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Research Article

Ecosystem Functioning under Climate Changes, Hydrological Confinement and Pollution Risks in the Shabla-Ezerets Lake System (Northern Bulgarian Black Sea Coast): Controlled Seasonal Outlet as a Pathway to Nature-based Restoration

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Abstract

This study provides an integrated geomorphological, hydrological, physico-chemical, ecological and macrolitter assessment of the Shabla–Ezerets coastal lake system. High-resolution LiDAR and bathymetric data reveal a shallow, low-energy basin with strong hydrological confinement, extensive littoral development and fine-sediment accumulation. Contemporary water-column profiles (2019–2024), compared with historical measurements (1950–1963), show a stable summer thermocline at 2–4 m depth and an increase of approximately 3–4 °C in summer surface temperatures. Near-bottom oxygen saturation frequently declines to 20–40% during summer, extending the spatial expression of historically observed low-oxygen conditions. Salinity remains uniformly oligohaline (0.1–2.1 ‰), contrasting with the more variable historical range. Ecological data indicate long-term shifts towards freshwater-tolerant ichthyofaunal

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assemblages and expanded reedbed dominance. Macrolitter surveys document moderate plastic-dominated accumulation across shoreline, surface-water and benthic compartments, reflecting limited flushing and efficient retention. The combined evidence shows that hydrological confinement, gradual climate-related warming and restricted water renewal jointly structure present-day ecosystem functioning. Controlled seasonal freshwater outflow is identified as an appropriate restoration measure for improving water-column renewal, reducing stagnation and decreasing litter retention while preserving the system's freshwater character.

Keywords

coastal lakes, UAS–LiDAR mapping, hydroacoustics, water-column stratification, hydrological confinement, ichthyofaunal change, macrolitter pollution, climate-related warming, nature-based restoration

Introduction

Coastal wetlands are among the most productive yet vulnerable ecosystems, providing biodiversity support, nutrient retention, carbon sequestration and natural coastal protection. However, these systems currently face the dual pressure of anthropogenic modification and rapidly changing climatic conditions. Recent global assessments indicate that lake surface temperatures are rising faster than air temperatures (O'Reilly et al. 2015; Woolway and Merchant 2019), driving phenological shifts in stratification (Woolway et al. 2021) and widespread deoxygenation in temperate water bodies (Jane et al. 2021). Liman-type coastal lakes represent a specific class of transitional systems in which marine, freshwater, and terrestrial processes interact within shallow, low-energy basins whose hydrological isolation amplifies ecological responses (Bird 1994; Bird 2008; Paerl and Huisman 2008; Day 2012; Newton et al. 2014; Newton et al. 2018). Their Holocene evolution typically involves barrier progradation, groundwater inflow and sediment infilling (Bird 2008), creating environments where geomorphology, hydrology and biological communities are tightly coupled and sensitive to disturbance (Finkl and Makowski 2019).

Across microtidal coasts, the functioning of coastal lakes is governed by connectivity, salinity gradients, inlet behaviour and seasonal water-level variability (Kjerfve 1986; Pérez-Ruzafa et al. 2007). Episodic inlet closure, together with anthropogenic pressures such as hydrological alteration, shoreline development and biological invasions, has reshaped species composition and ecological resilience in many Mediterranean and Black Sea sites (Sfriso et al. 2003; Pérez-Ruzafa and Marcos 2005; Pérez-Ruzafa et al. 2019). Natural variability often masks early degradation, the "estuarine quality paradox", which makes integrated diagnostic approaches essential for detecting system-level decline (Elliott and Quintino 2007). These vulnerabilities are further intensified by climate-driven changes in storm surges, precipitation regimes and sea-level rise

(Kennish 2002; Williamson et al. 2009; Kennish and Paerl 2010; Chapman 2012; Monfort et al. 2014; Cataudella et al. 2015).

At the European scale, liman-type and lagoonal systems are recognised under the Habitats Directive and Ramsar Convention for their biodiversity value, yet monitoring gaps remain substantial, particularly in Eastern Europe (Michev and Stoyneva 2007; EEA 2020). EU policies emphasise that hydromorphological integrity is central to ecosystem recovery: the EU Biodiversity Strategy for 2030 identifies transitional waters as priority restoration targets (EU2030 2021), while the Impact Assessment for the Nature Restoration Law demonstrates rapid ecological improvement when hydrological measures are applied (IAS 2023). The recently adopted EU Nature Restoration Regulation 2024/1991 (2024) reinforces this view by establishing binding restoration obligations for degraded inland and coastal wetlands, underscoring the need for updated, system-level assessments that can guide adaptive management.

Despite the extensive literature on coastal lagoons, liman-type coastal lakes of the western Black Sea remain poorly studied as fully integrated geomorphology–hydrology–ecology systems. Most existing works examine isolated components, morphology, water quality, vegetation or ichthyofauna, without analysing how these drivers interact under conditions of restricted water exchange (Kalchev et al. 2002; Stoyneva et al. 2015; Stoyneva-Gärtner et al. 2023; Doychev et al. 2024). In particular, there is no comprehensive assessment linking basin morphology, groundwater-dominated hydrology, ecological behaviour and macrolitter pathways within a unified interpretive framework. This constitutes a significant research gap, especially in view of the high restoration potential identified for semi-enclosed wetlands in EU-wide evaluations (De Wit and Boutin 2023) and the emerging priority for hydrology-centred measures under the Nature Restoration Regulation.

To address this gap, the present study investigates how geomorphological structure, hydrological constraints, ecological dynamics and macrolitter pathways interact to determine present-day ecosystem functioning and vulnerability in the Shabla–Ezerets coastal lake system. The Bulgarian Black Sea coast hosts a discontinuous chain of coastal lakes, lagoons, and limans, shaped by a narrow shelf, active barrier dynamics, and variable karstic groundwater input (Popov and Mishev 1974; Bird 2010; Finkl and Makowski 2019). Many of these systems have undergone hydromorphological alteration, particularly through the interruption or instability of sea–lake connectivity and reduced natural flushing, leading to increased residence time, sediment accumulation, eutrophication and habitat degradation (Ivanov et al. 1964; Michev and Stoyneva 2007; Geography of Bulgaria 2002). The Shabla–Ezerets complex is among the most representative liman-derived wetlands with a stable beach-dune barrier, supporting diverse hydrophyte, dune and reedbed communities and a rich assemblage of protected species within the Natura 2000 network (Marinova-Filipova et al. 2002; Georgiev et al. 2003; Prodanov et al. 2023). Its strong dependence on karstic groundwater, low-energy hydrodynamics, and restricted connectivity with the sea create a setting in which geomorphological stability may obscure progressive ecological vulnerability.

Aim of the study

This study aims to evaluate the drivers of ecological degradation in the Shabla–Ezerets coastal lake system by examining how basin geomorphology, hydrological confinement, and pollution pressures, particularly macrolitter dynamics, collectively regulate ecosystem functioning and vulnerability. A key objective is to determine whether controlled, seasonal outlet drainage can counteract stagnation-driven processes and thus serve as a viable, nature-based restoration measure grounded in enhanced freshwater renewal. To support this evaluation, the study integrates high-resolution geomorphological, hydrological, sedimentological, ecological, and macrolitter datasets, along with an assessment of ichthyofaunal composition and long-term shifts in fish community structure. This multidisciplinary evidence is used to characterise the hydrogeomorphological controls on basin behaviour, elucidate the dominant physical and biological processes shaping system dynamics, explain the mechanisms of macrolitter retention under restricted circulation, and assess ichthyofaunal responses as indicators of ecological status. These components are synthesised into a process-based conceptual model capable of diagnosing system-level degradation and informing evidence-based restoration planning.

Materials and methods

Study obeject

The Shabla–Ezerets coastal lake system is located in the northern Bulgarian Black Sea sector, a region characterised by a narrow continental shelf, active barrier formation and strong interactions between aeolian, marine and karstic processes (Ivanov et al. 1964, Popov and Mishev 1974, Geography of Bulgaria 2002, Bird 2010) - Fig. 1. The system comprises two adjacent closed limans, Shabla and Ezerets lakes, formed by the flooding of shallow erosion valleys incised into the Sarmatian limestone platform during the Holocene transgression and subsequently isolated from the sea by longshore-driven sand-barrier progradation (Popov and Mishev 1974, Peychev and Peev 2006, Cheshitev 1995). The lakes are connected by a narrow, reed-filled channel that permits only minimal, wind-modulated water movement and no effective exchange, consistent with their long-term semi-isolation. Karstified Miocene and Sarmatian limestones dominate the subsurface, supplying groundwater that constitutes more than 90% of the annual water balance (Georgiev et al. 2003). Today, the Shabla–Ezerets complex is one of the most ecologically significant wetland systems along the northern Bulgarian coast, supporting diverse habitats and regulating landscape-scale hydrological and geomorphological processes (Kotsev et al. 2018, Frantzova et al. 2024).

Coastal limans such as Shabla rank among the most fragile wetland types in Europe: shallow, low-salinity and semi-isolated from the sea, they respond strongly to land-use change, drainage, pollution and infrastructure that modify hydrology and accelerate ecological succession. De Wit et al. (2020) describe characteristic trajectories toward eutrophication or oligotrophication, often accompanied by regime shifts in primary

producers. Although now mostly disconnected from the sea, Shabla–Ezerets retains oligohaline features (1–3 ‰) due to occasional marine intrusions and limited outflow (Georgiev et al. 2003). Under the EU Water Framework Directive (2000/60/EC) and Bulgarian Ordinance N-4 (2012), the system is addressed for management and monitoring purposes as a transitional water body.

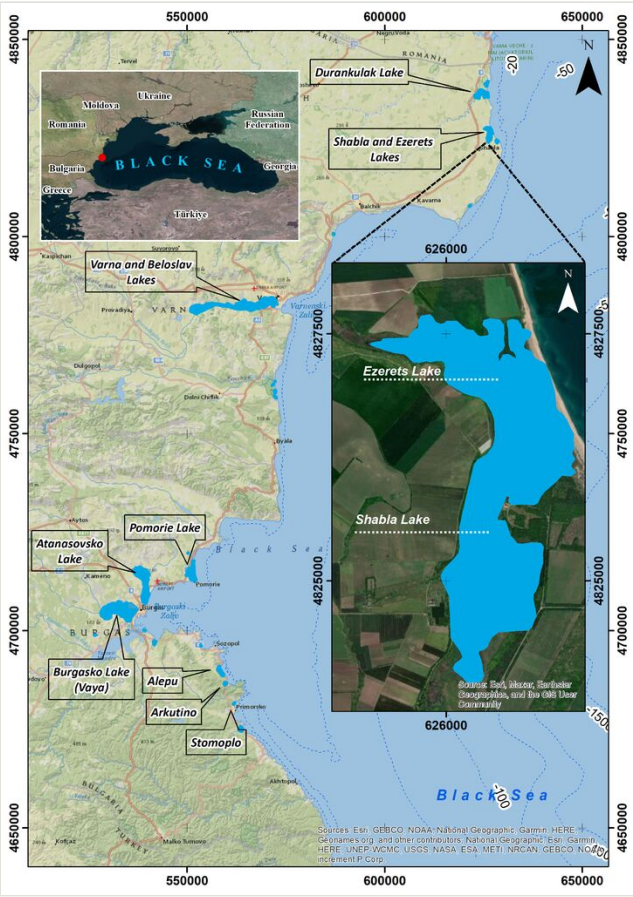

Figure 1.

Map of the coastal lakes and lagoons along the Bulgarian Black Sea Coast and the location of the Shabla–Ezerets Lake System.

The hydrogeological setting maintains a predominantly freshwater regime while favouring stratification, internal nutrient recycling and progressive littoral expansion. The coastal barrier comprises multiple dune ridges shaped by aeolian accumulation and storm overwash, including embryonic, white and grey dunes defining the seaward margin of the system (RDBRB 2015, Prodanov et al. 2023). Together with the reed-dominated palustrine fringe, these landforms govern sediment retention, macrophyte development and the degree of isolation from marine forcing.

The area lies within the Dobrudzha microclimatic zone of the Continental–Mediterranean domain, characterised by moderately cold winters, hot summers and pronounced influence from northeasterly winds (Ivanov et al. 1964, Georgiev et al. 2003). Seasonal hydrological fluctuations of several decimetres shape the extent of flooded littoral habitat, influence oxygen dynamics and modulate the distribution of submerged vegetation (Georgiev et al. 2003).

Vegetation reflects a mosaic of aquatic, marsh and dune habitats. Hydrophytic communities dominated by *Potamogeton* spp., *Myriophyllum* spp., *Nympaea alba and Nuphar lutea* occupy open-water zones; extensive reedbeds of *Phragmites australis*, *Typha* spp. and *Schoenoplectus lacustris* fringe the shoreline; and psammophytic cenoses typical of classes Cakiletea maritimae and Ammophiletea occur on the foredune and backdune systems (Marinova-Filipova et al. 2002). These plant communities form a coherent ecological zonation, with submerged vegetation stabilising the shallow basin, helophytes acting as efficient sediment and organic-matter traps that drive littoral progradation and terrestrialisation, and dune vegetation stabilising the barrier ridges. The resulting habitat mosaic enhances ecological heterogeneity and provides essential nursery and refuge areas for fish and invertebrates.

This structural complexity supports diverse ichthyofauna, including freshwater and Ponto-Caspian brackish species, but long-term hydrological isolation has driven the decline of euryhaline taxa historically present when the outlet was artificially maintained (Ivanov et al. 1964, Georgiev et al. 2003). Historical ichthyological surveys (Georgiev 1967) document the presence of several euryhaline and marine-associated species during periods of artificial connectivity, providing the earliest baseline for assessing subsequent faunal decline. This decline likely included several Ponto-Caspian gobiid species, whose former occurrence in regional coastal wetlands is well documented for Bulgaria (Vassilev et al. 2012). Historical observations indicate that several transitional and marine-associated species disappeared after the cessation of artificial sea–lake connectivity (after the late 1960s, when the managed sea–lake connection was no longer maintained), resulting in a simplified assemblage dominated by tolerant limnophilic taxa (Georgiev et al. 2003). Extensive macrophyte belts continue to provide important nursery habitats, although the overall functional diversity of the fish community has decreased due to hydrological confinement.

The entire complex lies within the Natura 2000 site BG0000621 “Ezero Shabla–Ezerets”, designated under the Habitats Directive for the protection of lagoon, dune, palustrine and steppe habitats, as well as species of European conservation importance (EU Commission 2019, Order RD-1044/17.12.2020 2020). The site is also a key ornithological area along the Via Pontica flyway, supporting protected species such as *Branta ruficollis* and *Pelecanus crispus*.

Overall, the Shabla–Ezerets system represents a geomorphologically stable but hydrologically constrained liman complex, where groundwater dominance, restricted marine exchange and extensive reed expansion create conditions conducive to stratification, nutrient retention and ecological vulnerability. These characteristics justify

its selection as a model system for examining geomorphology–hydrology–ecology interactions and for evaluating hydrology-centred restoration measures.

Data and Methods

This study applies a system-level, integrated methodological framework designed to evaluate the coupled geomorphological, hydrological, sedimentological, ecological, ichthyological and macrolitter pollution characteristics of the Shabla–Ezerets coastal lake system (Figs 2, 3). The approach combines high-resolution terrain and bathymetric mapping, sediment and water analyses, biological surveys and harmonised litter assessment protocols. All datasets were spatially integrated within a unified GIS environment to allow cross-component interpretation of morphology, water dynamics, biotic structure and anthropogenic pressures.

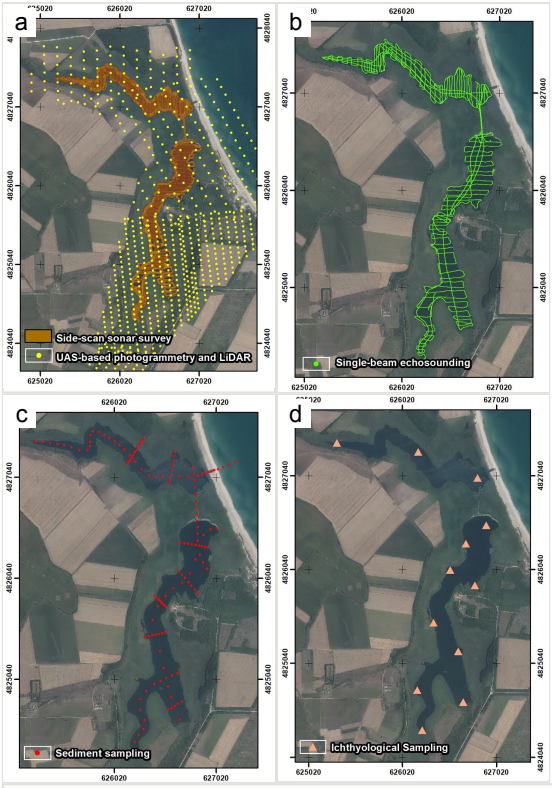

Figure 2.

Spatial coverage of fieldwork activities in the Shabla-Ezerets coastal lake system and adjacent sand barrier area

a: Areas of side-scan sonar, UAS and LiDAR syrveys
b: Single-beam echosounding
c: Sediment sampling
d: Ichthyological sampling

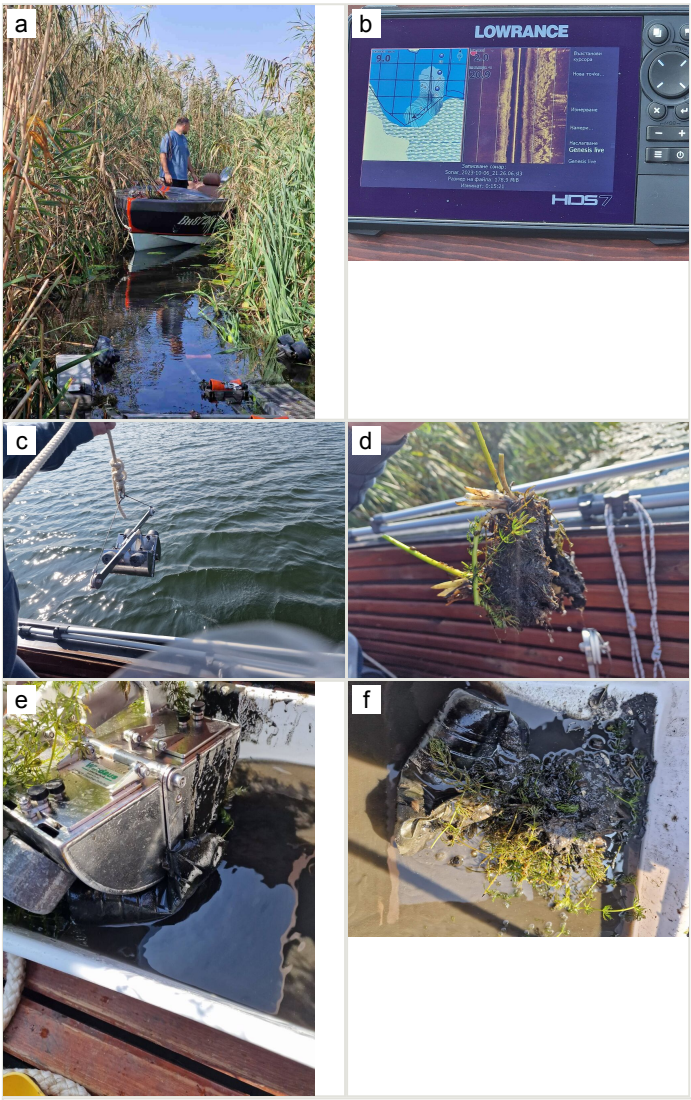

Figure 3.

Field work and samplig at the Shabla-Ezerets Lake system

a: Research boat positioned within the reed belt at the shoreline of the lake
b: Single-beam echosounding combined with side-scan sonar survey conducted along 50-m transects
c: Sediment sampling using a van Veen grab sampler (volume: 0.05 m³)
d: Organic-rich layer consisting of decaying aquatic vegetation intertwined with fine-grained bottom sediments
e: Close-up of the van Veen grab sampler with fine-grained, organic-rich sediments interwoven with submerged macrophytes, characteristic of the surficial depositional layer
f: Example of anthropogenic pollution on the lake bottom, a submerged plastic bottle colonised by aquatic plants

Topographical mapping

Topographic reconstruction and geomorphological settings were characterised using a combination of UAS-based LiDAR scanning, photogrammetry and hydroacoustic surveys (Fig. 2a, b). UAS flights were conducted with a DJI Matrice 400 equipped with a Zenmuse L2 LiDAR and integrated RGB camera, producing a dense point cloud (>250 pts·m^{-2}), a 0.15-m Digital Terrain Model (DTM) and a 1.5-cm RGB orthomosaic. Point-cloud classification and terrain modelling were performed in DJI Terra Professional, with subsequent processing in ArcGIS 10.8. Accuracy was validated using GNSS-RTK ground control points, yielding RMSE values of ±0.03 m horizontally and ±0.05 m vertically (BHS 1977, WGS84/UTM 35N). Geomorphological units, dune ridges, shoreline segments and hydrological features were digitised and incorporated into the GIS database.

Hydroacoustic mapping employed a Lowrance HDS-7 StructureScan HD system (800 kHz; lateral range 60 m), combining single-beam echosounding and side-scan sonar. A total of 66,521 georeferenced depth points and 51.5 km of survey tracks were used to construct a 2.25 km² Digital Bathymetric Model (DBM) and a 1.11 km² side-scan mosaic. Data processing was performed in ReefMaster and Global Mapper.

Sediment sampling and analysis

Sedimentological characterisation was based on 136 samples collected between February 2024 and May 2025 along predefined morpho-lithological transects (Fig. 2c). Samples were acquired using a van Veen grab (0.05 m²). Grain-size distribution was analysed by dry sieving and laser diffraction using a Mastersizer 3000, following Gradistat (Blott and Pye 2001) and the Wentworth scale (Wentworth 1922). Organic matter content was quantified through loss-on-ignition (LOI). Sediment data were georeferenced and integrated with geomorphological and bathymetric layers to identify depositional zones and sediment-water interaction patterns.

Hydrological, physicochemical and ecological parameters

Hydrological and physicochemical parameters were obtained through a combination of national Water Framework Directive (WFD) monitoring datasets and high-resolution field measurements conducted between 2010 and 2024. In situ vertical profiles of temperature, dissolved oxygen, electrical conductivity, salinity and pH were measured using portable multiparameter instruments. Dissolved oxygen was recorded with a Lovibond SD 400 Oxi L electrochemical oxygen meter equipped with automatic temperature compensation, while pH measurements were performed with a HACH Pocket Pro pH meter (P/N S531000). Electrical conductivity and total dissolved solids were analysed using a Lovibond SensoDirect Con110 to characterise the physicochemical conditions and document those relevant to electrofishing performance and standardisation. Chlorophyll *a* concentrations were quantified using a Turner Designs handheld fluorometer following WFD-compliant calibration procedures as an auxiliary indicator of trophic conditions/eutrophication pressure. Additional nutrient and ion concentrations were determined with a Lovibond Water Testing (Tintometer) field kit,

applying standardised colourimetric methods for selected indicators. Chlorophyll a and the additional nutrient/ion indicators were used as supporting contextual information rather than as focal response variables and are therefore not presented as separate results.

Historical environmental conditions and the legacy water-column structure of the Shabla Lake System were reconstructed using the earliest published hydrological and hydrochemical data (Ivanov et al. 1964), which include vertical profiles of temperature, salinity, and oxygen saturation obtained during both summer and early winter. These historical measurements provided a baseline for identifying long-term physicochemical trajectories, including the early onset of summer stratification, low-salinity freshwater dominance, and oxygen depletion in deeper layers.

Ichthyofaunal analysis

Ichthyofaunal dynamics were assessed through a synthesis of historical campaign-based datasets (1950–1966, 1995–1996, 2000–2009) and contemporary surveys (2010–2024). For the purposes of diversity indices, Bray–Curtis similarity, and temporal clustering, these raw periods were grouped into three standardised analytical intervals (1990–2000; 2001–2009; 2010–2024) to allow consistent temporal aggregation and ensure comparability across data sources. The original campaign periods are retained in Table 4 for transparency regarding historical species records. Recent sampling followed standard protocols for shallow transitional waters, including electrofishing using two devices - SAMUS 725G and HANS GRASSL IG200 (200–600 V, 50 Hz, PDC, 120 W) and seining with a 10-m net (5 mm mesh). Seining was used as a supplementary method (e.g., to improve the detectability of certain taxa), while the standardised electrofishing transect served as the reference unit for semi-quantitative abundance estimates. During the contemporary surveys (2010–2024), electrofishing was conducted under freshwater/low-salinity conditions; conductivity was recorded at each site to guide the field settings and ensure comparability among surveys. Species abundances were transformed into a semi-quantitative 0–5 scale based on density estimates to ensure comparability across surveys. For contemporary sampling (2010–2024), density was calculated as $D=(10{,}000 \cdot N)/S$, where D is abundance density (individuals·ha^{-1}), N is the number of captured individuals, and S is the surveyed area (m^2). Following the field protocol, each electrofishing replicate covered a fixed shoreline segment of 100 m with an effective sampling width of 2 m, i.e. S=200 m^2 per station/replicate. Density values were then converted into an ordinal 0–5 scale using $\log_{10}$ class bins: 0 = not detected (N=0); 1 = occasional ($0<D<10$ Individuals·ha^{-1}); 2 = low ($10 \le D<100$); 3 = moderate ($100 \le D<1{,}000$); 4 = high ($1{,}000 \le D<10{,}000$); and 5 = dominant ($D \ge 10{,}000$). Historical sources (1950–1966, 1995–1996, 2000–2009) typically reported abundance qualitatively (e.g., "rare", "common", "dominant" and/or "+" notations) without standardised surveyed area; these descriptors were harmonised to the same 0–5 ordinal scheme via a predefined cross-walk (absence/not reported is 0; single/occasional or "+" is 1; rare or "+ +" is 2; common or "+++" is 3; abundant or "++++" is 4; dominant or "+++++" is 5), preserving rank-order information for temporal multivariate analyses. Bray–Curtis

similarities were computed on square-root transformed values, and hierarchical cluster analysis (group-average linkage) and k-dominance curves were used to identify temporal assemblage shifts. Diversity metrics (S, Margalef's d, Shannon H′, Pielou J′, Simpson 1–λ′) were calculated following PRIMER v7 protocols (Clarke and Gorley 2015).

Macrolitter assessment

Macrolitter was evaluated through a multi-compartment survey of the beach–dune system, surface waters and lake-bottom sediments, following harmonised EU MSFD TSG-ML and GESAMP protocols (MSFD-TSML 2013, GESAMP 2019, Fleet et al. 2021, Galgani et al. 2023). Linear 100-m transects were established across the beach–dune interface. All items ≥2.5 cm were classified using the Joint List of Litter Categories. UAS photogrammetry (DJI Matrice 400 + Zenmuse P1, 45 MP) supported high-resolution identification of litter hotspots. To analyse the cleanliness status, the Clean Coast Index - CCI (Alkalay et al. 2007) and Plastic Abundance Index - PAI (Rangel-Buitrago et al. 2021) were calculated.

Floating litter was visually surveyed from an inflatable boat and via low-altitude UAS flights, and standardised to 10,000 m². Lake-bottom litter was sampled using a van Veen grab along bathymetric transects and classified according to MSFD guidance (Galgani et al. 2023). All litter data were integrated with geomorphological and hydrological datasets to analyse accumulation zones and transport pathways.

Data integration and analysis

All datasets, geomorphological, bathymetric, sedimentological, ecological, ichthyological and macrolitter, were spatially harmonised within a unified GIS environment. Cross-component interpretation enabled the evaluation of feedbacks among basin morphology, hydrological isolation, ecological structure, and anthropogenic pressure. This integrative analytical framework underpins the system-level assessment of ecosystem functioning and restoration potential presented in the Results and Discussion.

Results

Lake structure and geomorphological settings

The composed digital terrain model from LiDAR and echosounding data delineates a shallow, low-energy liman system composed of two interconnected basins with maximum depths of –9.0 m in Shabla Lake and –8.0 m in Ezerets Lake (Fig. 4; Tables 1, 2). The terrain exhibits low relief, with mean bottom gradients of 1.6–1.9° and limited elevation variability (STD ≈ 2.75 m), indicating a geomorphologically stable configuration dominated by fine-grained sediment accumulation. Shabla Lake covers 1.739 km² and stores 4.08 × 10^6 m³ of water, serving as the primary sediment and nutrient sink for the complex. Ezerets Lake (0.933 km²; 2.21 × 10^6 m³) displays stronger littoral encroachment and a higher shoreline-to-area ratio (6.35 km km^{-2}), consistent with its more advanced

terrestrialisation stage. Several distinct geomorphological zones were identified, including central depressions (–7 to –9 m), marginal terraces (–1 to –2 m), shallow littoral slopes (–1 to +0.5 m), dune ridges (+0.5 to +3 m) and palustrine flats (+3 to +8 m) - Table 1. The multi-ridge coastal barrier, with crest elevations between 2.3 and 3.1 m a.s.l., regulates hydrological isolation and determines the degree of marine influence. Together, these features define a mature liman morphology, predominantly shaped by groundwater inflow and limited hydrodynamic energy (Table 2).

Table 1.

Lake morphology, processes and functional classification of the Shabla–Ezerets Lake and coastal system.

Morphological forms	Elevation Range (m, a.s.l)	Representative Landforms	Geomorphological Processes	Hydrological / Ecological Function
Central lacustrine depressions	–7.0 to –9.0	Axial depressions; flat-bottom basins with organic-rich mud	Tectono-karstic subsidence; fine sediment and organic accumulation; long-term infilling	Sediment and nutrient sink
Subaqueous steep slopes	–2.0 to –7.0	Karst escarpments; erosional scarps; marginal slopes	Subaqueous mass wasting; slope instability; lateral erosion and groundwater inflow	Groundwater exchange; slope dynamics
Shallow sublacustrine terraces	–2.0 to –1.0	Benches; terraces; gently inclined shelves	Stillstand levels; lateral sediment transport; macrophyte colonisation	Sediment deposition; macrophyte habitat
Upper littoral and shoreline slope	–1.0 to +0.5	Shallow marginal slopes; seasonally flooded fringe	Alternating inundation and exposure; sediment redeposition; biostabilisation by vegetation	Amphibious interface; nutrient cycling
Coastal barrier and dune complex	+0.5 to +3.0	Barrier ridge; foredunes; embryonic and grey dunes	Aeolian accumulation; storm overwash; vegetation succession	Wave buffer; sediment and salinity control
Palustrine and floodplain fringe	+3.0 to +8.0	Palustrine flats; wet meadow and lowland marsh zone; alluvial fringes	Groundwater fluctuation, seasonal flooding, organic and alluvial buildup	Water storage; nutrient retention
Karst springs and groundwater discharge zones	Local slope breaks (~ –4.0 to –2.0)	Submerged springs; seepage fans; vent mounds	Upwelling of karst groundwater; vertical mixing; localised erosion	Vertical mixing; oxygenation; biogeochemical exchange

Table 2.

Morphometric characteristics of the Shabla-Ezerets coastal lake system based on echosounding and geodetic measurement.

Parameter	Shabla Lake	Ezerets Lake	Shabla–Ezerets Lake system	Interpretation
Area (km²)	1.74	0.93	2.67	Defines the total water surface; Shabla Lake dominates the complex (~65% of the total area).
Perimeter (km)	10.18	5.92	14.91	Indicates shoreline development; reflects littoral complexity and vegetation extent.
Maximum depth (m)	–9.0	–8.0	–9.0	Marks the deepest point controlling stratification potential and sediment focusing.
Mean bottom depth (m)	≈ -2.0	≈ -2.0	≈ -2.0	Confirms a shallow, low-relief basin morphology typical of coastal lakes. Confirms the shallow character and proneness to stratification and eutrophication.
Standard deviation of depth (m)	2.75	2.75	2.75	Low standard deviation indicates uniform bottom relief and geomorphic stability.
Maximum slope (°)	84.1	79.1	84.1	Represents local steep escarpments associated with karst inflows of limited areal extent.
Mean slope (°)	1.59	1.94	1.71	Indicates a gentle overall gradient; critical for sediment deposition and weak circulation.
Median slope (°)	0.67	0.49	0.61	Confirms dominance of very low-inclined surfaces (<1°), characteristic of calm depositional basins.
Dominant slope aspect	E (87°)	SE (135°)	E (109°)	Reveals general orientation toward the Black Sea and exposure to prevailing NE winds.
Shoreline-to-area ratio (km km⁻²)	5.86	6.34	5.58	Quantifies littoral complexity; higher values indicate greater wetland development potential.
Volume (m³)	4 083 543	2 212 410	6 295 954	Defines total freshwater storage, essential for hydrological and ecological resilience.
Dominant geomorphological type	Elongated trough; karst-fed basin	Shallow asymmetric basin	Coupled liman-type coastal lake system	Describes the genesis and functional morphology of the system.

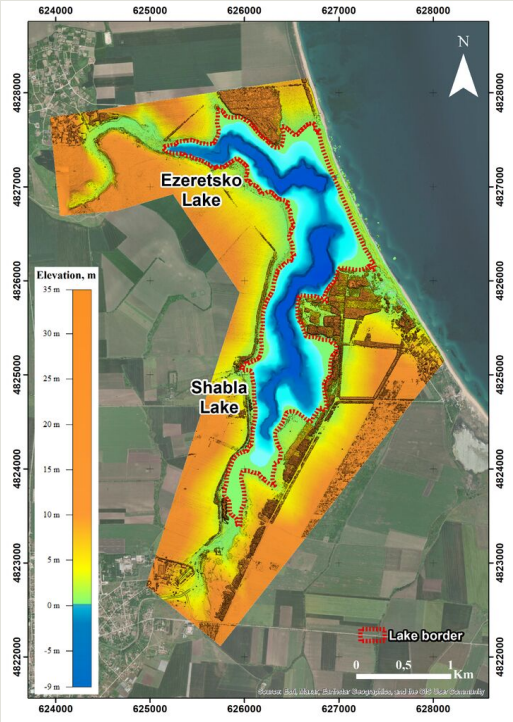

Figure 4.

Composed Digital Surface and Bathymetric Model of the Shabla-Ezerets Lake system and sand-dune barrier spit.

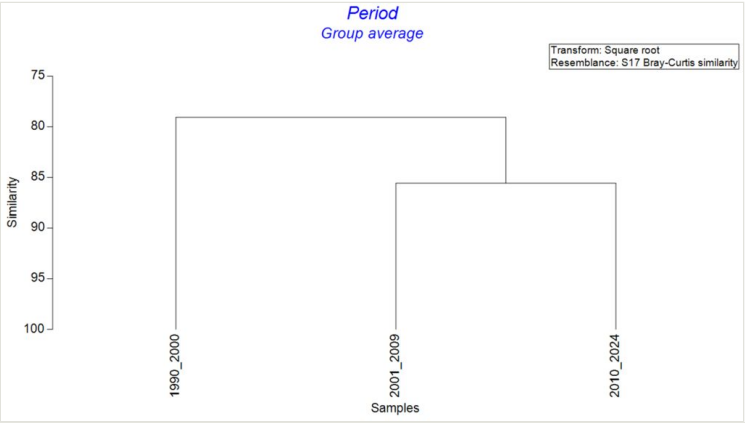

Figure 5.

Cluster dendrogram (group-average linkage; Bray–Curtis similarity) of fish assemblage composition across three standardised analytical periods (1990–2000; 2001–2009; 2010–2024) in the Shabla–Ezerets lake system (semi-quantitative abundance scale 0–5; square-root transform).

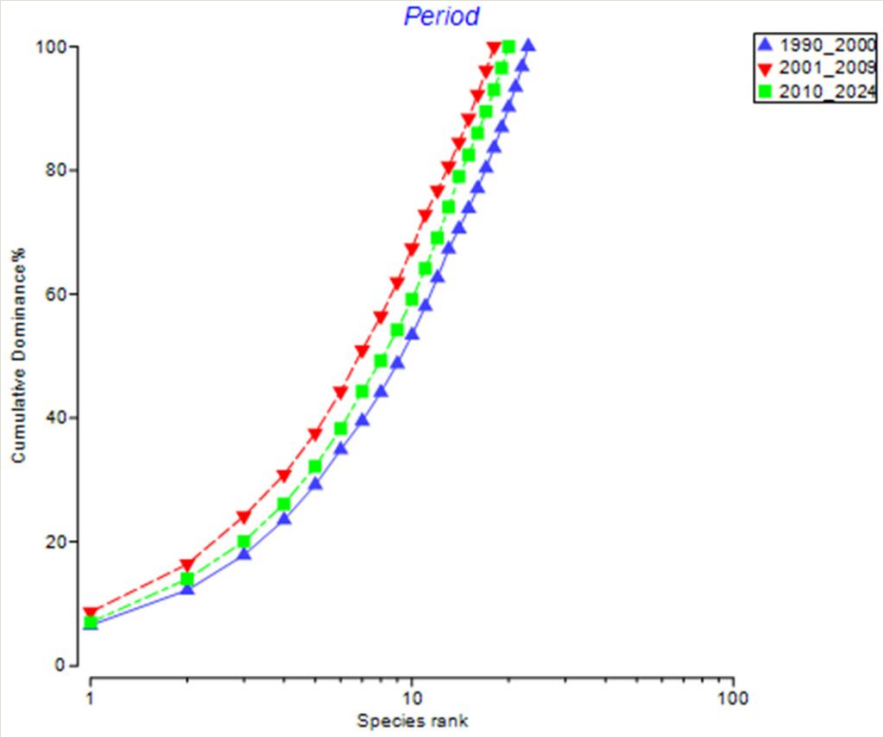

Figure 6.

K-dominance curves of fish assemblages across the three analytical periods in the Shabla–Ezerets lake system. Curves largely overlap, indicating stable dominance structure/evenness among periods.

Hydrological and physicochemical characteristics

Water-column measurements reveal clear seasonal stratification patterns (Fig. 11). In summer, temperature profiles exhibit warm surface waters (24–26 °C) overlying cooler bottom layers (10–14 °C), with a thermocline typically positioned between 2–4 m depth. Winter profiles show vertically uniform temperatures ranging between 3–6 °C. Historical measurements (1950–1962) display lower summer maxima (<20 °C) and reduced vertical gradients (Suppl. material 1).

Contemporary salinity remains within oligohaline (near-freshwater) ranges throughout the year in the Shabla–Ezerets coastal lake system. In 2019–2024, summer salinity is 0.1‰ from the surface down to −7 m, increasing to 0.9‰ at −9 m, indicating very weak vertical gradients (Fig. 13). Winter salinity in 2019–2024 is 0.1–0.3‰ (0.3‰ at the surface; 0.1‰ below −1 m), with minimal vertical variation. Historical (1950–1963) measurements show higher salinities: 1.1–2.0‰ in summer (increasing with depth) and 1.8–2.1‰ in winter, with a more distinct summer increase toward the bottom compared to the contemporary profile (Suppl. material 1).

Figure 7.

Examples of macro-litter accumulation in the Shabla–Ezerets coastal system with reference to the Joint List of Litter Categories (Fleet et al. 2021)

a: Mixed debris at the Central artifcial chanel: wood, plastic bottle (>0.5 L), and other items, including plastic drink bottles >0.5 L (pl_fc_b&c_dbot_lage, J8) and processed wood >50 cm (wo_nn_owo_larg, J172)

b: Artificial channel - north; Mixed wood and plastic debris accumulated at the temporary outlet channel, including small plastic drink bottles (pl_nn_b&c_dbot_smal, J7), foamed polystyrene fragments (pl_nn_frg_fopy_smal, J82), and processed wood pieces (wo_nn_owo_smal, J171)

c: Vehicle plastic component (e.g., wheel hub cover) mixed with driftwood, classified as plastic vehicle parts (pl_vk_prt, J19)

d: Anthropogenic waste among dune vegetation: plastic panel, rope, and wood , e.g., plastic rope >1 cm (pl_nn_rps_rope, J49) and wooden crates (wo_nn_box, J162)

e: Scattered small plastics embedded in the upper embryo dune, plastic fragments 2.5–50 cm(pl_nn_frg_nofp_smal, J79) and foamed polystyrene fragments (pl_nn_frg_fopy_smal, J82)

f: Storm-cast debris at the upper beach , large wooden planks (wo_nn_owo_larg, J172), metal rods (me_nn_ome_larg, J199*), and rope fragments (pl_nn_rps_rope, J49)

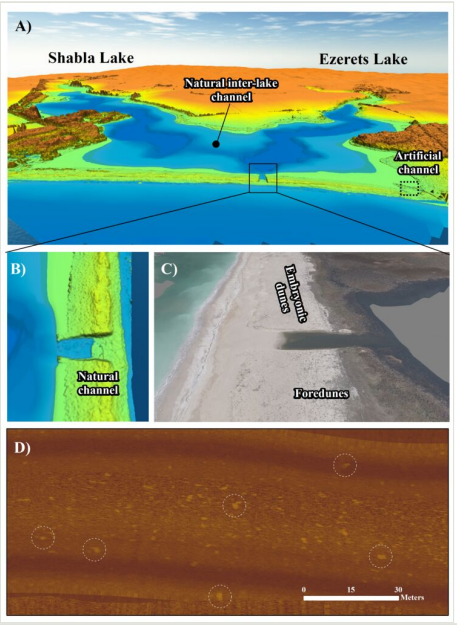

Figure 8.

Integrated 3D visualisation of the Shabla coastal lake system; (A) 3D terrain view of Shabla and Ezerets lakes with the sand barrier and adjacent terrain; (B) DTM of the artificial channel through the barrier; (C) 3D photorealistic model of the beach-dune system; (D) Side-scan sonar image of the lake bottom with circled features interpreted as possible karstic spring vents.

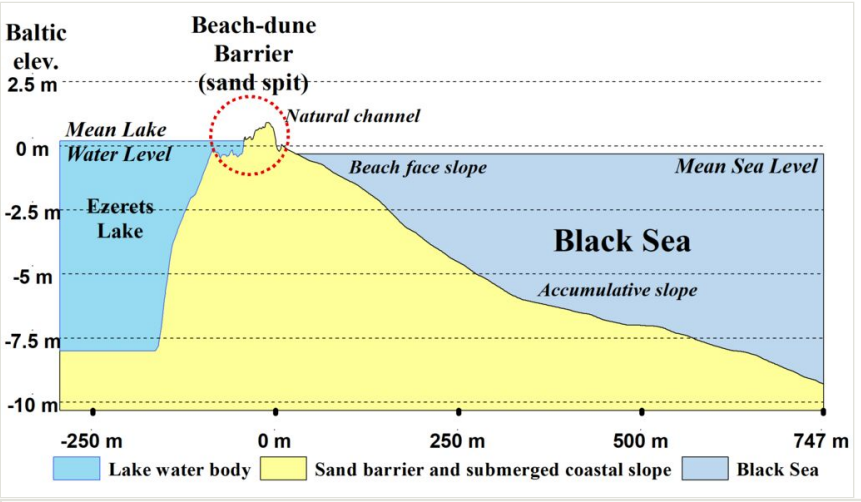

Figure 9.

Morphological cross-section of the Shabla–Ezerets barrier showing the perched natural outlet channel and the elevation relationship between lake level, barrier crest and mean sea level.

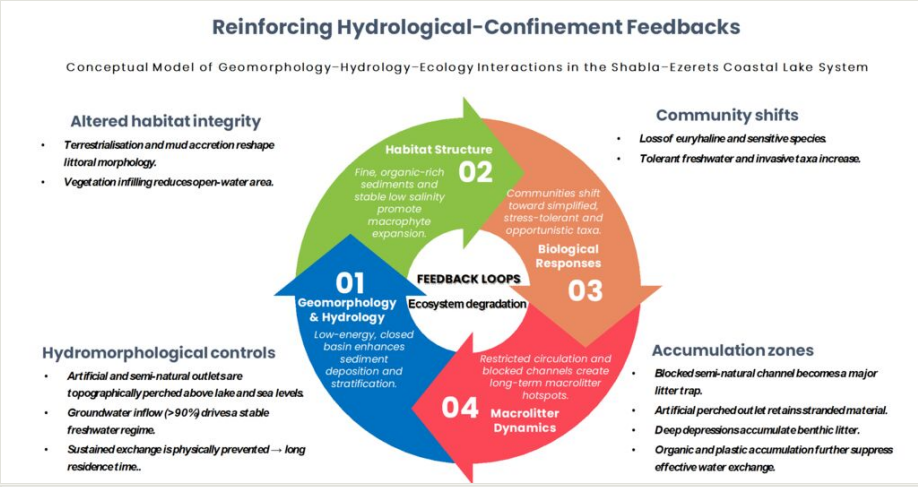

Figure 10.

Conceptual model of reinforcing hydrological-confinement feedbacks structuring geomorphology, ecology and macrolitter dynamics in the Shabla–Ezerets coastal lake system.

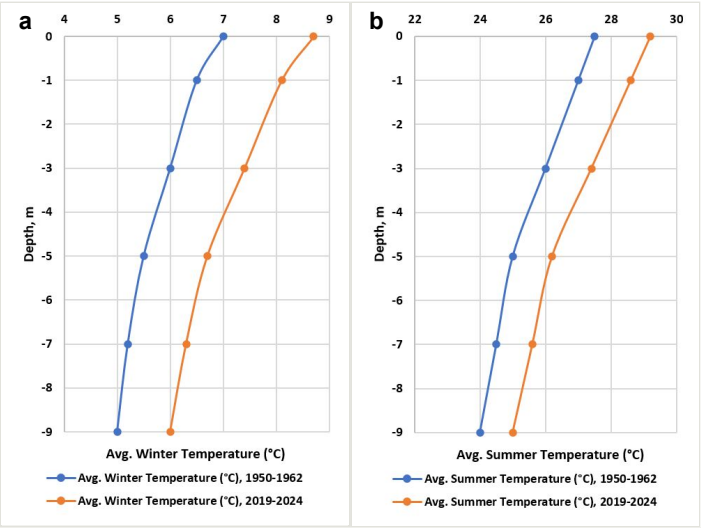

Figure 11.

Vertical temperature profiles illustrating historical (1950–1962) and contemporary (2019–2024) thermal structure of the Shabla–Ezerets coastal lake system.

a: Winter temperature profiles (1950–1962 vs. 2019–2024)
b: Summer temperature profiles (1950–1962 vs. 2019–2024)

Oxygen saturation shows strong seasonal structure (Fig. 12). Winter profiles are vertically uniform, with saturation commonly between 70–95%. Summer profiles display elevated surface oxygenation (60–90%) and reduced values with depth, frequently reaching 20–40% in deeper layers. The lowest values occur within the central depressions. Historical

profiles show higher and more uniform oxygen saturation across the water column (Suppl. material 1).

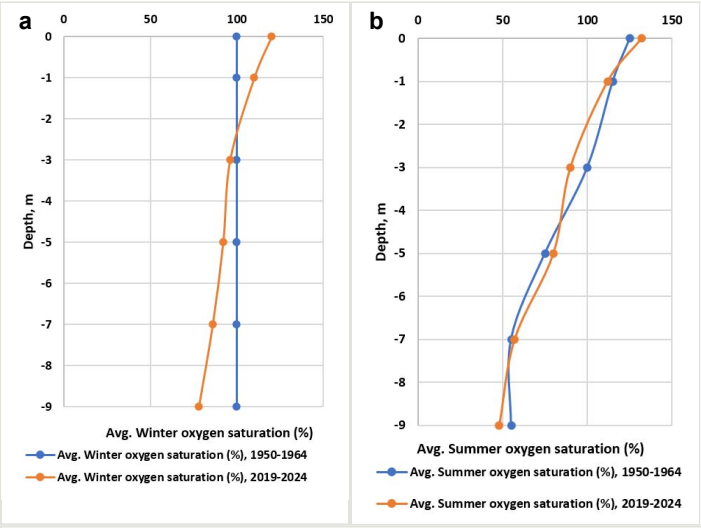

Figure 12.

Vertical
oxygen-saturation profiles illustrating historical (1950–1963) and contemporary (2019–2024) conditions in the Shabla–Ezerets coastal lake system.

a: Winter oxygen saturation profiles (1950–1963 vs. 2019–2024).
b: Summer oxygen saturation profiles (1950–1963 vs. 2019–2024).

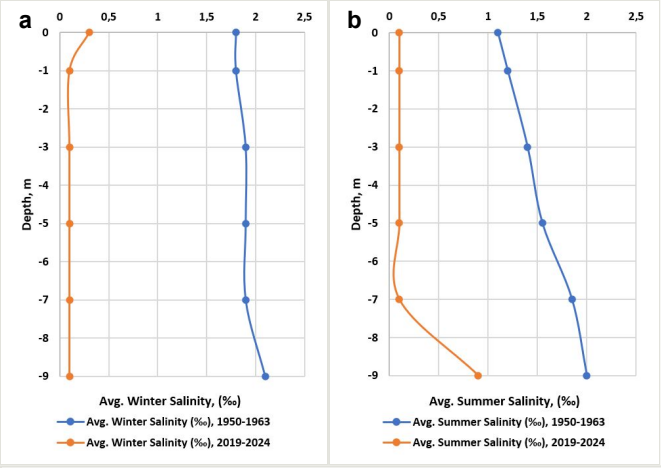

Figure 13.

Vertical salinity profiles illustrating historical (1950–1963) and contemporary (2019–2024) conditions in the Shabla–Ezerets coastal lake system.

a: Winter salinity profiles (1950–1963 vs. 2019–2024).
b: Summer salinity profiles (1950–1963 vs. 2019–2024).

Organic-rich littoral sediments and vegetation mats indicate active internal nutrient recycling. Central depressions dominated by fine silts show loss-on-ignition (LOI) values up to 18%.

Ecological conditions and vegetation structure

The distribution of aquatic vegetation is strongly conditioned by basin morphology, water depth and hydrological isolation. Rooted and floating hydrophytes (*Potamogeton* spp., *Myriophyllum spicatum*, *Nymphaea alba*, *Nuphar lutea*) dominate open-water areas, while extensive reedbeds of *Phragmites australis*, *Typha* spp. and *Schoenoplectus lacustris* cover the shallow littoral margins. Since the 2010s, reedbed/macrophyte overgrowth and related eutrophication–succession processes have required active management (reed mowing and measures to improve water exchange) in the Shabla Lake complex, consistent with increased organic accumulation, reduced renewal, and sediment retention in the littoral zone (Report 2023).

Ichthyofauna diversity

Long-term ichthyofaunal data suggest directional ecological change consistent with increasing hydrological isolation and cumulative anthropogenic pressures (Figs 5, 6, 14) Cluster analysis based on Bray–Curtis similarity shows that the assemblages for 2001–2009 and 2010–2024 are most similar (85.57%), whereas 1990–2000 is comparatively distinct (pairwise similarities 77.68–80.44%), consistent with a temporal shift in community composition (Fig. 5; Table 2). Species richness declined from 23 (1990–2000) to 18 (2001–2009), followed by a partial recovery to 20 (2010–2024) (Fig. 6; Table 3). The near-overlap of k-dominance curves in Fig. 6 indicates a broadly stable dominance structure and evenness across periods. Diversity remained comparatively high across periods (Shannon H′(ln)=3.106, 2.851 and 2.968; Simpson 1–Lambda′=0.9862, 0.9779 and 0.9817), with evenness consistently near unity (J′=0.9907, 0.9863 and 0.9908), indicating that temporal changes primarily reflect species turnover rather than dominance shifts. A complete list of species recorded in the contemporary surveys (2010–2024) is provided in Table 4. The absence of marine and euryhaline visitors (*Mugil cephalus*, *Chelon* spp., *Atherina boyeri*, *Platichthys flesus*) after the cessation of outlet maintenance is consistent with a transition toward a freshwater-dominated, low-salinity (oligohaline) regime (Table 4). Sensitive oligohaline and locally restricted taxa (*Misgurnus fossilis*, *Knipowitschia longicaudata* and *Gasterosteus aculeatus*) show long-term decline or near-extirpation in the recent surveys, whereas tolerant freshwater and non-native taxa (*Carassius gibelio*, *Gambusia holbrooki*) increased in relative importance (Table 4). Because historical datasets differ in sampling effort and gear, we interpret between-period differences conservatively as robust descriptive patterns; standardisation into three analytical intervals and the use of a semi-quantitative abundance scale (0–5) were applied to reduce detectability bias. These patterns collectively point to functional simplification and a shift toward a disturbance-tolerant assemblage.

Table 3.

Indices of ichthyofaunal diversity for the Shabla–Ezerets Lake system.

Periods	S	Margalef d	H' (loge)	J'	1-Lambda'
1990 - 2000	23	6.433	3.106	0.9907	0.9862
2001 - 2009	18	5.229	2.851	0.9863	0.9779
2010 - 2024	20	5.668	2.968	0.9908	0.9817

Table 4.

Quantitative abundance (0–5), temporal trends and conservation status of fish species in the Shabla–Ezerets coastal lake system.

Family	Species	1950–66	1995–96	2000–09	2010–24	Trend*	Status**
Resident Species							
Clupeidae	*Clupeonella cultriventris*	1	2	0	0	Decline	LC
Esocidae	*Esox lucius*	1	2	2	3	Increasing	LC
Cyprinidae	*Rutilus rutilus*	1	4	4	3	Increasing	LC
Cyprinidae	*Scardinius erythrophthalmus*	1	3	1	2	Fluctuating	LC
Cyprinidae	*Abramis brama*	1	2	2	2	Stable	LC
Cyprinidae	*Rhodeus amarus*	0	1	3	2	Increasing	Annexe II HD
Cyprinidae	*Carassius gibelio*	0	2	3	3	Increasing	Invasive
Cyprinidae	*Cyprinus carpio* (wild)	1	1	1	0	Collapse	VU
Cyprinidae	*Cyprinus carpio* (cultured)	0	1	2	3	Increasing	Domesticated
Cyprinidae	*Ctenopharyngodon idella*	0	1	1	2	Increasing	Introduced
Cyprinidae	*Hypophthalmichthys molitrix*	0	2	3	2	Peak then decline	Introduced
Cobitidae	*Misgurnus fossilis*	1	1	0	0	Decline	VU
Siluridae	*Silurus glanis*	1	1	1	2	Increasing	LC
Poecilidae	*Gambusia holbrooki*	0	1	5	4	Invasive ↑	Invasive
Percidae	*Sander lucioperca*	0	2	1	2	Fluctuating	LC

Family	Species	1950–66	1995–96	2000–09	2010–24	Trend*	Status**
Percidae	*Perca fluviatilis*	1	3	1	3	Fluctuating	LC
Gobiidae	*Knipowitschia caucasica*	1	3	2	1	Decline	VU
Gobiidae	*Knipowitschia longicaudata*	0	1	0	0	Near extirpation	Endemic, CR
Gobiidae	*Neogobius melanostomus*	1	3	2	2	Stable	LC
Gobiidae	*Neogobius gymnotrachelus*	1	1	3	1	Fluctuating	LC
Gobiidae	*Proterorhinus marmoratus*	1	2	4	2	Increase → decline	LC
Gobiidae	*Benthophiloides brauneri*	1	0	0	1	Reappearing	CR
Gasterosteidae	*Pungitius platygaster*	1	1	0	1	Fluctuating	NT
Gasterosteidae	*Gasterosteus aculeatus*	0	1	0	0	Rare	LC
Marine/euryhaline species (historically present before inlet closure)							
Syngnathidae	*Syngnathus abaster* / *S. nigrolineatus*	1	3	1	1	Stable	LC
Mugilidae	*Mugil cephalus*	1	0	0	0	Not recorded	LC
Mugilidae	*Chelon auratus*	1	0	0	0	Not recorded	LC
Mugilidae	*Chelon saliens*	1	0	0	0	Not recorded	LC
Atherinidae	*Atherina boyeri*	1	0	0	0	Not recorded	LC
Pleuronectidae	*Platichthys flesus*	1	0	0	0	Not recorded	LC

* Legend (abundance): 0 – absent; 1 – single; 2 – rare; 3 – common; 4 – abundant; 5 – dominant.

** Legend (status): LC – Least Concern; NT – Near Threatened; VU – Vulnerable; EN – Endangered; CR – Critically Endangered; Annex II HD – EU Habitats Directive Annex II; Invasive – invasive alien species; Introduced – stocked/introduced; Domesticated – cultured form; Endemic – locally restricted species.

Macrolitter distribution

Macrolitter assessments reveal persistent, moderate pollution across the beach–dune, surface-water and lake-bottom compartments of the system (Fig. 7). Beach–dune transects recorded 293–344 items·100 m^{-1}, corresponding to CCI values of 3.31–3.51,

which classify the coastal strip as “clean”, and PAI values of 1.13–1.74, indicating moderate plastic abundance (Table 5). Plastics accounted for 85–90% of all items, followed by glass, metal and processed wood. Floating macrolitter density reached 38.5 items·100000 m², placing the system within the moderate pollution class for transitional waters according to MSFD D10C1 baselines. Lightweight polymer items (EPS fragments, bottle caps, films, and packaging) dominated the assemblage (78.6%), reflecting retention within a low-energy, semi-enclosed basin. Benthic litter averaged 3 items·m^{-2}, with maxima of 6 items·m^{-2} near reedbeds and the artificial canal. These values correspond to moderate pollution under MSFD guidance for lake-bottom macrolitter. The presence of embedded plastic fragments within fine, organic-rich muds indicates long residence times, chronic accumulation and progressive fragmentation into microplastics. The spatial overlap between geomorphological features, reed expansion and litter hotspots demonstrates that the Shabla–Ezerets system functions as an effective natural retention zone. The barrier–dune complex, palustrine flats and marginal terraces act as persistent sinks, enhancing litter deposition and limiting natural removal processes.

Figure 14.

Representative fish species from the Shabla–Ezerets lake system

a: *Carassius gibelio*
b: *Esox lucius*
c: *Perca fluviatilis* and *Rutilus rutilus*
d: *Rhodeus amarus*

Table 5.

Classification, abundance, and environmental significance of macrolitter types in the Shabla–Ezerets coastal lake system.

Category	Abundance	Cleanliness / Pollution Level	Material composition and environmental significance
1. Beach macrolitter (beach–dune system)	293–344 items·100 m^{-1} (293 ± 21 in 2024–2025; 327–344 in 2023)	CCI: 3.31–3.51 (clean); PAI: 1.13–1.74 (moderate plastic abundance)	Plastics dominate (85–90%), followed by glass/ceramics (4–5%), metal (3–4%), wood and rubber. Higher accumulation on active beach sectors compared to dunes. Reflects moderate human pressure, with seasonally enhanced accumulation along the sediment-rich, low-energy embayment.
2. Floating macrolitter (surface waters)	38.5 items·10 000 m^{-2} (2024 survey; ~2 118 items across 0.55 km^2). Historical range (2018–2023): 10–25 items·10 000 m^{-2}	Moderate	Lightweight artificial polymers dominate (78.6%), including EPS fragments, bottle caps, films and packaging. Paper/cardboard 8.5%, processed wood 7.2%, rubber 5.7%. Accumulation enhanced by restricted water exchange typical of liman–lake systems; floating plastics act as a secondary source of microplastics.
3. Benthic macrolitter (lake-bottom litter)	0.8–6 items·m^{-2} (mean ≈ 3 items·m^{-2}; 34 Van Veen grab samples)	Moderate	Plastics: 61.5%; Metals: 13.2%; Glass/ceramics: 9.7%; Wood: 7.4%; Textiles/ropes: 5.1%; Rubber/other: 3.1%. Persistent deposition in organic-rich muds represents a long-term reservoir that contributes to sediment–water interactions and the fragmentation of microplastics.

Discussion

Geomorphological and hydrological conditions governing system functioning

The Shabla–Ezerets system shows the characteristics of a mature, low-energy liman-type coastal lake formed through isolation from the sea and progressive sediment infilling. Its narrow hypsometric range (–9 to +8 m), low mean slopes (1.6–1.9°), and limited elevation variability (STD ≈ 2.75 m) indicate a stable configuration with subdued relief and minimal erosional potential. Together with substantial water storage (~6.29 × 10^6 m^3) and moderate shoreline complexity (5.58 km km^{-2}), these features define a quasi-equilibrium system sustained mainly by karstic groundwater rather than marine or fluvial inflow. Limans of this type differ fundamentally from classical coastal lagoons because their functioning is controlled not by tidal exchange, but by the balance between

freshwater supply and restricted outflow (Kjerfve 1986, Bird 1994). The dominance of low-mineralised groundwater, combined with the shallow basin morphology, favours long residence times, persistent stratification and enhanced accumulation of fine, organic-rich sediments, conditions frequently observed in microtidal, semi-enclosed lakes globally (Søndergaard et al. 2003, Kennish and Paerl 2010, Newton et al. 2014). Seasonal water-level variability in groundwater-fed coastal lakes typically ranges within several decimetres and reflects the balance between karst recharge, precipitation and evaporation. Periodic flooding of palustrine margins enhances nutrient turnover and provides favourable conditions for fish spawning, whereas seasonal drawdown exposes littoral muds, facilitating oxygenation and organic-matter mineralisation. Similar hydrological–biogeochemical feedbacks have been documented in European coastal lakes and lagoons, where limited flushing reinforces nutrient retention and promotes eutrophication trajectories analogous to those described for the Mar Menor system (Rodrigues-Filho et al. 2023).

The barrier configuration, including multi-ridge progradation and aeolian reworking, reinforces hydrological isolation (Bird 2010). Episodic overwash events may deposit thin sandy laminae but do not alter the prevailing freshwater regime. This pattern corresponds to the evolutionary trajectory described by Bird (Bird 1994, Bird 2008), in which liman-type systems in humid temperate settings trend progressively toward closed freshwater lakes, especially where groundwater inflow exceeds marine influence. The observed extensive reed expansion, narrowing of open-water habitats and vertical accretion of muds further indicate a system undergoing terrestrialisation, a process documented in similar semi-enclosed wetlands worldwide (Søndergaard et al. 2003, Katsuki et al. 2008).

Hydrological confinement is similarly reflected in the spatial distribution of macrolitter. Beach–dune litter is driven primarily by local recreation rather than maritime inputs, consistent with low marine connectivity. Floating litter persists in sheltered, weakly circulating surface waters, while benthic litter accumulates in deep, stagnant depressions. Similar spatial patterns, in which backdunes and vegetated margins act as major accumulation zones, have been documented in other Mediterranean lagoon systems (Newton et al. 2014, Vlachogianni et al. 2018). Such retention patterns match global observations for poorly renewed lakes and closed lagoon basins (UNEP/MED 2021) and highlight that restricted water renewal is the primary physical mechanism driving ecological vulnerability.

Historical hydrochemical studies indicate that eutrophication-related symptoms, including ammonium enrichment, oxygen depletion and nutrient/organic matter accumulation, have been recorded in the Shabla–Ezerets system for decades (Dimitrova and Hainadjieva 2004). In the present study, we do not treat these historical observations as stand-alone evidence of continuous, monotonic deterioration. Rather, they provide temporal context for processes that are independently supported by our contemporary evidence: persistent summer stratification, recurrent deep-water oxygen depletion in the central depressions (Fig. 14), organic-rich sediments (LOI up to 18%), and recurrent seasonal peaks in chlorophyll-a together with repeated summer–autumn declines in dissolved oxygen in the long-term state-monitoring record for Shablensko and Ezeretsko lakes (Suppl.

material 2). Taken together, these lines of evidence support the interpretation that hydrological confinement remains a major control on residence time, oxygen dynamics and trophic vulnerability in the Shabla–Ezerets lake system.

The geomorphological configuration of the outlet channels themselves further strengthens this confinement. As illustrated by the cross-sectional profile (Fig. 9), both the centrally located semi-natural channel and the northern artificial channel are perched above mean lake level and sit on the crest of the sand–dune barrier. Their elevation relative to both lake and sea levels prevents the establishment of any sustained gravitational outflow or marine inflow under normal hydrometeorological conditions, thereby reinforcing hydrological confinement. In practice, the semi-natural central channel has become a depositional hotspot where floating and stranded litter accumulates due to stagnation and vegetation blockage, while the northern channel, entirely artificial, reaches the sea only during rare high-water events, resulting in negligible drainage efficiency. Taken together, these perched and non-functional outlets amplify the system's effective isolation, prolong residence times and facilitate the long-term retention of nutrients and pollutants, consistent with the role of the central depressions as the primary sediment and nutrient sink (Tables 1–2) and the documented organic enrichment (LOI up to 18%). These interacting geomorphological–hydrological constraints and their ecosystem-level consequences are synthesised in the conceptual model presented in Fig. 10, which highlights the reinforcing feedback loops linking hydrological confinement, habitat transformation, biological reorganisation and macrolitter accumulation. Integrated evidence indicates that, in present-day ecohydrological terms, the Shabla–Ezerets system functions as a freshwater-dominated, oligohaline coastal lake system, whose dynamics are controlled primarily by groundwater supply, long residence times and barrier-mediated isolation. This statement refers to the system's current functional behaviour and long-term environmental trajectory, rather than to its formal typological classification under regulatory assessment frameworks. These system-level dynamics are consistent with global conceptual models of lagoonal and coastal lake ecosystems, which highlight the strong linkage between hydrological confinement, reduced ecological function and increased vulnerability (Rodrigues-Filho et al. 2023).

Climate-related environmental change and ecosystem responses

Historical hydrochemical investigations described the Shabla–Ezerets system as an oligohaline lake complex with seasonal thermal stratification and periodic near-bottom oxygen depletion (Ivanov et al. 1964; Dimitrova and Hainadjieva 2004). Here, we compare historical (1950–1963) and contemporary (2019–2024) temperature-salinity-oxygen profiles to isolate long-term change and its ecosystem implications under increased hydrological confinement and climate warming.

Contemporary summers show a more persistent stratified state (thermocline at ~2–4 m), accompanied by a broader and more intense deep-water oxygen deficit in the central depressions (summer saturation commonly ~20–40%). This coupling of stronger thermal

stability and expanded seasonal hypoxia is consistent with mechanisms reported for hydrologically confined coastal lakes, reduced vertical mixing and enhanced organic matter-driven oxygen demand and is expected to increase internal nutrient recycling and favour cyanobacterial dominance (Søndergaard et al. 2003; Paerl and Huisman 2008; Newton et al. 2014; Kennish and Paerl 2010; Jane et al. 2021).

Salinity has also become more uniformly oligohaline: contemporary profiles remain largely within 0.7–2.0 ‰, contrasting with the higher and more variable historical range (1.5–3.5 ‰), indicating reduced salinity variability and weaker marine influence. These shifts align with global evidence of rapid lake surface warming and prolonged stratification, as well as regional warming-driven sensitivity in adjacent coastal wetlands (Williamson et al. 2009; O'Reilly et al. 2015; Woolway et al. 2020; Woolway et al. 2021; Ivanova et al. 2025).

Ecological responses and ichthyofaunal dynamics in relation to hydrology and pollution

The ecological structure of the Shabla–Ezerets system reflects a long-term regime shift toward reduced marine influence and a more stably low-salinity (oligohaline) state, consistent with the liman-type character of the Shabla-Ezerets coastal lake system (Michev and Stoyneva 2007). Ichthyofaunal changes documented over the past three decades reveal a progressive decline in euryhaline and transitional species (e.g., *Atherina boyeri*, *Platichthys flesus*, Mugilidae) that depend on intermittent marine connectivity. Their decline corresponds to reductions in salinity variability and the loss of intermediate-salinity habitats, a pattern widely described in Mediterranean and Black Sea limans with restricted exchange (Katselis et al. 2007, Pérez-Ruzafa et al. 2019). In contrast, freshwater and tolerant species such as *Perca fluviatilis*, *Esox lucius*, *Rutilus rutilus*, *Carassius gibelio*, and others persist or increase, reflecting community reorganisation under stable low-salinity, low-oxygen, and low-energy conditions (Newton et al. 2014). For some taxa, however, temporal trajectories may also reflect management-driven inputs rather than habitat change alone. The protected area management plan explicitly documents the artificial stocking of introduced species, indicating that observed increases in such taxa should be interpreted in light of both hydrological confinement and stocking history (Georgiev et al. 2003).

This stabilisation mirrors the ecological restructuring observed in the adjacent Razim-Sinoe lagoon system (Danube Delta), where the artificial closure of marine inlets similarly led to the replacement of pontic relics with freshwater communities (Dinu et al. 2015, Begun et al. 2020; Dinu et al., 2015), confirming that hydrological isolation is the primary driver of biodiversity loss in Western Black Sea coastal lakes. This ichthyofaunal shift parallels global evidence that the salinity regime is the dominant ecological driver in coastal lakes and lagoons (Pérez-Ruzafa et al. 2019). When marine inputs decline, faunal assemblages converge toward freshwater compositions, particularly in systems exhibiting stratification, eutrophication and macrophyte overgrowth (Katsuki et al. 2008). The high diversity indices observed in recent years likely reflect balanced but simplified

communities, an expected outcome in freshwater-dominated limans with limited functional niches.

Macrophyte dynamics also align with hydrological confinement. The proliferation of *Phragmites australis* and helophyte belts is characteristic of nutrient-rich, weakly renewed basins where sediment trapping and oxygen depletion reinforce vegetation encroachment (Søndergaard et al. 2003). Similar macrophyte dominance driven by hydro-chemical isolation has been reported for the Venice Lagoon and other Mediterranean systems by Sfriso et al. (2003), who noted that reduced exchange promotes rapid reed expansion and biomass accumulation. This expansion reduces open-water habitats, strengthens organic loading and further suppresses circulation, creating a feedback loop strongly influenced by hydrological stagnation.

Pollution patterns (Table 5) integrate into this ecological context. Plastic-dominated macrolitter accumulates across three compartments, beach–dune, surface and benthic, each reflecting specific hydrodynamic constraints (Prodanov and Bekova 2023, Bekova and Prodanov 2023, Bekova and Prodanov 2024). Reedbeds function as passive litter traps, consistent with global observations that vegetated margins of enclosed basins accumulate floating and stranded debris (MSFD-TSML 2013, Hanke et al. 2019, UNEP/MED 2021, Galgani et al. 2023). Moreover, the role of passive litter traps in Reedbeds functions, a capacity recently quantified for freshwater reeds, which show significantly higher retention rates than unvegetated zones (Ryan et al. 2021, Yin et al. 2021). This retention mechanism explains the spatial heterogeneity of pollution in the system, where plastic items remain entrapped within the rhizomes.

Benthic litter concentrations indicate long-term sediment–water residence and minimal disturbance, similar to patterns reported from semi-closed European systems such as Mar Menor and Orbetello (Pérez-Ruzafa and Marcos 2005, Giusti et al. 2010).

These ecological trends are broadly consistent with regional hydrological stress patterns identified by satellite-based monitoring in nearby coastal wetlands. For example, remote-sensing analyses of the neighbouring Shabla Tuzla coastal lake indicate reduced water extent/availability during dry periods, along with changes in vegetation-related spectral indices (Ivanova et al. 2025). In the present study, we use this comparison only as regional contextual evidence of climate-sensitive hydrological variability in the northern Bulgarian coastal wetland complex, not as direct proof of macrophyte cover change or water-quality alteration in Shabla–Ezerets. Our conclusions regarding macrophyte expansion, habitat contraction and reduced ecological resilience in Shabla–Ezerets are based on the multiple independent lines of evidence presented here, with the regional satellite record serving only as supporting context for the broader importance of reduced water renewal and hydrological confinement.

Taken together, ichthyofaunal shifts, macrophyte expansion, eutrophication and litter retention form a single integrated degradation pathway driven by hydrological confinement. Restricted water renewal represents a central process structuring the contemporary functioning of the Shabla–Ezerets system (Report 2023). Prolonged

residence time under hydrological confinement favours internal organic matter accumulation, persistent stratification and material retention, while simultaneously influencing biological assemblages. The observed ichthyofaunal restructuring, extensive littoral macrophyte dominance, and accumulation of anthropogenic debris are consistent with a low-flushing environment, in which limited exchange constrains dispersal, enhances retention capacity, and reduces physical disturbance. In such systems, hydrodynamic stability becomes a primary driver of ecological organisation.

Within this context, controlled freshwater outflow through the artificial spillway (operational since November 2023) represents a mechanism aimed at partially counteracting hydrological confinement by enhancing water renewal. However, the hydraulic performance of this structure is intrinsically linked to the morphodynamic state of the beach–barrier outlet zone. Coastal sediment redistribution and seasonal reshaping of the beach front may alter the outlet cross-section and crest elevation, thereby influencing the operational overflow threshold and the efficiency of discharge. The effectiveness of regulated freshwater release, therefore, depends not only on structural control but also on the stability of hydraulic connectivity at the barrier interface. Regular morphological monitoring of the outlet sector is required to evaluate the persistence of functional connectivity and to assess whether the intended reduction in residence time can be sustained under ongoing coastal morphodynamic variability.

Hydrology-centred restoration: controlled freshwater outflow as the appropriate management pathway

Given the freshwater-dominated hydrology, ecological composition, and conservation designations of Shabla–Ezerets, potential restoration options must be evaluated under the present geomorphological, hydrological and legal constraints. Within this framework, controlled freshwater outflow represents the most scientifically and legally consistent restoration pathway rather than the only possible trajectory. As shown by the barrier cross-section (Fig. 9), the topographically perched position of both outlet channels physically prevents any reliable marine inflow, making lagoon-type reconnection physically constrained under current barrier morphology and ecologically inappropriate.

Scenario 1: Full reconnection to the sea. Full marine reconnection would require structural modification of the barrier ridge and long-term inlet stabilisation. Numerous case studies demonstrate that increasing marine exchange in freshwater or oligohaline lakes, whether by dredging or stabilising inlets, can result in salinisation, reed dieback, shoreline erosion and collapse of freshwater communities (Bird 1994, Kennish and Paerl 2010). Comparable functional responses to controlled outlet opening have been documented in intermittently closed and open lakes and lagoons, where managed drainage improves oxygenation and reduces stagnation (Schallenberg et al. 2010). Such outcomes would conflict with the ecological requirements of Natura 2000 habitat 3150, threaten freshwater species of European conservation concern, and violate the non-deterioration obligations of the Habitats Directive (EU Commission 2019). In addition, the newly adopted EU Nature Restoration Regulation 2024/1991 (2024) explicitly prioritises

the recovery of natural freshwater hydrological regimes and connectivity, reinforcing the need for restoration to strengthen, not diminish, the freshwater dominance of such systems.

The physical configuration of the existing outlets further constrains any management option involving marine connectivity. As seen in the cross-sectional profile (Fig. 9), both the centrally located semi-natural channel and the northern artificial channel are topographically perched above mean lake level and the adjacent swash zone (Fig. 8). Their elevated position prevents sustained gravitational outflow and renders marine inflow physically impossible under normal conditions. The central channel, lacking maintenance, primarily serves as a depositional trap for floating and stranded litter, while the northern channel, despite being artificially excavated, rarely reaches the sea due to its high elevation on the barrier ridge. Re-establishing permanent lagoon-type exchange would therefore require continuous engineering intervention and would introduce geomorphological instability and salinity variability incompatible with the documented system state.

Scenario 2: Non-intervention (continued confinement). Maintaining the present hydrological configuration without active management would likely prolong high residence time, persistent stratification and material retention. Integrated evidence from hydrology, ichthyofauna, macrophytes, sedimentology and macrolitter indicates that restricted water renewal promotes organic accumulation, spatially extended low-oxygen conditions and debris retention. Under projected climate-related warming, continued confinement may increase the frequency and intensity of seasonal oxygen depletion and amplify ecosystem sensitivity to hydrological extremes.

Scenario 3: Controlled freshwater outflow. A hydrology-centred approach based on enhanced freshwater renewal through seasonal, shallow, unidirectional outlet drainage directly addresses the system's core vulnerabilities. European and Mediterranean restoration syntheses demonstrate that hydrology-centred, low-impact interventions are among the most effective strategies for recovering coastal lagoon and coastal lake ecosystems (De Wit et al. 2020, De Wit and Boutin 2023). This approach aligns with successful hydrological reconnection projects in the Danube Delta region and broader European contexts, which have demonstrated that restoring water exchange leads to rapid improvements in water quality and habitat heterogeneity (De Wit and Boutin 2023). In this context, periodic, controlled freshwater discharge through the artificial spillway (operational since November 2023) represents an intermediate and low-impact intervention that enhances water renewal while avoiding sustained marine intrusion.

The hydraulic effectiveness of this approach is contingent upon the morphodynamic stability of the beach–barrier outlet zone. Sediment redistribution along the beach front may modify outlet cross-sections and crest elevations, influencing discharge efficiency. Continuous morphological monitoring is therefore required to assess the persistence of hydraulic connectivity and long-term operational functionality. Improving freshwater outflow would:

- reduce water residence time and alleviate the thermal stratification that drives deep-water deoxygenation;
- improve oxygenation of deeper layers;
- moderate excessive reed expansion and disrupt the stagnant conditions that favour cyanobacterial dominance in warming waters;
- enhance ecological niches for freshwater fish communities;
- reduce floating and benthic litter retention by enabling export from stagnant zones;
- maintain the freshwater-dominated regime essential for habitat 3150.

Short-term benefits of such controlled channel opening include:

- rapid release of stagnant, oxygen-poor surface and near-bottom layers;
- immediate reduction in floating litter accumulation within reedbeds;
- measurable improvement in water clarity following export of suspended organic material;
- enhanced conditions for mobile freshwater fish by reducing short-term hypoxic events.

Long-term benefits include:

- sustained improvement of the hydrological regime through repeated renewal cycles;
- progressive limitation of terrestrialisation processes by slowing reed over-expansion;
- gradual reduction of benthic organic loading as residence time decreases;
- improved ecological resilience against climate-driven stressors, including the increasing frequency of lake heatwaves (Woolway et al. 2020);
- improved ecological resilience of the system against climate-driven hydrological extremes; following recent guidance that restoration planning in European coastal systems should be anchored in formalised restoration agreements and multi-actor platforms, which integrate technical, financial and governance enablers to ensure adaptive and climate-resilient outcomes, as outlined by Dietrich et al. (2025);
- long-term stabilisation of freshwater fish communities by maintaining low-salinity, oxygenated habitats;
- decreased macrolitter retention capacity through enhanced hydrodynamic flushing of shallow margins.

Importantly, controlled freshwater outflow prevents significant marine intrusion, thereby avoiding the risks associated with salinity increases. This ensures full compatibility with the objectives of the Water Framework and Marin Strategy Framework directives for litter reduction, and the binding restoration requirements of the Nature Restoration Regulation EU Nature Restoration Regulation 2024/1991 (2024).

Finally, the Shabla–Ezerets coastal lake system is a freshwater liman whose functioning and vulnerability are shaped by geomorphological isolation, long residence times and

hydrological confinement. Within the evaluated management scenarios, controlled freshwater outflow represents the most feasible and ecologically coherent pathway for restoring ecosystem functioning while preserving the system's freshwater identity under current physical and legal constraints.

Conclusions

This study provides the first integrated geomorphological, hydrological, physico-chemical, sedimentological, ecological and macrolitter assessment of the Shabla–Ezerets
coastal lake system, supported by a direct comparison between historical (1950–1963) and contemporary (2019–2024) water-column measurements. A shallow basin structure characterises the system, strong hydrological confinement and persistent stratification, conditions that favour fine-sediment accumulation and organic enrichment.

LiDAR and bathymetric mapping reveal low-relief morphology and depositional central depressions. Sediment analyses indicate high organic content (LOI up to ~18%), while macrophyte development is concentrated along shallow littoral terraces and palustrine fringes. Contemporary hydrological profiles document a stable summer thermocline (2–4 m), with surface temperatures of 24–26 °C and bottom temperatures of 10–14 °C. Compared with historical profiles, summer surface temperatures have increased by approximately 3–4 °C, and stratification is more consistently expressed. Near-bottom oxygen saturation commonly declines to 20–40% during summer, extending the occurrence of low-oxygen conditions previously reported. Salinity remains uniformly oligohaline (0.7–2.0 ‰), contrasting with the historically more variable 1.5–3.5 ‰ range.

Ichthyofaunal records indicate long-term restructuring towards freshwater-tolerant assemblages, with the absence of historically present euryhaline species. Macrolitter assessments reveal persistent moderate pollution levels across shoreline, surface-water and benthic compartments. Beach–dune transects yield CCI values of 3.31–3.51 ("clean"), while plastic-dominated assemblages (85–90%) produce PAI values of 1.13–1.74. Floating litter reaches 38.5 items·10,000 m², and benthic litter ranges between 0.8–6 items·m², reflecting the system's limited flushing capacity and the retention of lightweight polymers and embedded debris in organic-rich muds.

The combined evidence indicates that hydrological confinement governs present-day ecosystem functioning, while gradual climate-related warming and reduced salinity variability further influence stratification strength, oxygen conditions and habitat structure. These interacting physical and ecological processes increase the system's sensitivity to hydrological and climatic extremes. In this context, hydrology-centred restoration, specifically controlled seasonal freshwater outflow, offers a suitable measure to improve water renewal, moderate stagnation, reduce macrolitter retention, and support ecological resilience, while maintaining the freshwater character required under the EU Nature Restoration Regulation 2024/1991 2024.

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Author contributions

R.B. and *B.P.* conceptualised the research design. *B.P.* conducted the geological and geomorphological investigations and performed the GIS analyses. *B.P., T.L.* and RB designed and carried out the LiDAR scanning, UAS surveys, Structure-from-Motion processing, and the generation of DSMs and orthomosaics. *R.B.* performed the ichthyological, ecological and statistical assessments. *C.G.* wrote the vegetation section; *R.B.* and *B.P.* assessed macrolitter pollution. *R.B.* and B. P. provided supervision and critical revision of the manuscript.

Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary materials

Suppl. material 1: Historical and contemporary seasonal vertical profiles of temperature, salinity and oxygen saturation in the Shabla–Ezerets coastal lake system

Authors: Radoslava Bekova and Bogdan Prodanov

Data type: environmental measurements, hydrological profiles, limnological data, climatic reconstructions

Brief description: This supplementary file contains the full dataset used to analyse historical (1950–1963) and contemporary (2019–2024) vertical profiles of temperature, salinity and oxygen saturation in the Shabla–Ezerets coastal lake system. The table includes depth-resolved measurements for both summer and winter seasons, allowing direct comparison of long-term thermal, hydrological and oxygenation changes. The dataset corresponds to Figures 12, 13, 14 in the main manuscript and supports all numerical values presented in the Results section.

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Suppl. material 2: Long-term state-monitoring hydrochemical data for Shablensko and Ezeretsko lakes (2008–2024)

Authors: The Environmental Agency (EEA)
Data type: Monitoring data
Brief description: This supplementary file contains the full tabulated state-monitoring dataset used to support the interpretation of long-term hydrochemical dynamics in the Shabla–Ezerets lake system. The tables include sampling dates and times, water temperature, dissolved oxygen, oxygen saturation, chlorophyll-a, ammonium nitrogen ($N\text{-}NH_4$), nitrate nitrogen ($N\text{-}NO_3$), nitrite nitrogen ($N\text{-}NO_2$), total nitrogen (N-tot), orthophosphates ($PO_4\text{-}P$), and total phosphorus (P-tot) for Shablensko Lake and Ezeretsko Lake. These data are provided to document recurrent seasonal nutrient variability, chlorophyll-a peaks, and summer–autumn oxygen minima that are directly relevant to the assessment of trophic vulnerability, episodic eutrophication, and hydrological confinement in the lake system.
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