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Black Sea Environmental Innovative Monitoring System

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Abstract

The Black Sea is a highly sensitive, semi-enclosed marine ecosystem exposed to significant anthropogenic pressures, including pollution, climate change, and coastal development. The Black Sea Smart Marine Environmental Outcome System (BS-SEOS), supported by the INTERREG NEXT Black Sea Basin Programme, an innovative framework designed to improve monitoring and management of one of the world's most sensitive marine ecosystems. The system integrates uncrewed surface vehicles equipped with multisensory instruments to collect high-resolution, real-time data on key environmental parameters, including temperature, pH, dissolved oxygen, and chlorophyll-a. These observations are processed through a structured data pipeline and analyzed using advanced AI models to predict ecological risks such as hypoxia and harmful algal blooms. By enabling continuous, transnational data sharing and early warning capabilities, BS-SEOS supports informed decision-making and proactive environmental management. The project enhances regional cooperation, strengthens ecosystem resilience, and contributes to sustainable development and long-term protection of the Black Sea.

Keywords: Black Sea, Climate Change, Innovative Monitoring, AI forecasting, uncrewed surface vehicles - drones

Introduction

The Black Sea is one of the most unique and sensitive marine ecosystems in the world. Almost entirely enclosed, shared by six countries, and strongly influenced by human activity, it reacts faster to environmental pressure than open oceans. Pollution, climate change, overfishing, coastal development, and geopolitical complexity have placed the Black Sea under constant stress. At the same time, rapid advances in technology are creating new opportunities to understand, monitor, and protect this vulnerable sea. Even small changes in temperature, nutrient input, or circulation can trigger large-scale ecological consequences such as algal blooms, biodiversity loss, or ecosystem collapse. Traditional monitoring methods: coastal line, ship-based measurements. The Black Sea requires multydirection continuous, real-time, and transnational observation to detect changes early and respond effectively. Black Sea Smart Marine Environmental Outcome System: BS-SEOS project initiated under financial support of INTERREG NEXT Black Sea Basin funding mechanism in order to address these challenges by establishing a comprehensive, reliable, and integrated environmental monitoring system for the Black Sea Basin. BS-SEOS project designed to enhance the health and sustainability of the Black Sea. The Innovative Environmental Monitoring System, by leveraging cutting-edge AI forecasting and uncrewed surface vehicles - drones, will collect, analyze, and share critical environmental data across borders, ensuring a resilient and thriving marine ecosystem.

Innovative monitoring system

BS-SEOS is a collaborative project aimed at enhancing the understanding of the Black Sea's ecosystem by collecting and sharing environmental data. Using innovative technologies like uncrewed surface vehicles (USV) - drones (**Figure 1. USV-drone's System**), the project facilitates continuous monitoring of key marine parameters such as:

- Temperature: Measuring range -5° to +40°C (Accuracy ±0.5°C);
- Conductivity: Measuring range 0 – 200 mS/cm (Accuracy ± 1%);
- Dissolved Oxygen: Optical sensor, range 0 – 40.00 mg/L;
- pH: Accuracy ± 0.2 pH;
- Chlorophyll-a: Optical with autoscaling, range 0 – 500 μg/l.

Calculated Parameters:

- Salinity, Water Resistivity, Total Dissolved Solids, Water Density.

Data Acquisition:

- Multi-GNSS receiver for precise positioning;
- Sampling rate: At least one measurement every 30 seconds.

The drone-mobile stations will be used along the coast and will monitor selected physical and chemical parameters via multi sensors from three vertical depths including surface, 5m, and 10m, for water quality assessment in bathing areas. It will provide immediate data acquisition in case of risk events (accidental pollution, algal blooms, etc.) regarding physical and chemical parameters.

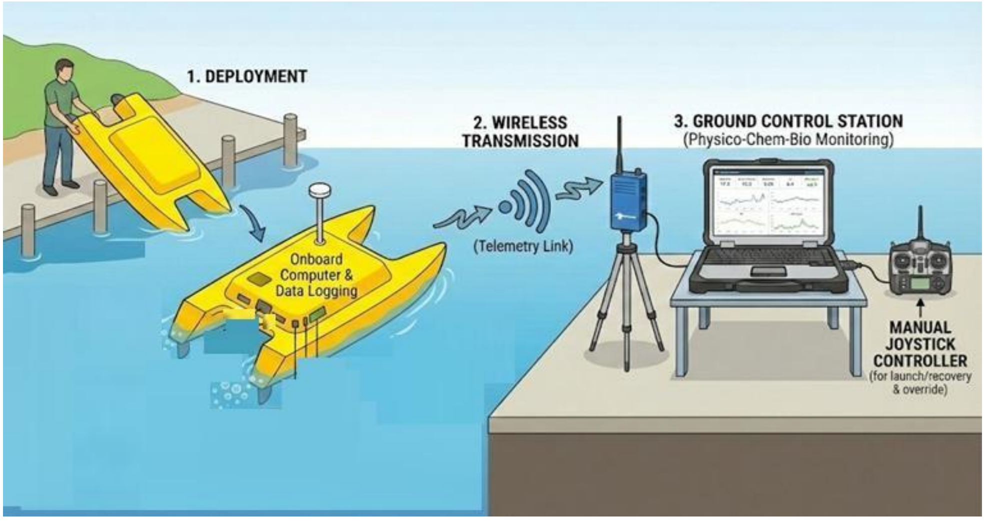

Fig. 1. USV-Drone's System

In Georgia drone-mobile stations will be used along the coast in *Sarpi* and *Poti* areas (**Figure 2. USV-drones Location in Georgia**) is based on their strategic significance, water quality, transboundary impacts, and the need for robust water quality data to support environmental management and will monitor selected physical and chemical parameters.

- **Sarpi**: Located at the Georgia-Turkey border, Sarpi experiences heavy cross-border traffic, including trucks, passenger vehicles, and maritime activities;
- **Poti**: As a major port city, Poti has intense shipping activities, industrial operations, and energy production;

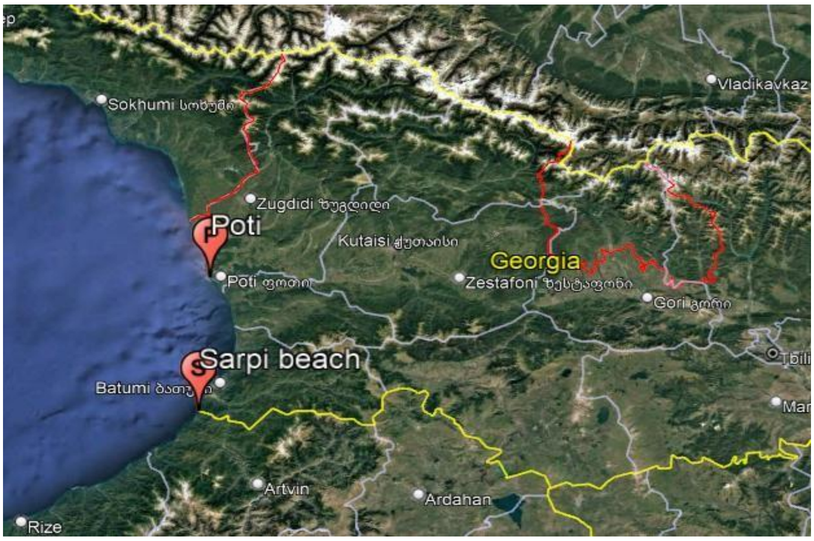

Fig. 2. USV-drones Location in Georgia

Research object and methodology

Using a multifunctional drone to measure water and air parameters—pH, Chlorophyll a, dissolved oxygen (DO), and water and air temperature—represents an innovative and efficient solution of Black Sea environmental monitoring system.

pH – Water pH directly reflects changes in marine acidity, which are linked both to increasing CO_2 levels (ocean acidification) and to industrial and domestic discharges;

Chlorophyll a – Chlorophyll is the main indicator of phytoplankton biomass. Its monitoring is essential for: detecting eutrophication processes; early prediction of algal blooms; and assessing marine productivity;

DO - (Dissolved Oxygen) – The level of dissolved oxygen determines the biological viability of marine ecosystems. Its depletion leads to the formation of "dead zones," posing a threat to fish and other organisms. A drone enables rapid detection of hypoxic zones and real-time monitoring of their dynamics;

Water Temperature – Water temperature affects chemical reactions, oxygen solubility, and biological processes. Detailed mapping of sea surface temperature using drones is particularly important for: monitoring climate change; identifying thermal stress zones; and predicting biological processes;

Simultaneous Measurement of Air and Water Temperature – Measuring both simultaneously allows for a better understanding of energy and heat exchange processes at the sea surface. These data are important for both meteorological and ecological modeling.

BS-SEOS data flow for Mobile Multisensory Stations-drones: All sensor data will be transmitted to the ground stations, from the ground station to partner's local premises for data formatting/standardization and data quality control. Standardized and Quality Controlled datasets will be transmitted, in delayed mode, to the Joint BS-SEOS Data Center developed by Istanbul University) to be integrated into the BS-SEOS database and further on the BS-SEOS Dashboard and AI models. Standardized and Quality Controlled datasets will be submitted, by each partner, (via EMODnet Data Ingestion) to the SeaDataNet/EMODnet thematics as it is illustrated in Figure 3 below.

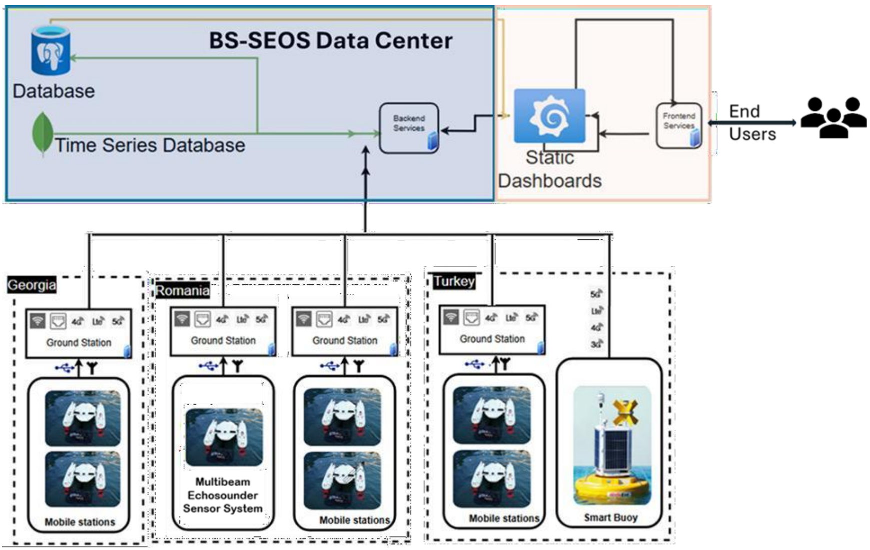

Fig. 3. Drone-Mobile Stations Data Flow

AI-driven marine risk prediction in the BS-SEOS framework follows a structured five-stage pipeline. Each stage transforms the raw observational data into a form progressively closer to operational environmental intelligence.

Stage 1 — Data Ingestion & Quality Control

Raw sensor streams — CTD profiles, dissolved oxygen time-series, chlorophyll fluorescence, meteorological parameters, satellite SST, and river discharge records — are ingested into the BS-SEOS data system. Automated quality control (QC) algorithms flag outliers, detect sensor drift signatures, and interpolate short gaps using ensemble Kalman filter methods. Mihailov et al. (2020) established a Romanian hydrodynamic index framework that underpins the QC procedures applied to NW shelf data.

Stage 2 — Feature Engineering

Raw measurements are transformed into model-ready features. This includes temporal lagging (values from the previous 7–14 days are included as predictors), spatial averaging across sensor network nodes, anomaly computation relative to climatological baselines, and derived physical indices such as the Mixed Layer Depth (MLD) and the Brunt–Väisälä frequency (a measure of stratification strength). Mihailov (2024) demonstrated that upwelling indices derived from

ECMWF reanalysis wind fields are among the strongest predictors of near-surface nutrient anomalies on the western Black Sea shelf.

Stage 3 — Model Training & Inference

Multiple AI model architectures are trained on historical data (typically 2010–2022 for the Black Sea) and evaluated on held-out test periods. As detailed in Section 3, the primary architectures employed are LSTM (Long Short-Term Memory) networks for temporal sequence modelling, CNN-LSTM hybrids for spatiotemporal prediction, and XGBoost ensemble methods for tabular risk classification tasks. Mihailov and colleagues demonstrated the superiority of CNN approaches over classical ARIMA models for sea level forecasting (Mihailov et al., 2021), a finding replicated across DO and HAB prediction tasks.

Stage 4 — Risk Scoring

Model outputs are converted into standardised risk scores (0–1) for three primary hazards: hypoxia probability, HAB outbreak probability, and anomalous upwelling intensity. Calibrated uncertainty bounds are computed using ensemble prediction intervals or Monte Carlo dropout, ensuring that risk scores communicate not just a prediction but its reliability.

Stage 5 — Decision Support & Feedback

Risk scores feed into an operational dashboard accessible to environmental managers, fisheries authorities, and researchers. Alert thresholds trigger automated notifications when hypoxia probability exceeds 0.65 or HAB risk score exceeds 0.70. Observed outcomes are logged and fed back into the retraining pipeline, enabling continuous model improvement — a critical capability in a system whose underlying dynamics are themselves changing under climate forcing.

Results

Project's outcomes

- Development of a centralized platform for sharing regional environmental data • Enhanced collaboration among scientists, policymakers, and industries
- Improved monitoring and assessment of marine ecosystem health
- Informed decision-making for conservation and sustainable practices
- Increased public awareness about the importance of marine ecosystem health
- strengthened resilience to environmental challenges in the Black Sea region

Conclusion

The Black Sea stands at a critical intersection of environmental vulnerability and technological opportunity. As a semi-enclosed and highly sensitive marine basin, its health depends on the ability of surrounding nations to monitor changes continuously, respond rapidly, and cooperate effectively. The BS-SEOS project demonstrates how innovation can transform traditional environmental monitoring into a dynamic, real-time, and data-driven system. By integrating uncrewed surface vehicles, advanced multisensory measurements, and AI-based forecasting models, the project provides a comprehensive framework for understanding complex marine processes and anticipating ecological risks.

Through its structured data pipeline and cross-border collaboration, BS-SEOS not only enhances the accuracy and availability of environmental data but also supports timely decision-making and proactive management. The system's ability to detect early warning signals—such as hypoxia events, algal blooms, or temperature anomalies—represents a significant step toward preventing large-scale ecological damage.

Ultimately, the success of BS-SEOS lies in its holistic approach: combining science, technology, and regional cooperation to safeguard the Black Sea ecosystem. By strengthening resilience, promoting sustainability, and increasing public and institutional awareness, the project contributes to a more stable and thriving marine environment. Continued development and expansion of such integrated monitoring systems will be essential for ensuring the long-term health of the Black Sea in the face of growing environmental and climatic pressures.

AI-driven risk prediction in BS-SEOS directly serves the EU Marine Strategy Framework Directive (MSFD), which requires Member States to achieve and maintain Good Environmental Status (GES) in their marine waters. Early prediction of hypoxic events, harmful algal blooms, and upwelling anomalies enables pre-emptive management actions — adjusting fishing effort, issuing aquaculture alerts, triggering emergency monitoring protocols — that reactive monitoring systems cannot support. More broadly, the BS-SEOS AI framework contributes to the European Green Deal and the EU Biodiversity Strategy for 2030 by building the evidence base for ecosystem-based management of the Black Sea. The sea's ecological condition cannot be separated from the political and economic futures of the communities along its shores — and AI-powered environmental intelligence is becoming a foundational tool for navigating that connection.

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შავი ზღვა წარმოადგენს მაღალმგრძნობიარე, ნახევრადჩაკეტილ საზღვაო ეკოსისტემას, რომელიც ექვემდებარება მნიშვნელოვან ანთროპოგენურ ზეწოლას, მათ შორის დაბინძურებას, კლიმატის ცვლილებასა და სანაპირო განვითარების პროცესებს. Black Sea Smart Marine Environmental Outcome System (BS-SEOS), რომელიც მხარდაჭერილია INTERREG NEXT Black Sea Basin Programme-ის მიერ, წარმოადგენს ინოვაციურ პლატფორმას, რომელიც მიზნად ისახავს მსოფლიოს ერთ-ერთი ყველაზე მგრძნობიარე საზღვაო ეკოსისტემის მონიტორინგისა და მართვის გაუმჯობესებას. სისტემა აერთიანებს უპილოტო ზედაპირულ აპარატებს, რომლებიც აღჭურვილია მრავალსენსორული მოწყობილობებით, მაღალი გარჩევადობის რეალურ დროში მონაცემების შეგროვებისთვის გარემოს ძირითადი პარამეტრების შესახებ, მათ შორის ტემპერატურა, pH, გახსნილი ჟანგბადი და ქლოროფილ-ა. მიღებული მონაცემები მუშავდება სტრუქტურირებულ მონაცემთა ნაკადში და ანალიზდება თანამედროვე ხელოვნური ინტელექტის მოდელების გამოყენებით ეკოლოგიური რისკების, როგორიცაა ჰიპოქსია და მავნე წყალმცენარეთა აყვავება, პროგნოზირებისთვის. უწყვეტი ტრანსნაციონალური მონაცემთა გაზიარებისა და ადრეული გაფრთხილების შესაძლებლობების უზრუნველყოფით, BS-SEOS ხელს უწყობს ინფორმირებული გადაწყვეტილებების მიღებას და პროაქტიულ გარემოსდაცვით მართვას. პროექტი აძლიერებს რეგიონულ თანამშრომლობას, ზრდის ეკოსისტემის მდგრადობას და ხელს უწყობს შავი ზღვის მდგრად განვითარებასა და გრძელვადიან დაცვას.

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Чёрное море является высокочувствительной, полузамкнутой морской экосистемой, подверженной значительному антропогенному воздействию, включая загрязнение, изменение климата и прибрежное развитие. Система Black Sea Smart Marine Environmental Outcome System (BS-SEOS), поддерживаемая программой INTERREG NEXT

Black Sea Basin Programme, представляет собой инновационную платформу, направленную на улучшение мониторинга и управления одной из самых уязвимых морских экосистем в мире. Система интегрирует без экипажные надводные аппараты, оснащённые мультисенсорными приборами, для сбора высокоточных данных в реальном времени по ключевым экологическим параметрам, включая температуру, pH, растворённый кислород и хлорофилл-а. Полученные данные обрабатываются в рамках структурированного потока данных и анализируются с использованием современных моделей искусственного интеллекта для прогнозирования экологических рисков, таких как гипоксия и вредоносные цветения водорослей. Обеспечивая непрерывный транснациональный обмен данными и возможности раннего предупреждения, BS-SEOS способствует принятию обоснованных решений и проактивному экологическому управлению. Проект усиливает региональное сотрудничество, повышает устойчивость экосистем и способствует устойчивому развитию и долгосрочной защите Чёрного моря.