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An Integrated Methodological Framework for Comparative Assessment of Coastal Seawater in the Black Sea Basin

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Abstract

The Black Sea is a unique semi-enclosed marine ecosystem heavily impacted by coastal urbanization, port infrastructure, and industrial activity. Traditional monitoring approaches predominantly focus on quantifying specific chemical pollutants, providing crucial yet piecemeal information regarding individual water body components. This study presents an integrated methodological framework combining physical, physicochemical, rheological, and chemical analyses to establish a comprehensive multi-parameter evaluation of coastal seawater quality across three distinct Black Sea basins: Batumi (Georgia), Varna (Bulgaria), and Istanbul (Turkey). Spatial stratification was structured using a three-tier station design (port/industrial zone, urban/recreational area, and spatial control). Preliminary assessment

under representative summer conditions revealed estimated dynamic viscosities of 0.94 mPa·s (Batumi, 25.0 ∘C), 0.98 mPa·s (Istanbul, 23.5 ∘C), and 1.00 mPa·s (Varna, 22.5 ∘C), demonstrating a clear inverse relationship with temperature. Dynamic viscosity is established as a complementary physical indicator reflecting the holistic state of the fluid, which must be normalized against natural controlling factors (temperature and salinity) rather than interpreted as a standalone pollution metric. The developed protocol standardizes field sampling, temperature-controlled rheometry, GC-MS/HPLC organic contaminant profiling, and multi-variable data integration, providing a robust operational standard for regional Black Sea ecological monitoring.

KEYWORDS: Black Sea; environmental monitoring; seawater rheology; dynamic viscosity; petroleum hydrocarbons; integrated methodology; coastal zone management; standardized sampling

Introduction

The Black Sea constitutes one of the most critical semi-enclosed marine ecosystems globally, uniting the ecological, economic, and social interests of six riparian countries [1,2]. Its coastal zones are characterized by dense urban populations, major shipping routes, expanding port infrastructure, and seasonal tourist hubs [3,4]. These anthropogenic drivers impose intense pressure on marine ecosystems through the Introduction of petroleum hydrocarbons, combustion byproducts, heavy metals, nutrients, and synthetic organic pollutants [5,6]. Traditional marine environmental monitoring relies almost exclusively on direct chemical determinations of specific target contaminants [7,8]. While chemical analysis yields precise quantitative data for individual substances, it frequently fails to capture the aggregate physical and structural transformations occurring within the complex multicomponent seawater matrix [9,10]. In recent years, physical and rheological parameters have gained attention as potential complementary metrics in aquatic ecosystem assessment [11,12]. Seawater dynamic viscosity (η) reflects the macroscopic deformation and flow resistance of the fluid, integrating the combined influences of temperature, salinity, suspended particulate matter, surfactant films, and dissolved organic matter [13,14]. However, a major scientific gap persists: seawater rheological properties are rarely integrated into standardized ecological monitoring protocols, and non-specific physical variations are frequently

misinterpreted without proper baseline normalization [15,16]. This paper introduces a comprehensive, multi-parameter methodological framework designed for comparative coastal water assessment across three major Black Sea coastal nodes: Batumi (Georgia), Varna (Bulgaria), and Istanbul (Turkey). The study defines standardized protocols for spatial sampling, field parameters, physical-chemical characterization, rheological measurement, chemical identification, and multi-variable data integration.

Experimental Part

Study Design and Spatial Stratification

The study employs a comparative spatial design focused on peak summer conditions to evaluate spatial variability while controlling for major seasonal fluctuations. Three major coastal basins of the Black Sea were selected: Batumi (Georgia), Varna (Bulgaria), and Istanbul (Turkey). To capture anthropogenic gradients within each coastal basin, a standardized three-level spatial stratification scheme is established: Station A (High Impact Zone): Located inside or in immediate proximity to primary commercial port infrastructure and industrial maritime channels; Station B (Urbanized Coastal Zone): Located along municipal beach lines and recreational areas characterized by moderate urbanization and seasonal runoff; Station C (Spatial Reference/Control Zone): Located in relatively undisturbed marine waters removed from major direct point-source discharges.

Standardized Sampling and Field Measurements

Sampling is conducted using a unified protocol across all basins. Samples are collected at a standard surface depth of 0.5 m using pre-cleaned, inert fluorinated container vessels to prevent organic contamination. Sample handling minimizes mechanical agitation, bubble entrainment, and phase separation. Each sample is assigned a standardized unique code: BASIN-STATION-NUMBER-DATE (e.g., BAT-A-01-2026). Standardized field registrations include precise GPS coordinates, sampling timestamp, sea state, surface weather conditions, ambient water temperature, Secchi disk transparency, visual surface oil film observations, and proximity to active vessel traffic.

Physicochemical and Rheological Analytical Protocols

Basic physicochemical parameters (pH, electrical conductivity, salinity, and turbidity) are determined immediately using calibrated multi-parameter field probes (WTW MultiLine / YSI ProDSS). Rheological measurements are performed using a temperature-controlled rotational rheometer (e.g., Anton Paar MCR series or Haake Viscotester) equipped with a double-gap coaxial cylinder geometry optimized for low-viscosity

fluids. To eliminate thermal artifacts, rheological measurements are standardized at precise target temperatures (20.0 ^{0}C, 25.0 ^{0}C) using a Peltier temperature control unit (± 0.01 ∘C). Dynamic viscosity (η, mPa·s) is measured across a controlled shear rate range ($\dot{\gamma}$=10–1000 s−1) to verify Newtonian behavior and evaluate potential non-Newtonian anomalies induced by heavy organic loads or colloidal dispersions.

Chemical Contaminant Identification

Chemical analysis targets priority organic pollutants, total petroleum hydrocarbons (TPH), and polycyclic aromatic hydrocarbons (PAHs). Volatile and semi-volatile organic fractions are extracted via liquid-liquid extraction with dichloromethane (DCM) and quantified using Gas Chromatography-Mass Spectrometry (GC-MS, Agilent 7890B/5977B). Polar organic surfactants and specific chemical markers are identified via High-Performance Liquid Chromatography (HPLC-DAD/FLD).

Results and Discussion

Preliminary Physicochemical and Rheological Baseline Assessment

A preliminary baseline model was established for the three representative Black Sea coastal areas (Batumi, Istanbul, and Varna) based on representative summer sea surface temperatures and a standard Black Sea surface salinity of approximately 18. The values represent baseline physical calculations and reference models for standardizing future field campaigns. The assumed summer surface water temperatures were highest in Batumi (25.0 ∘C), intermediate in Istanbul (23.5 ∘C), and lowest in Varna (22.5 ∘C). Correspondingly, the estimated dynamic viscosity values increased from 0.94 mPa·s in Batumi to 0.98 mPa·s in Istanbul and 1.00 mPa·s in Varna (Table 1). The total viscosity difference between Varna and Batumi was 0.06 mPa·s, representing a 6.4% variation relative to the Batumi baseline. The observed ordering for viscosity (Batumi < Istanbul < Varna) was exactly inverse to the temperature ordering (Batumi > Istanbul > Varna), adhering strictly to the pure thermophysical fluid behavior governed by the Andrade-Arrhenius equation for liquid water viscosity.

TABLE 1. PRELIMINARY BASELINE TEMPERATURE AND ESTIMATED SEAWATER DYNAMIC VISCOSITY ACROSS THE STUDY AREAS

Study Area	Assumed Water Temp. (^{0}C)	Estimated Dynamic Viscosity (mPa·s)	Relative Rheological Position
Batumi (Georgia)	25.0	0.94	Lowest estimated viscosity
Istanbul (Turkey)	23.5	0.98	Intermediate estimated viscosity
Varna (Bulgaria)	22.5	1.00	Highest estimated viscosity

Preliminary Seawater pH Profiling

Preliminary reference ranges for seawater pH across the three basins were established (Table 2). All three regions exhibit weakly alkaline conditions characteristic of carbonate-buffered Black Sea surface waters.

TABLE 2. PRELIMINARY ESTIMATED PH RANGES AND PRIMARY ENVIRONMENTAL CONTROLLING FACTORS

Study Area	Preliminary pH Range	Range Midpoint	Main Factors Requiring Field Verification
Batumi (Georgia)	8.0-8.2	8.10	Freshwater discharge (Rioni/Chorokhi), localized precipitation, primary production
Istanbul (Turkey)	8.1-8.2	8.15	Bosphorus hydrodynamic mixing, steep salinity gradients, organic turnover
Varna (Bulgaria)	8.2-8.3	8.25	Coastal freshwater inputs, regional circulation, seasonal phytoplankton blooms

Integrated Multidimensional Profile

Combining thermal, rheological, pH, and anthropogenic exposure parameters yields a unified data structure for baseline comparative monitoring (Table 3). The baseline calculations clearly highlight that raw dynamic viscosity cannot be directly utilized as a standalone pollution indicator. The 6.4% difference in viscosity between Batumi and Varna is fully accounted for by the 2.5^{0}C thermal gradient. Consequently, ranking water bodies by pollution level based on uncorrected field viscosity would lead to erroneous ecological Conclusions (e.g., misinterpreting colder, cleaner water in Varna as more polluted than warmer, heavily impacted water in Batumi) [17,18]. Therefore, all com-

parative monitoring protocols must either execute laboratory rheometry under identical temperature conditions (e.g., strictly at 20.0^{0}C or 25.0^{0}C) or mathematically normalize viscosity values to a standard reference temperature (Tref=20^{0}C) using empirical thermophysical state equations for seawater [19,20]. A vital distinction established in this framework is the physical separation between bulk seawater dynamic viscosity and floating surface petroleum films. A visible petroleum slick on the sea surface represents a distinct immiscible phase [21,22]. Unless oil is emulsified into sub-micron droplets or dissolved as light aromatic fractions, it does not alter the dynamic viscosity of the underlying bulk water column. Therefore, visual surface oil films must be recorded as categorical field descriptors, while dissolved and emulsified petroleum hydrocarbons (TPH) in bulk water are quantified via GC-MS and correlated with normalized rheological residual values [23,24,25,26].

TABLE 3. INTEGRATED PRELIMINARY PHYSICOCHEMICAL AND RHEOLOGICAL PROFILE OF THE BLACK SEA STUDY AREAS

Parameter	Batumi (Georgia)	Istanbul (Turkey)	Varna (Bulgaria)
Assumed Temperature (0C)	25.0	23.5	22.5
Estimated Viscosity (mPa·s)	0.94	0.98	1.00
Estimated pH Range	8.0-8.2	8.1-8.2	8.2-8.3
Anthropogenic Exposure Category	High/Port & Tourist	High/Urban & Maritime	High/Port & Industrial
Viscosity Interpretation	Temperature-sensitive	Temperature-sensitive	Temperature-sensitive
Data Status	Calculated baseline	Calculated baseline	Calculated baseline

Conclusions

This study successfully establishes an integrated methodological framework for multi-parameter assessment of coastal seawater across the Black Sea basin. By combining standardized spatial sampling, field registrations, physicochemical profiling, temperature-controlled rheometry, and GC-MS organic chemical identification, the framework bridges physical fluid mechanics and marine environmental chemistry. The key findings include:

1. Seawater dynamic viscosity (η) is a valuable bulk physical parameter that integrates structural changes in liquid media, but it cannot be used as an isolated

pollution metric.

2. Temperature exerts the primary control on raw seawater viscosity. Uncorrected field viscosity measurements across different temperatures will lead to misleading ecological assessments.
3. Comparative ecological assessments require strict thermal standardization during laboratory rheometry or mathematical normalization to reference conditions (20.0 ◦C).
4. The three-tier station scheme (Batumi – Istanbul – Varna) provides a scalable operational blueprint for transboundary Black Sea environmental monitoring.

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Conflict of Interest. The authors declare no conflict of interest.

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