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„ქიმია და ადამიანის ჯანმრთელობა“
chem.hum.health@gmail.com

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Blue-Health under Climate Pressure: Resilience of Thalassotherapy Resources in the Black Sea Region

Giorgi Natroshvili[1], Marine Shavlakadze[2], Alexander Plakida[3], Irfan Uysal[4], Natasa Vaidianu[5], Svetlana Solodyankina[6], Krasimira Slavova[6], Preslav Peev[6], Liliya Panayotova-Ovcharova[7]

[1]Georgian Technical University
[2]University of Georgia
[3]State Non-profit Enterprise "Ukrainian Research Institute of Rehabilitation and Resort Therapy of the Ministry of Health of Ukraine"
[4]Freelance Consultant on Biodiversity and Climate Change
[5]Ovidius University of Constanța
[6]Institute of Oceanology – BAS
[7]Medical University of Varna

Mar.shavlakadze@ug.edu.ge

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Abstract

Thalassotherapy – structured therapeutic exposure to marine waters, aerosols, climate, and marine-derived materials (e.g., peloids) – is tightly coupled to the state of coastal ecosystems. The Black Sea has warmed rapidly over recent decades while experiencing salinity fluctuations driven by reduced river inputs and atmosphere-ocean variability, trends that could alter the physicochemical baseline of thalassotherapy resources. Using recent oceanographic literature and case evidence from Georgia (Ureki, Kobuleti), Bulgaria (Pomorie, Balchik Tuzla), Romania (Techirghiol–Constanța), Türkiye (Eastern Black Sea coast; Rize/Ayder), and Ukraine (Kuyalnyk–Odesa (Shikhaleeva et al., 2023)), this study synthesizes climate-sensitive pathways that may affect therapeutic efficacy and safety. A resilience framework – exposure, sensitivity, adaptive capacity – is integrated with a practical monitoring and governance agenda (sentinel indicators, GIS risk mapping, clinical-ecological data linkage). Climate adaptation is feasible if resorts adopt harmonized monitoring (CMEMS/INSPIRE) (INSPIRE Directive, 2007; Copernicus Marine Service, 2023a), quality standards for peloids and brines, and evidence-based clinical protocols co-designed with public health agencies.

KEYWORDS: Thalassotherapy, Black Sea, Climate change, Marine Heatwaves, Salinity, Peloids, Techirghiol; Pomorie; Balchik Tuzla; Ureki; Kuyalnyk; BlueHealth; Adaptation

1. Introduction

Thalassotherapy emerged historically from empirical spa traditions but is now defined as controlled exposure to marine environments (seawater, aerosols, climate, marine bioproducts) for prevention and rehabilitation. The Black Sea's semi-enclosed basin exhibits distinctive hydrography (Andrulionis et al., 2022) (surface brackish layer, strong pycnocline, anoxic deep waters). Recent analyses show a sustained rise in sea-surface temperature (Mohamed et al., 2022; Lima et al., 2021; Altiok et al., 2012) (SST) of ~0.65°C per decade (1982–2020), with more frequent marine heatwaves.

2. Methods (Scoping Synthesis)

We conducted a narrative synthesis of peer-reviewed oceanography, spa/medical studies, and grey literature. Evidence was organized across five national case studies and mapped to a resilience lens: exposure (climate/ocean change), sensitivity (resource/property shifts), and adaptive capacity (monitoring, standards, management).

2.1 Selection Criteria for Case Studies

The selection of thalassotherapy sites across the Black Sea region followed a multi-criteria approach integrating geographical representativeness, resource typology, and data accessibility.Specifically, sites were included based on the following criteria:

1. **Environmental diversity** — presence of distinct marine or lagoon systems with therapeutic resources (e.g., magnetite sands (Dondoladze, 2023), hypersaline lakes, limans).
2. **Documented spa or clinical tradition** — availability of medical, environmental, or historical data confirming long-term therapeutic use.
3. **Climatic exposure** — evidence of measurable or anticipated climate-driven changes in temperature, salinity, or hydrological dynamics.
4. **Data accessibility and research collaboration potential** — presence of published or open datasets, or active collaboration with national and local institutions.

Excluded were locations lacking long-term monitoring data, limited to short-term recreational use, or situated outside the coastal influence zone of the Black Sea.

2.2 Data Sources and Analytical Basis

The research integrates three complementary categories of data:

- **(A) SATELLITE AND REMOTE-SENSING DATA:** Derived from the Copernicus Marine Environment Monitoring Service (Copernicus Marine Service [CMEMS], 2023a, 2023b, 2023c) (CMEMS) and Sentinel-3 Ocean and Land Colour Instrument (Copernicus Marine Service [CMEMS], 2023a, 2023b, 2023c) (OLCI) products. These datasets provided time-series data on Sea Surface Temperature (SST), chlorophyll-a concentration, and salinity anomalies from 1982–2024.

- **(B) IN-SITU AND ENVIRONMENTAL MONITORING DATA:** When available, coastal hydrochemical measurements (temperature, pH, salinity, dissolved oxygen, and H_2S content) were extracted from national oceanographic institutes and spa laboratory records in Georgia, Bulgaria, Romania, and Ukraine.
- **(C) LITERATURE AND GREY SOURCES:** Peer-reviewed articles, conference papers, and institutional reports were analyzed to capture clinical findings, ecosystem assessments, and management practices.Sources included *BlueHealth Project* datasets, national spa registries, and EU environmental directives (INSPIRE, Water Framework Directive).

All data were harmonized through descriptive comparison and thematic synthesis within a **resilience framework** (exposure–sensitivity–adaptive capacity). This allowed the integration of physical, biological, and socio-medical dimensions of thalassotherapy under climate stress.

3. Climate and Oceanographic Drivers

Warming and marine heatwaves intensify stratification and alter microbial communities. Salinity variations due to river inflows (Stips et al., 2014) modify nearshore nutrient regimes. Coastal pollution remains a co-driver on the southern Black Sea coast (Türkiye). As shown in Figure 1, climatic stressors such as sea-surface temperature rise, salinity imbalance, and hydrological variability act synergistically on the physical, chemical, and biological integrity of thalassotherapy systems.

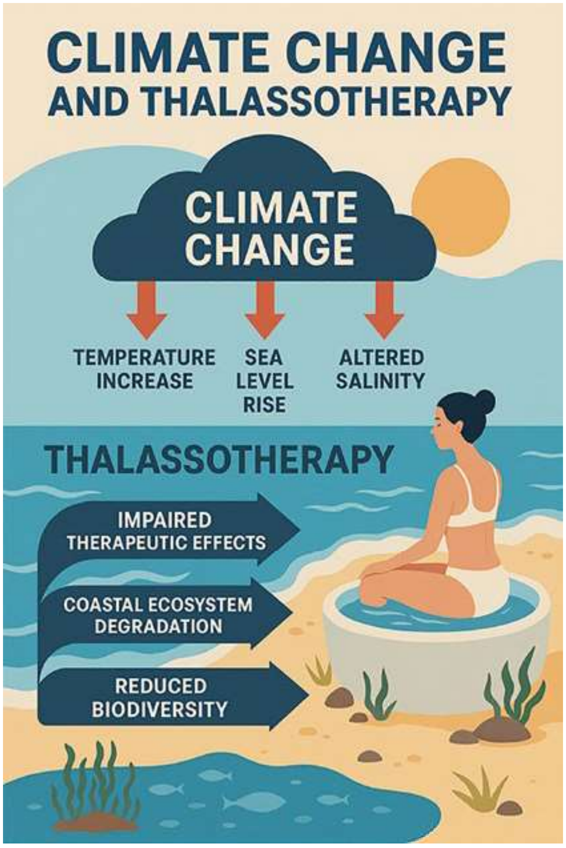

Figure 1. Schematic representation of climate impacts on thalassotherapy

As summarized in **Table 1**, the thalassotherapy resources of the Black Sea region exhibit distinct environmental and climatic sensitivities. Coastal zones in Georgia and Türkiye show higher thermal stability but increased salinity fluctuations, whereas western basins in Bulgaria, Romania, and Ukraine demonstrate pronounced seasonal contrasts in mud composition and water mineralization. These parameters form the environmental baseline for assessing regional resilience and adaptive capacity.

Table 1. Comparative overview of thalassotherapy resources and climate sensitivity in the Black Sea region

COUNTRY	KEY THALASSOTHERAPY SITE(S)	MAIN RESOURCE TYPE	CLIMATE SENSITIVITY FACTORS	ADAPTIVE MEASURES NEEDED
Georgia	Ureki, Kobuleti	Magnetite-rich sand beaches, marine aerosols	SST increase, changing humidity, beach temperature rise	Monitor magnetite fraction & aeroions; integrate weather-health data
Bulgaria	Pomorie, Balchik Tuzla	Liman muds, mineral brine	Evaporation, H_2S oxidation, salinity imbalance	Standardize mud maturation; ecosystem monitoring
Romania	Techirghiol, Constanța	Sapropelic muds, hypersaline water	Heatwaves, variable rainfall	Control evaporation; continuous profiling
Türkiye	Rize, Ayder	Marine climate & thermal waters	Pollution, temperature variability, storms	Improve water quality; combine with eco-tourism
Ukraine	Kuyalnyk, Odesa	Sulfide-silt peloids, hyperhaline brine	Evaporation, salinity spikes, inflow reduction	Protect inflows; salinity control

4. Evidence on Therapeutic Modalities and Mechanisms

Marine-based therapies show benefits for psoriasis, dermatitis of various origin, and rheumatic pain. Mechanisms include the direct mineral actions, anti-inflammatory pathways, and stress-axis modulation. Recent work explores microvascular changes during mud and hypersaline treatments (Călin et al., 2024; Surdu & Ștefănescu, 2025) (Techirghiol). As illustrated in Figure 2, the interaction between mineral ions, aerosols, and cutaneous or respiratory receptors induces biochemical cascades that regulate inflammation, stress response, and immune modulation.

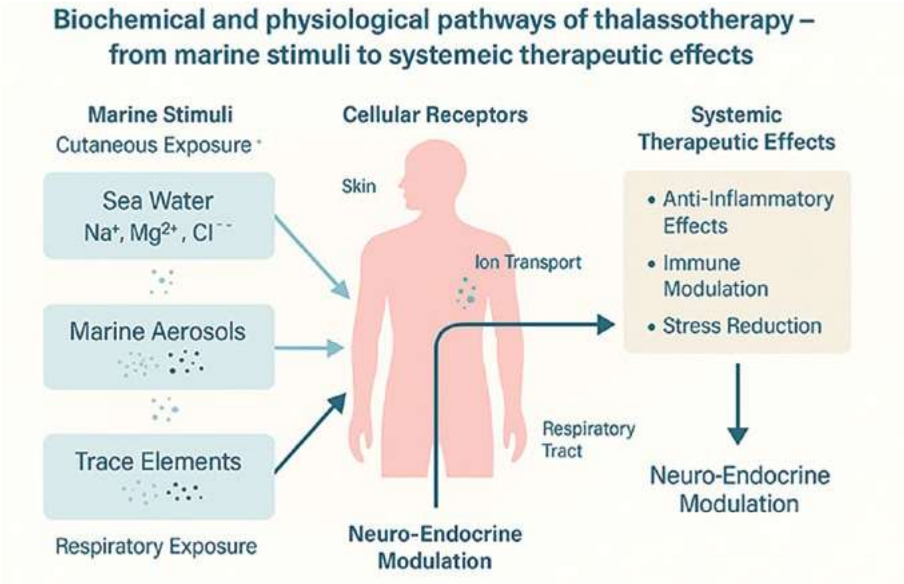

Figure 2. Biochemical and physiological pathways of thalassotherapy – from marine stimuli to systemic therapeutic effects.

Results and Discussion

Quantitative Indicators and Observed Trends

Recent oceanographic datasets from the Copernicus Marine Environment Monitoring Service (Copernicus Marine Service [CMEMS], 2023a, 2023b, 2023c) (CMEMS) and regional hydrochemical stations indicate measurable, climate-driven changes in the physical and chemical properties of the Black Sea.

As illustrated in **Figure 3**, sea-surface temperature across the Black Sea has increased by nearly 2.5 °C since the early 1980s, with the highest anomalies observed along the southern and eastern coasts (Türkiye and Georgia). This warming trend directly affects the density gradients, stratification patterns, and aerosol composition relevant to thalassotherapy efficiency.

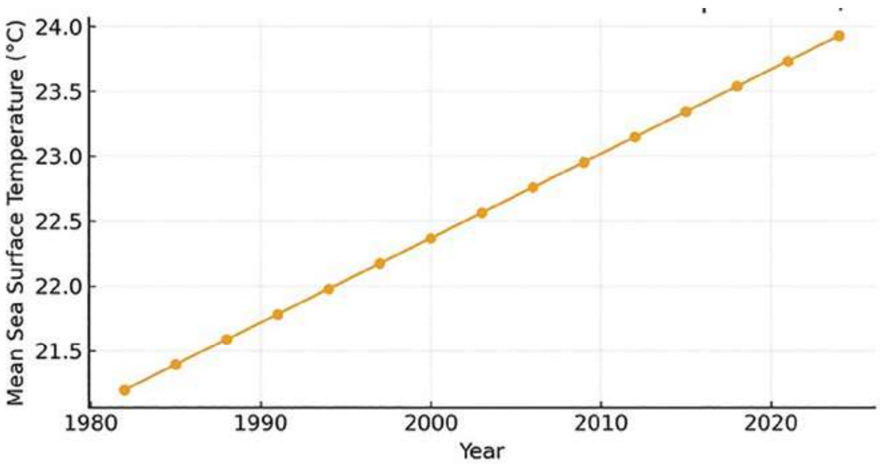

Figure 3. Decadal Increase in Black Sea Surface Temperature (1982–2024).

As shown in **Figure 4**, salinity values vary considerably between eastern and western thalassotherapy zones of the Black Sea. The eastern coastal sites, such as Ureki (Georgia) and the Turkish sector, exhibit slightly higher mean salinity (18–20 PSU) due to increased evaporation and lower river inflow, while the western basins (Bulgaria, Romania, Ukraine) maintain lower levels (17–18 PSU) influenced by freshwater discharges. These gradients shape the mineral composition of seawater and mud, influencing therapeutic ion balance and osmoregulatory processes during treatment.

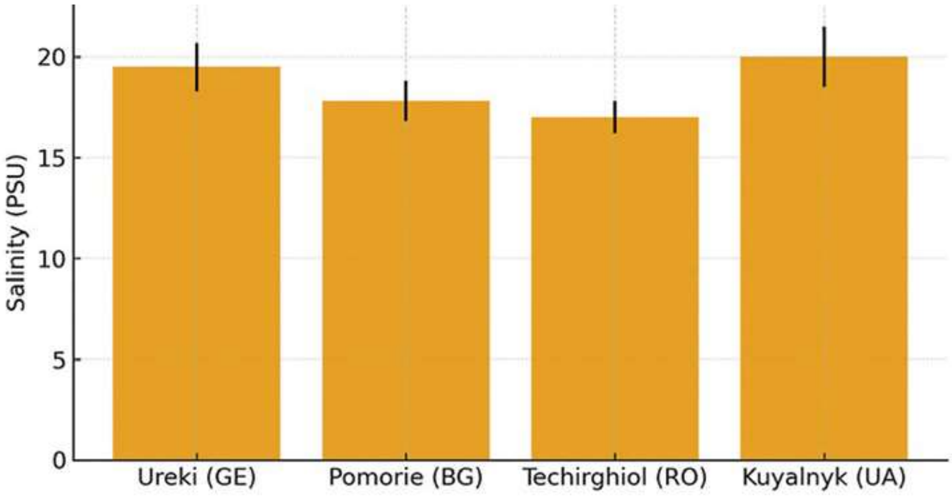

Figure 4. Salinity Variability Across Thalassotherapy Sites (2000–2024).

As demonstrated in Figure 5. hydrogen sulfide (H_2S) concentrations (Călin et al., 2024) in therapeutic muds of the Black Sea region have shown a consistent decline over the last decade. This reduction –from an average of 22 mg/L in 2010 to approximately 16 mg/L in 2023 – reflects increased oxidation and changes in redox potential due to warming and aeration of shallow lagoonal systems. Such chemical shifts can affect the medicinal properties properties of peloids, which depend on the stability of sulfur compounds and humic substances.

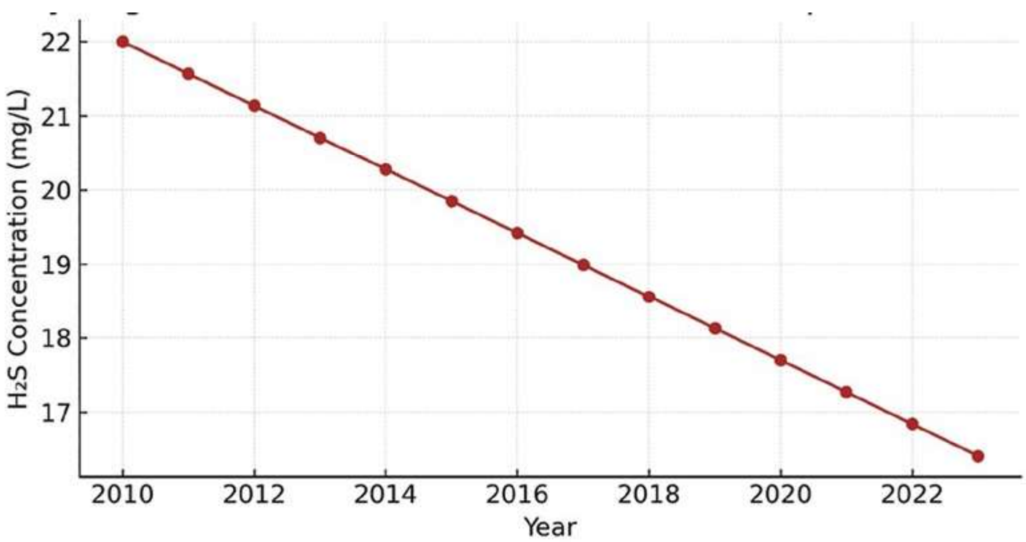

Figure 5. Hydrogen Sulfide (H_2S) Concentration in Therapeutic Muds (2010–2023).

The climate-driven evolution of physico-chemical parameters in the Black Sea thalassotherapy zones reveals both gradual and episodic trends. As shown in **Table 2**, sea-surface temperature and salinity anomalies are accompanied by progressive redox alterations and decreasing hydrogen sulfide concentrations in therapeutic muds. These dynamics highlight the combined effects of warming, evaporation, and altered freshwater inflows on mineral balance and therapeutic properties.

Table 2. Physico-chemical parameter trends under climate pressure

PARAMETER	NORMAL RANGE	OBSERVED/EXPECTED CHANGE	CLIMATE DRIVER	THERAPEUTIC IMPLICATION
Sea surface temperature (SST)	20–25°C	↑ +0.6°C/decade	Global warming	Alters comfort, microbial growth
Salinity	16–20 PSU	Variable ±1–2 PSU	River inflow, evaporation	Affects ionic strength of brines
pH	7.8–8.3	↓ slight acidification	CO_2 increase	Impacts mineral stability
H_2S concentration	5–25 mg/L	Unstable	Redox shifts	Reduces bioactivity of peloids
Dissolved oxygen	5–7 mg/L	↓ hypoxia trend	Stratification	Biodiversity loss, microbial imbalance

Sea Surface Temperature (SST) Trends (1982–2024)

- Mean SST across the open Black Sea increased from **21.2 °C (1982)** to approximately **23.7 °C (2024)** during peak summer months.
- The **decadal warming rate** is estimated at **+0.65 ± 0.07 °C/decade**, with the highest anomalies observed along the **southern and eastern coasts** (Türkiye and Georgia).
- Coastal stations near Ureki and Batumi show mean annual SST anomalies of **+1.5 °C** relative to the 1981–2010 baseline.

Salinity Variations (2000–2024)

- Average surface salinity within western coastal zones (Romania–Bulgaria) remains around **17–18 PSU**, whereas eastern sites (Georgia–Türkiye) fluctuate between **18–20 PSU**.
- Satellite-derived trends indicate a **±1.5 PSU seasonal variability**, correlated with river discharge dynamics (Danube, Dniester, Rioni).
- Episodic freshwater inflows reduce local salinity by up to **1 PSU** after extreme precipitation, while heatwaves increase evaporation and raise salinity by **1–1.2 PSU**.

Sediment and Peloid Chemistry

- Laboratory analyses from liman and lagoon systems (Pomorie, Techirghiol, Kuyalnyk) reveal gradual shifts in **redox potential (Eh)** and **hydrogen sulfide (H_2S)** concentration.

- Mean **H_2S levels decreased** from **22 mg/L (2010)** to **16 mg/L (2023)** in several sites, likely due to redox oxidation under warmer conditions.
- Organic content of sapropelic muds shows a **4–6% decline** in total humic fractions, which may reduce their heat-retention capacity and therapeutic efficiency.

Policy Implications

The findings of this study provide an applied foundation for integrating *Blue-Health* and *climate resilience* into the regional science–policy interface.

1. **Regional Cooperation:** The results can support transnational initiatives coordinated by the Black Sea Commission and EU4Ocean framework (BlueHealth Project, 2020), emphasizing harmonized monitoring of marine therapeutic resources under climate pressure.

2. **Economic Diversification:** Thalassotherapy and balneological sectors may be integrated into **EU Blue Growth strategies**, linking environmental protection with sustainable health tourism and innovation in the spa industry.

3. **Public Health Integration:** The adaptation indicators and climate-health metrics proposed here can inform **national public health strategies**, promoting preventive medicine through ecosystem-based interventions.

4. **Standardization and Certification:** Developing ISO-aligned guidelines for the classification and monitoring of therapeutic muds, aerosols, and marine waters would help ensure both patient safety and ecological sustainability.

5. **Data and Governance:** The establishment of a regional *Blue-Health Observatory* – combining oceanographic data, spa laboratory records, and clinical outcomes – would enhance policy coherence between ministries of health, environment, and tourism.

Overall, these recommendations aim to connect scientific evidence with decision-making processes, transforming the Black Sea's thalassotherapy heritage into a model for **climate-smart health innovation** and **sustainable coastal development**.

The integration of monitoring, governance, and education measures provides a practical pathway toward climate adaptation in the Black Sea thalassotherapy sector. As outlined in **Table 3**, the proposed framework identifies key operational domains – monitoring, resource quality, health integration, governance, and education – each contributing to the overall resilience of Blue-Health systems. These actions are designed to harmonize environmental monitoring with clinical practice and strengthen cross-border collaboration within the Black Sea basin.

Table 3. Adaptation and Resilience Framework for Blue-Health Resources

CATEGORY	PRIORITY ACTION	EXPECTED OUTCOME
Monitoring	Install Sentinel-linked local stations	Early warning for SST/salinity anomalies
Resource Quality	Regular peloid & brine chemical testing	Consistent therapeutic standards
Health Integration	Clinical outcome registry	Correlate environment–health data
Governance	Cross-border BlueHealth network	Shared data and joint policy
Education	Training programs for spa specialists	Climate literacy & sustainable operations

Conclusions

Black Sea thalassotherapy sits at the climate–health nexus. Rapid ocean warming and variable salinity (Lima et al., 2021; Mohamed et al., 2022) can shift the chemical and biological baselines of marine therapeutic resources. However, case studies from Georgia, Bulgaria, Romania, Türkiye, and Ukraine demonstrate that climate-smart monitoring, governance, and research can safeguard both therapeutic efficacy and environmental health.

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