion that the monitored coastal waters maintained **good ecological status** throughout the annual observation period. The interactions among the monitored variables are consistent with those expected for a healthy temperate coastal ecosystem and establish a valuable scientific baseline for future long-term monitoring and environmental assessment (Figure 33).

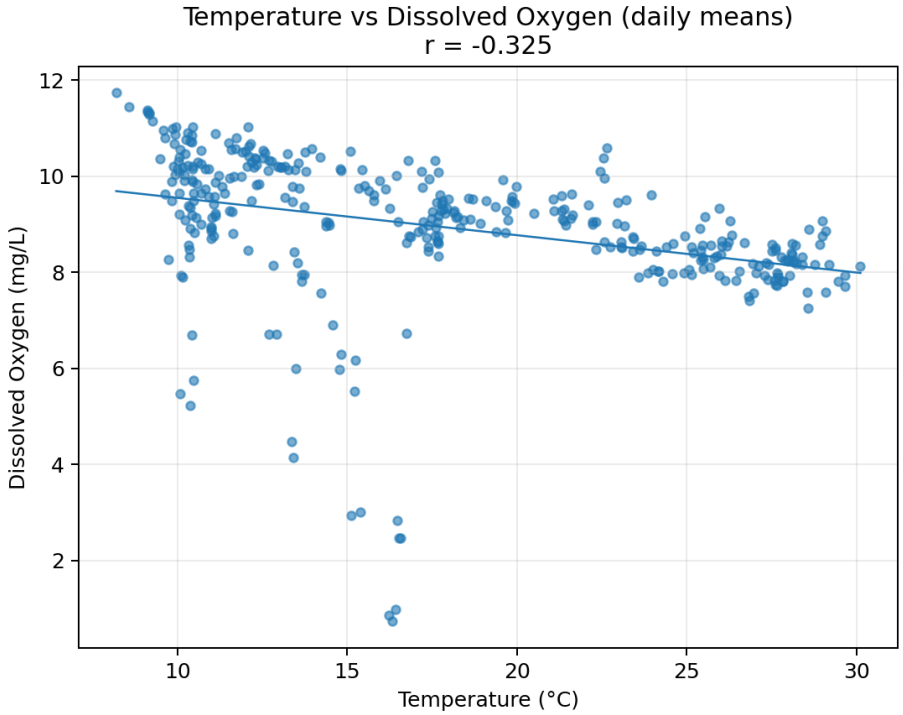


Figure 33. Scatter plot showing the relationship between water temperature and dissolved oxygen.

3.9. Seasonal Dynamics

Seasonal variability represents one of the defining characteristics of temperate coastal marine ecosystems. Throughout the annual cycle, environmental conditions are continuously modified by changes in solar radiation, atmospheric temperature, wind regime, precipitation, and hydrodynamic circulation. These seasonal drivers regulate the physical structure of the water column, influence chemical processes, and determine the intensity of biological productivity. The continuous observations obtained over 1 year during the EfxINNOs monitoring program provide a comprehensive picture of how these interacting processes shaped the annual evolution of the monitored coastal waters.

The annual dataset demonstrates that the environmental dynamics of the Poti coastal zone were primarily governed by predictable seasonal climatic forcing. While individual short-term events temporarily modified several environmental parameters, the overall ecosystem behaviour followed a consistent annual progression characteristic of the eastern Black Sea. This observation confirms that natural seasonal variability remained the dominant mechanism controlling environmental conditions throughout the monitoring period.

3.9.1. Summer Conditions

The monitoring program began during the summer season, when water temperature reached its highest annual values. Elevated solar radiation and extended daylight hours led to strong surface-water warming and stimulated phytoplankton productivity. During this period, chlorophyll-*a* concentrations generally increased, reflecting favourable conditions for primary production. At the same time, dissolved oxygen concentrations and oxygen saturation tended to decline because warmer water holds less dissolved oxygen and biological respiration becomes more intensive. Despite these seasonal changes, oxygen availability remained well within environmentally acceptable limits, indicating that the ecosystem maintained healthy conditions throughout the summer period.

3.9.2. Autumn Transition

Autumn was characterized by a gradual reduction in water temperature accompanied by progressive recovery of dissolved oxygen concentrations. Decreasing solar radiation reduced phytoplankton production, while stronger winds and increased vertical mixing enhanced oxygen exchange between the atmosphere and the water column.

Several short-term turbidity events were recorded during autumn, most likely associated with increased storm activity and episodic rainfall. These events temporarily increased suspended particle concentrations but did not result in persistent changes in water quality. Conductivity remained relatively stable throughout the season, indicating that freshwater influence was generally limited to brief hydrological episodes.

The autumn observations illustrate the transition from a biologically dominated summer regime towards a physically controlled winter environment.

3.9.3. Winter Conditions

Winter represented the period of maximum physical mixing within the monitored coastal waters. The lowest annual water temperatures were accompanied by the highest dissolved oxygen concentrations owing to increased oxygen solubility and enhanced vertical circulation.

Reduced solar radiation limited phytoplankton productivity, resulting in comparatively low chlorophyll-*a* concentrations. Water clarity generally remained high, although occasional storms temporarily increased turbidity through sediment resuspension.

The combination of low temperature, efficient mixing, and favorable oxygen conditions indicates that winter plays an important role in restoring environmental equilibrium within the coastal ecosystem by redistributing oxygen and nutrients throughout the water column.

3.9.4. Spring Recovery

Spring marked the beginning of renewed biological activity within the monitored ecosystem. Increasing solar radiation and gradually rising water temperatures promoted phytoplankton development, resulting in progressively increasing chlorophyll-*a* concentrations.

At the same time, dissolved oxygen remained relatively high because warming occurred gradually while vertical mixing was still active during early spring. This combination of favorable light conditions, nutrient availability, and adequate oxygen created optimal conditions for biological productivity.

The spring observations demonstrate the transition from the physically dominated winter period towards the biologically active summer season, illustrating the strong coupling between

climatic forcing and ecosystem response.

3.9.5. Seasonal Evolution of Individual Parameters

The integrated annual dataset demonstrates that each monitored parameter responded differently to seasonal forcing:

Water temperature exhibited the strongest and most regular seasonal cycle, closely following changes in atmospheric conditions.

Conductivity remained relatively stable throughout the year, with only temporary decreases associated with freshwater inflow following rainfall or river discharge events.

Dissolved oxygen displayed an inverse seasonal relationship with temperature, reaching maximum values during winter and minimum values during summer while remaining within environmentally favorable limits.

Oxygen saturation followed a similar seasonal pattern and reflected the balance between atmospheric exchange, biological production, and oxygen consumption.

Turbidity was dominated primarily by episodic storm events and river discharge rather than gradual seasonal trends.

Chlorophyll a increased during periods favorable for phytoplankton growth but returned rapidly to background levels after temporary productivity peaks, indicating a balanced biological system.

3.9.6. Integrated Seasonal Behaviour

The combined interpretation of all monitored parameters indicates that the annual dynamics of the coastal ecosystem followed a coherent, internally consistent seasonal progression. Physical drivers, particularly temperature and water-column mixing, regulated oxygen availability, while biological productivity responded primarily to seasonal changes in solar radiation and environmental conditions. Short-term hydrological events temporarily altered turbidity and conductivity but did not alter the ecosystem's long-term seasonal trajectory.

The annual observations, therefore, indicate that environmental variability within the monitored coastal waters was predominantly controlled by natural seasonal processes rather than persistent anthropogenic disturbance. The absence of prolonged oxygen depletion, sustained turbidity increases, or continuous chlorophyll a enrichment supports the conclusion that the ecosystem maintained stable ecological functioning throughout the monitoring period.

3.9.7. Seasonal Synthesis

Taken together, the seasonal analyses reveal a coastal ecosystem operating within its expected natural range of variability. Summer conditions promoted biological productivity, autumn initiated physical recovery, winter restored oxygen-rich conditions through vertical mixing, and spring triggered renewed ecosystem development. This continuous seasonal succession represents the normal functioning of temperate Black Sea coastal waters and provides an essential ecological baseline for evaluating future environmental change.

The one-year monitoring program, therefore, demonstrates not only the value of continuous autonomous observations but also the importance of interpreting environmental parameters as components of an integrated seasonal system rather than as isolated measurements. Such an ecosystem-based approach provides a more robust scientific foundation for environmental assessment, climate-change studies and sustainable coastal management (Figure 34).

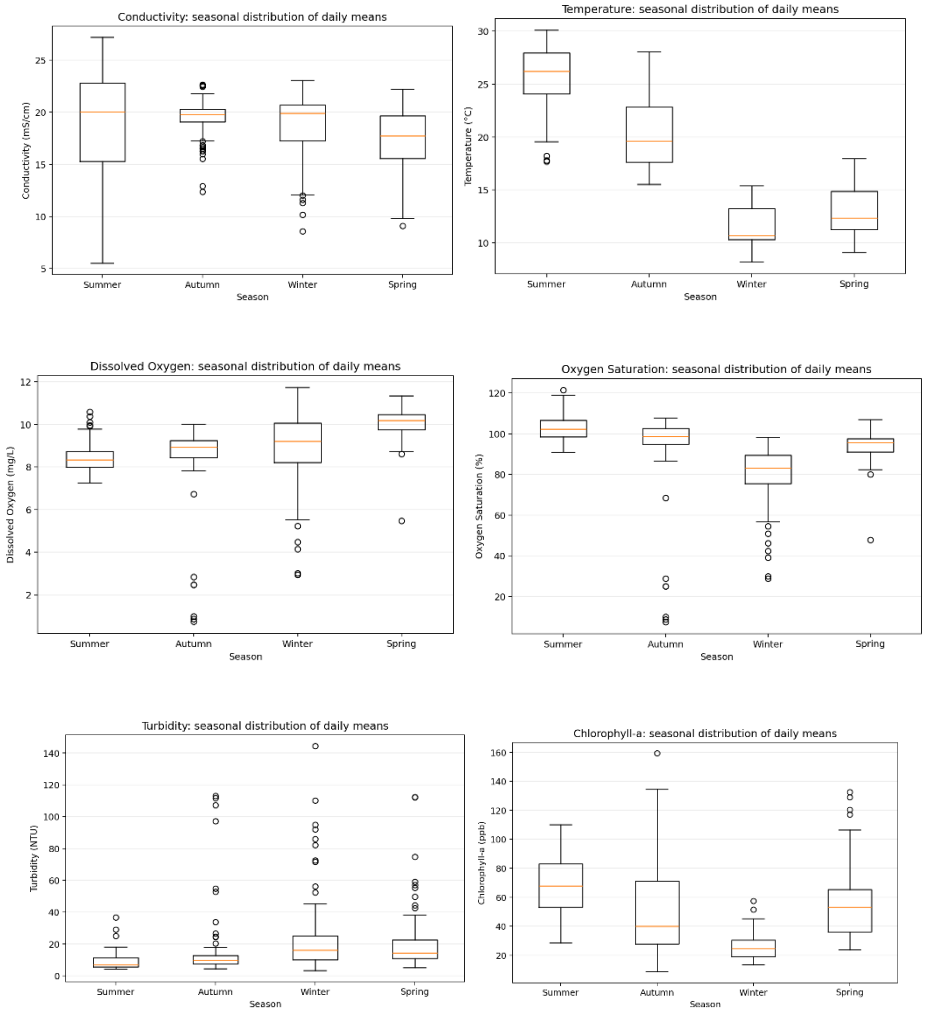


***Figure 34**. Seasonal distribution of daily means of measured variables.*

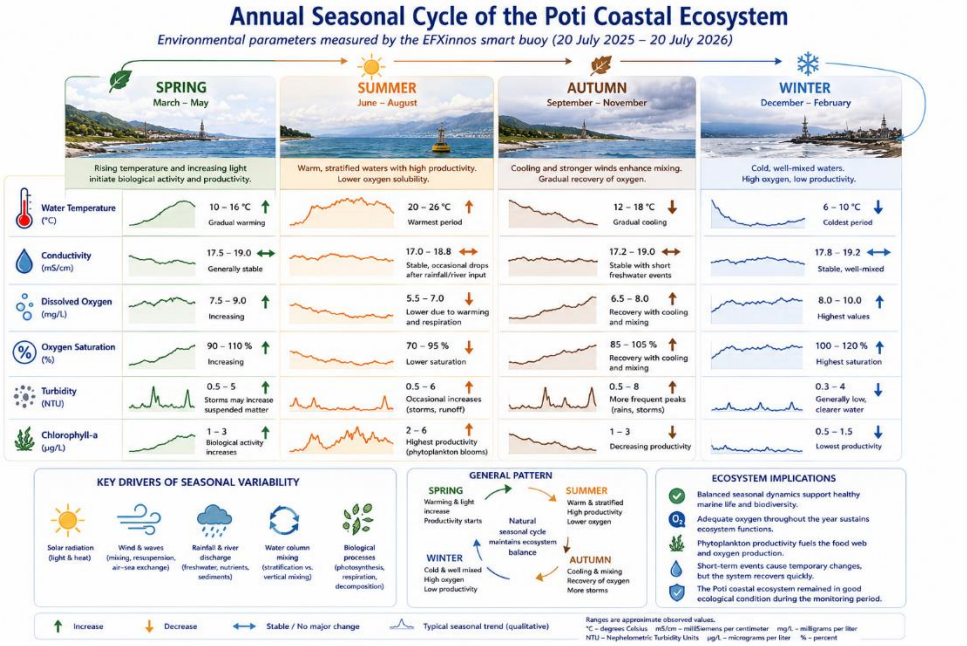


Figure 35. Annual seasonal Cycles of the Poti ecosystem.

3.10. Overall Ecological Status

Based on the complete annual dataset, the ecological condition of the monitored coastal waters can be summarised as follows:

Environmental Component	Assessment
Physical Status	Good
Chemical Status	Good
Biological Status	Good
Oxygen Conditions	Good
Hydrological Stability	Good
Ecosystem Resilience	High

The integrated evaluation indicates that the monitored coastal waters remained in **Good Ecological Status** throughout the monitoring period. Seasonal environmental variability was governed predominantly by natural climatic and hydrological processes, while the ecosystem demonstrated strong resilience and rapid recovery following temporary disturbances.

3.11. Conclusions

The first annual monitoring cycle of the EfxINNOs smart buoy programme has successfully established a comprehensive environmental baseline for the Georgian sector of the Black Sea. Continuous high-frequency observations collected between **20 July 2025 and 20 July 2026** provided an integrated assessment of the physical, chemical and biological characteristics of the monitored coastal waters and demonstrated the value of autonomous monitoring

technologies for long-term environmental observation.

The monitoring results showed that environmental variability was dominated by natural seasonal processes. Water temperature followed the expected annual thermal cycle, conductivity remained generally stable, dissolved oxygen and oxygen saturation reflected normal seasonal oxygen dynamics, turbidity responded primarily to short-term hydrological and meteorological events, and chlorophyll-*a* exhibited seasonal fluctuations consistent with natural phytoplankton productivity. Collectively, these observations indicate that the monitored ecosystem functioned within its expected natural range throughout the study period.

Continuous monitoring proved particularly valuable for identifying short-duration environmental events that would likely have remained undetected using conventional sampling programs. Storm-induced turbidity peaks, temporary freshwater inflow episodes, and transient increases in biological productivity were successfully captured and interpreted using simultaneous multiparameter observations. Importantly, all identified events were followed by rapid recovery to baseline conditions, demonstrating the resilience of the monitored coastal ecosystem.

The integrated interpretation of environmental parameters confirmed the close coupling between physical, chemical, and biological processes within the coastal environment. Seasonal changes in water temperature regulated oxygen availability and influenced biological productivity, while hydrological events temporarily modified conductivity and turbidity. These interactions illustrate the importance of evaluating coastal ecosystems through an integrated, multiparameter approach rather than interpreting individual variables in isolation.

One of the principal outcomes of the monitoring program is the confirmation that the investigated coastal waters remained in **good ecological status** throughout the annual observation period. No evidence of persistent hypoxia, chronic turbidity increase, prolonged conductivity disturbance or sustained chlorophyll-*a* enrichment was observed. Instead, the recorded variability reflected normal ecosystem functioning under changing seasonal conditions.

The experience gained during the deployment and operation of the smart buoy further demonstrated the practicality and reliability of autonomous monitoring systems under the environmental conditions of the Georgian Black Sea coast. Routine maintenance, systematic quality-control procedures, and continuous data acquisition ensured the production of a high-quality dataset suitable for scientific analysis and environmental assessment.

Beyond its immediate scientific findings, the monitoring program establishes a robust foundation for future environmental observation and research. The dataset provides an important reference for evaluating long-term climatic trends, assessing ecosystem resilience, and supporting evidence-based coastal management. Integration of autonomous buoy observations with satellite remote sensing, laboratory analyses, numerical modeling, and machine-learning approaches offers significant opportunities to enhance future monitoring and forecasting capabilities.

The EfxINNOs monitoring program, therefore, represents an important step towards the development of an integrated marine observation system for the Georgian Black Sea coast. Continued long-term monitoring, expansion of observation networks and strengthened regional scientific collaboration will contribute to improved understanding of Black Sea ecosystem dynamics and support sustainable management of marine resources within the framework of the Blue Economy.

SECTION B – Machine Learning Modeling

4. Technical Framework and Innovations

A machine-learning–based forecasting system will be developed to generate short-term predictions for water temperature, oxygen concentration, and chlorophyll-a levels. The system will be designed to exceed the capabilities of traditional statistical approaches by integrating advanced data-cleaning procedures with modern predictive modeling techniques, including tree-based ensemble methods and sequence-learning architectures.

Through this combined methodology, the system will be able to handle noisy sensor signals, capture nonlinear interactions among environmental variables, and learn temporal dependencies across multiple time horizons.

The overarching objectives of the system are to deliver high predictive accuracy, maintain adaptability to changing environmental and sensor conditions, and ensure interpretability so that model outputs can support scientific understanding and operational decision-making.

4.1. Core System Enhancements

The system's design incorporates several methodological enhancements to ensure robust and reliable forecasting performance.

XGBoost will serve as the primary predictive model, as it is well-suited for small-to-medium time-series datasets and demonstrates strong resilience to noisy sensor measurements. Optionally, recurrent neural networks such as LSTMs can be explored as an advanced extension to capture long-term temporal patterns, though they are not required for the core implementation.

Data quality will be safeguarded through a rigorous cleaning pipeline that includes range validation, anomaly detection, and light noise-reduction procedures, ensuring that only trustworthy observations are used during model training and prediction.

To promote transparency and interpretability, the system will generate feature-importance analyses for all models, while SHAP values may be optionally computed as an advanced interpretability module for deeper insights into how variables such as turbidity, conductivity, and oxygen saturation influence predictions.

Finally, an adaptive deployment strategy is planned, where the system may dynamically select the best-performing model for each target variable. Continuous monitoring would allow the system to adjust to evolving environmental conditions and sensor performance.

4.2. Advanced Modeling Extensions

In addition to the primary modeling approaches, several optional techniques may be incorporated to further enhance forecasting performance depending on data availability and project scope.

A Random Forest model will serve as a simpler tree-based baseline, providing a useful comparison point for evaluating the added value of more complex algorithms. For situations where short-term spikes or distinct temporal patterns need to be captured more effectively, hybrid architectures such as CNN-LSTM or temporal convolutional networks (TCN) may be explored, as they can model both local temporal structures and broader sequential dynamics.

Furthermore, attention-based architectures, including Transformer models, may be considered for longer datasets where complex seasonal cycles, long-range dependencies, or multiscale temporal relationships are present, offering a more advanced mechanism for learning patterns over extended time horizons.

5. Implementation Strategy

5.1. Data Quality Control Pipeline

Because sensor-derived environmental data often contain errors, inconsistencies, and noise, a structured, comprehensive cleaning pipeline will be implemented before any modeling.

This process will begin with range filtering, where values that fall outside physically plausible limits are discarded to prevent unrealistic readings from influencing the models. Outlier detection techniques, such as rolling medians, z-scores, and interquartile-range–based methods, will then be applied to identify and remove short-term spikes and sensor noise.

To further stabilize the time series, smoothing procedures, including moving averages or median filters, will be used. Missing data will be handled through interpolation or forward/backward filling, and all imputed values will be flagged to preserve information about data reliability. Once the dataset is structurally consistent, numeric features will be normalized or scaled to ensure that the learning algorithms can process the data effectively.

For datasets extending beyond four months, additional adaptive adjustments such as drift correction and seasonal trend decomposition will be incorporated to account for gradual sensor drift and multi-month environmental cycles, ensuring that long-term patterns are accurately represented.

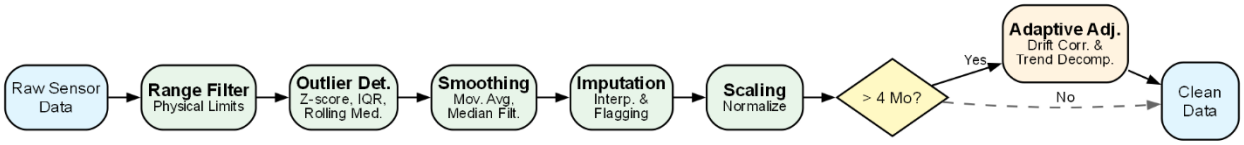


Figure 36. Comprehensive sensor data cleaning and pre-processing pipeline.

5.2. Predictive Feature Development

To enable the forecasting models to fully capture the complex temporal and biogeochemical dynamics that influence water temperature, oxygen concentration, and chlorophyll-a levels, a comprehensive feature-engineering framework will be implemented.

This framework is designed to enrich raw sensor data with additional temporal, statistical, and ecological context, enabling models to recognize both short-term fluctuations and broader environmental patterns. By incorporating information about recent history, long-term trends, diurnal and weekly cycles, rates of change, and biologically meaningful interactions among variables, the models will have access to a much deeper representation of the system's behavior than the raw measurements alone can provide.

The engineered features will also help the models remain robust in the presence of noise, generalize across varying conditions, and support more accurate short- and medium-term predictions. The main categories of features included in this framework are outlined below:

1. **Lag Features (High Priority)**
   - Past values of each variable over multiple time windows to capture temporal dependencies.
   - Example windows: short-term (t-1,t-2,t-3), medium-term (t-6,t-12,t-24).
2. **Rolling Statistics (High Priority)**

- Summary statistics over short- and medium-term windows to highlight trends and variability.
- Examples: rolling mean, median, and standard deviation over 3-6 hour and 12-24 hour windows.

3. **Time-Based / Cyclical Features (High Priority)**
   - Encode daily and weekly cycles to capture recurring patterns.
   - Examples: hour-of-day, day-of-week, and sine/cosine transformations of hourly cycles.
4. **Rate-of-Change Features (Medium Priority)**
   - Capture how quickly variables change over time.
   - Example: Δvalue/Δtime for temperature, oxygen, and chlorophyll-a.
5. **Cross-Variable Interactions (Medium Priority)**
   - Combine variables in biologically meaningful ways to capture relationships.
   - Example: oxygen concentration ÷ saturation, temperature × chlorophyll-a.
6. **Seasonal and Long-Term Features (Optional / Low Priority)**
   - Capture longer-term trends and seasonal patterns for datasets spanning months or years.
   - Examples: month-of-year, multi-week rolling averages, and seasonal decomposition components.

Table 2. Feature Types and Suggested Implementations for Short- and Medium-Term Environmental Forecasting.

Feature Type	Description	Suggested Implementation
Lag Features	Past values of each variable to capture temporal dependencies	Short-term: t-1,t-2,t-3 Medium-term: t-6,t-12,t-24
Rolling Statistics	Summarize recent history to detect trends and variability	Rolling mean, median, std over windows: 3h, 6h, 12h, 24h
Rate-of-Change	Speed of change for each variable	$\Delta value/\Delta time = value_t - value_t - 1$ (can use multiple lags)
Time-Based / Cyclical	Encode recurring daily and weekly patterns	Hour-of-day, day-of-week, sine/cosine transformations: $sin(2\pi * hour/24)$, $cos(2\pi * hour/24)$
Cross-Variable Interactions	Biologically meaningful combinations	$Oxygen \div Saturation$, $Temperature \times Chlorophyll - a$
Seasonal / Long-Term (Optional)	Capture monthly or multi-week trends	Month-of-year, multi-week rolling averages (e.g., 2-week, 4-week), seasonal decomposition components (trend, seasonal, residual)

5.3. Model Architecture and Selection

The modeling strategy will be structured around a combination of baseline, primary, and optional architectures to ensure both methodological rigor and flexibility.

As a starting point, simple baseline models such as persistence (which assumes the next value equals the most recent observation) and moving-average forecasts will be implemented to establish reference benchmarks against which more advanced models can be evaluated. Building on this foundation, the primary modeling approaches will include XGBoost, optimized through systematic hyperparameter tuning using Optuna, to capture nonlinear relationships and interactions within the dataset, as well as LSTM networks, which are particularly well suited

for learning long-term temporal dependencies and sequential patterns in water quality data.

Beyond these core methods, a range of optional models will be considered to address specific forecasting challenges or leverage longer datasets. These include Random Forests as an additional tree-based benchmark, CNN-LSTM hybrids and temporal convolutional networks (TCN) for detecting short-term spikes and localized temporal structures, and attention-based architectures such as Transformers, which become especially valuable when datasets extend beyond four months and contain complex seasonal or long-range dependencies.

The system will also evaluate both single-output and multi-output modeling strategies, with multi-output architectures becoming increasingly reliable as the dataset length grows. Finally, probabilistic forecasting capabilities will be incorporated through techniques such as quantile regression with XGBoost or Monte Carlo dropout applied within LSTMs, enabling the generation of prediction intervals and uncertainty estimates that support risk-aware decision-making.

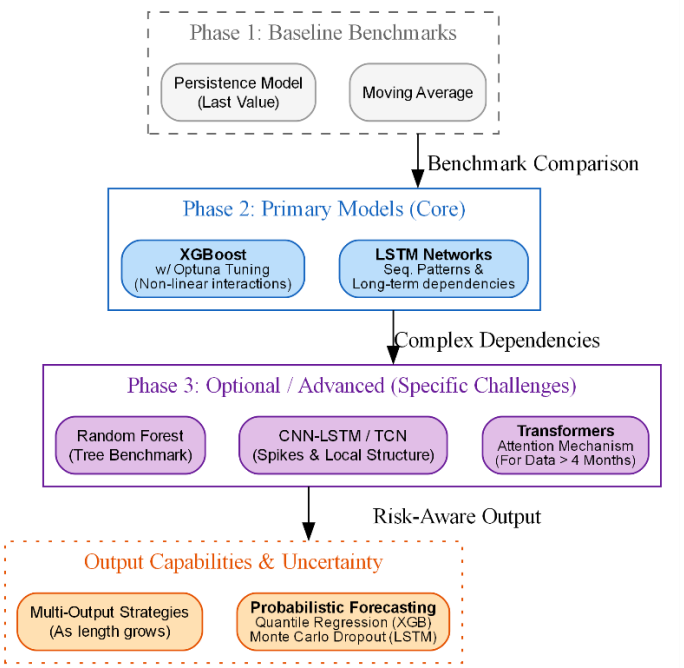


Figure 37. Modeling Strategy Overview.

5.4. Performance Assessment Framework

Model evaluation will be conducted using a rigorous validation framework that reflects real operational conditions. A walk-forward validation strategy will be applied, allowing the models to be trained on historical data and tested on future, unseen segments in a sequential manner that closely mimics real-world forecasting scenarios.

Performance will be quantified using a suite of error metrics, including RMSE, MSE, sMAPE, and MASE, to ensure not only overall accuracy but also meaningful improvements over naive baseline models. In addition to these metrics, detailed residual analysis will be performed to identify systematic patterns in prediction errors, such as consistent underestimation during high-chlorophyll events or biases associated with rapid environmental transitions.

Where appropriate, statistical significance tests will be employed to rigorously assess whether observed performance differences between competing models are meaningful and not the

result of random variation. This multifaceted evaluation process will provide a comprehensive understanding of model behavior and reliability.

6. Monitoring Infrastructure and Variables

The dataset will span approximately 4 months or more, providing continuous monitoring of key environmental parameters. This extended coverage ensures the collection of high-resolution temporal data, which is essential for detecting trends, seasonal changes, and potential anomalies in the aquatic environment. Continuous monitoring over this period enables robust analysis of both short-term fluctuations and longer-term patterns in water quality.

The primary target variables for this dataset are:

- **Water Temperature (°C)**, is a critical indicator of the thermal state of the water body, influencing both chemical and biological processes
- **Oxygen Concentration (mg/L)**, is vital for assessing the health and sustainability of aquatic ecosystems, as it directly affects the respiration of aquatic organisms, and,
- **Chlorophyll a (ppb)** serves as a proxy for phytoplankton biomass and overall primary productivity, providing insights into the trophic state of the water body.

In addition to the target variables, several supporting predictors will also be collected to enhance the interpretation of the dataset. These are:

- **Oxygen Saturation (%)**, complements oxygen concentration by providing information on the relative saturation of oxygen in water under ambient conditions,
- **Turbidity (NTU)**, reflects the clarity of the water and can indicate the presence of suspended particles, including sediments or organic matter,
- **Uncompensated Conductivity (mS/cm)**, helps assess the ionic content of the water, which can influence various chemical and biological processes, and,
- **Battery Voltage (Volts, for sensor health monitoring)**, is included to track the operational health of the sensors, ensuring data quality and reliability throughout the monitoring period.

6.1. Data Quality Strategy

To ensure the quality and reliability of the dataset, valid ranges will be defined for each measured parameter, and any impossible or clearly erroneous readings will be removed. This initial step helps eliminate outliers caused by sensor malfunctions, environmental anomalies, or data entry errors, providing a solid foundation for subsequent analysis.

Sensor drift and battery-related issues will be carefully monitored. Instances where measurements are affected by gradual sensor degradation or low battery performance will be flagged and either corrected through calibration or discarded if correction is not feasible. This process ensures that the data remains accurate and consistent over the entire monitoring period.

Missing data is an unavoidable aspect of long-term monitoring and will be addressed according to the length of the gaps. Short gaps in the data will be filled using interpolation techniques, while longer gaps may be handled through model-based imputation methods or, if necessary, excluded from analysis. This approach minimizes the risk of introducing bias while maintaining the continuity of the dataset.

After cleaning, the dataset will be stored alongside confidence flags that indicate the reliability of each measurement. These flags allow downstream analyses to weigh data appropriately, ensuring that results are informed by the quality of the underlying measurements.

For datasets extending beyond four months, additional adjustments will be applied to account for seasonal trends and potential long-term sensor drift. These corrections help maintain the integrity of the dataset over longer temporal scales, enabling robust analysis of both short-term variations and seasonal patterns in the monitored environment.

7. Recommendations & Practical Scope

The modeling framework for this dataset will include both mandatory and optional approaches to ensure robust and reliable predictions. Mandatory models will consist of XGBoost and LSTM networks, which are well-suited for handling short to moderately long datasets. XGBoost provides powerful gradient-boosted decision tree capabilities, while LSTM networks excel at capturing temporal dependencies in sequential data, making this combination highly effective for accurate forecasting.

In addition to the mandatory models, several optional approaches can be considered depending on the dataset's length and complexity. These include Random Forest, CNN-LSTM hybrid networks, Temporal Convolutional Networks (TCN), and attention-based architectures. Such models are particularly advantageous for datasets that extend beyond six to twelve months, as they can better capture long-term dependencies and complex patterns in the data.

A strong emphasis will be placed on several key focus areas to maximize model performance and reliability. Data cleaning, walk-forward validation, feature engineering, and interpretability will be prioritized throughout the modeling process. These steps ensure that the models are trained on high-quality data, validated in a realistic forecasting setting, and remain interpretable, allowing for actionable insights from the predictions.

For longer datasets, additional modeling strategies can be employed to capture more intricate temporal dynamics. Multi-output learning approaches, seasonal decomposition techniques, and more sophisticated network architectures will be used to identify and leverage long-term patterns. These enhancements are particularly useful when the dataset spans multiple seasons or years, enabling the models to produce more nuanced and accurate forecasts.

8. Expected Deliverables and Products

The forecasting system will generate a structured set of outputs, carefully designed to balance scientific rigor with practical applicability. This structured approach ensures that results are not only accurate and reliable but also meaningful for decision-making and further analysis. By organizing outputs according to their importance and complexity, the system provides a clear roadmap for both immediate needs and potential extensions.

To enhance clarity and usability, outputs are categorized into three levels: Mandatory, Recommended, and Optional. Mandatory outputs represent essential results that must be produced to meet the core objectives of the forecasting system. Recommended outputs provide additional insights that add value and deepen understanding, supporting more informed decisions. Optional outputs represent advanced or "stretch" goals, which may be pursued if resources, time, or dataset length allow, offering the potential for more sophisticated analyses and long-term insights.

This tiered structure ensures that the system remains practical and achievable, while still allowing flexibility for expansion and refinement. It also provides a framework for prioritizing resources and efforts, ensuring that the most critical outputs are delivered reliably, while more advanced analyses can be incorporated progressively as conditions permit.

8.1. Mandatory Outputs (Core Deliverables)

These outputs are designed to be essential for demonstrating the effectiveness of the forecasting system and for achieving the project's primary objectives. They provide a comprehensive view of both predicted environmental conditions and the system's performance, enabling rigorous evaluation while remaining directly relevant for practical applications. The following outputs outline the key predictions, forecast horizons, and evaluation metrics that will guide the assessment of the system.

1. **Predicted Variables**
    - Water Temperature (°C): A critical parameter for aquatic ecosystem stability.
    - Oxygen Concentration (mg/L): Determines habitability for fish and other organisms.
    - Chlorophyll-a (ppb): A proxy for algal activity, relevant for bloom detection.
    - Each will be predicted as a time series aligned with the input sampling frequency (e.g., hourly).
2. **Short-Term Forecasts (1-6 hours ahead)**
    - These will serve as the core forecasting horizon because they are achievable with 4 months of data and directly relevant for real-time monitoring.
    - Forecasts will provide early warning for rapid changes (e.g., oxygen depletion events).
3. **Evaluation with Error Metrics**
    - Mean Squared Error (MSE) and Root Mean Squared Error (RMSE): To measure prediction accuracy.
    - Symmetric Mean Absolute Percentage Error (sMAPE): To allow scale-independent comparisons.
    - Mean Absolute Scaled Error (MASE): To benchmark against naive models.
    - This ensures the models are not just accurate but also validated against meaningful baselines.

4. **Baseline Model Comparison**
    - Persistence (last observed value) and moving average forecasts will be used as benchmarks.
    - These comparisons will show the added value of ML models in real-world conditions.

8.2. Recommended Outputs (optional)

These outputs are not strictly required for the core functioning of the forecasting system but are expected to enhance usability, build trust, and strengthen the scientific robustness of the results. They provide additional insights into medium-term predictions, uncertainty, and interpretability, supporting informed decision-making and facilitating communication of results to a broader audience.

1. **Medium-Term Forecasts (1–3 days ahead)**
    - If temporal dependencies are strong, forecasts will be extended up to several days.
    - This provides value for management decisions (e.g., planning interventions).
2. **Prediction Intervals (Uncertainty Estimates)**
    - Forecasts will include confidence bands (e.g., 10th–90th percentile) rather than just point estimates.
    - This allows decision-makers to gauge risk levels (e.g., probability of oxygen < 4 mg/L).
    - Methods: quantile regression (XGBoost) or MC dropout (LSTM).
3. **Feature Importance Analysis (Global Level)**
    - XGBoost will be used to rank predictors by importance.
    - Example: Turbidity may emerge as a key driver for chlorophyll prediction.
    - Helps explain why predictions are made and supports domain knowledge.
4. **Basic Visualization Dashboard**
    - Time-series plots of observed vs predicted values.
    - Overlay of uncertainty ranges for interpretability.
    - Simple user interface
    - This makes results more accessible to non-technical users.

8.3. Optional / Extended Scope

These outputs will be considered if time and resources permit or may be developed in a follow-up phase. They represent advanced functionalities that demonstrate deployment-readiness and the application of sophisticated machine learning techniques. By providing detailed interpretability, scenario testing, and extended forecasting capabilities, these outputs add value for both operational decision-making and scientific research.

1. **Local Interpretability (e.g., SHAP Values)**
    - Per-prediction explanations: why did the model predict low oxygen at a specific time?
    - Example: Rising turbidity + falling saturation flagged as drivers of low oxygen.
    - Adds trust for operators and regulators.

2. **Residual Analysis & Statistical Testing**
    - Error distributions will be analyzed over time to identify systematic bias (e.g., underprediction in high-chlorophyll periods).
    - Statistical significance tests will confirm whether improvements over baselines are meaningful.
3. **Threshold-Based Alerts**
    - Rules will be defined for critical thresholds (e.g., oxygen < 4 mg/L, chlorophyll > 50 ppb).
    - Forecast-driven alerts will be generated and could be sent as automated warnings.
    - This feature supports operational decision-making.
4. **Scenario Testing (What-if Analysis)**
    - Users could modify inputs (e.g., simulate increased turbidity or conductivity) to see how forecasts respond.
    - Useful for research and management planning.
5. **Extended Forecasts (Seasonal Horizons, 1-4 weeks)**
    - If datasets extend beyond 4 months, models will incorporate seasonal patterns.
    - Advanced architectures (e.g., CNN-LSTM, TCN) may then be tested.
    - This enables medium-to-long-term water quality planning.

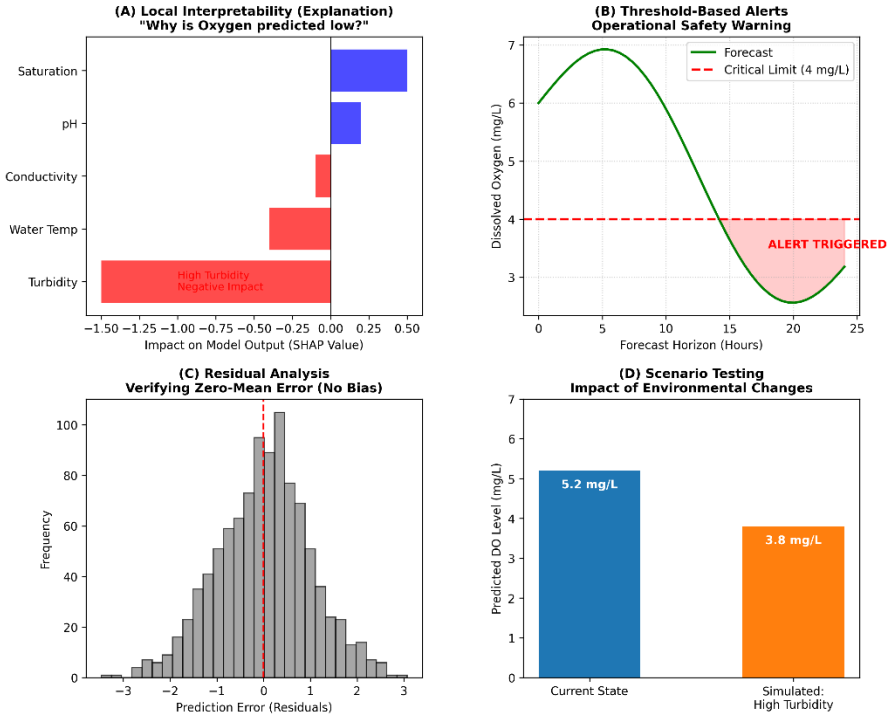


Figure 38. Advanced Operational Outputs & Interpretability.