J. Black Sea/Mediterranean Environment
Vol. 32, No. 1: 32-43 (2026)

RESEARCH ARTICLE

Bathymetric and benthic characterisation of Çardak Lagoon, Turkish Straits System

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Abstract

This study presents the first integrated bathymetric and benthic habitat characterisation of Çardak Lagoon, a coastal lagoon adjacent to the Çanakkale Strait. High-resolution mapping was performed via systematic field surveys across 45 stations, distributed on a 200 × 200 m regular GIS grid. Bathymetric data were obtained through dual-method verification (handheld echo sounder and manual sounding), while benthic substrates were characterised at each station using *in situ* scientific diving. Bathymetric surfaces were reconstructed using Triangulated Irregular Network interpolation, and benthic habitats were spatially delineated via Voronoi tessellation. The lagoon encompasses a surface area of 1.39 km^2 with a total water volume of 1.22×10^6 m^3 and a volumetrically weighted mean depth of 0.88 m (maximum depth: 3.10 m). The system is dominated by six benthic habitat types: sand–gravel, fine sand, algae–gravel, mixed *Zostera*–shell substrates, mud/silt, and silt–clay. Coarser-grained sediments are predominantly confined to the high-energy inlet zone, whereas finer-grained facies accumulate within the central and inner basins, reflecting distinct hydrodynamic energy gradients. Due to its pronounced shallowness and restricted marine connectivity (single 57.5 m wide outlet), the lagoon is exceptionally sensitive to atmospheric forcing, and thermal fluctuations. This physical baseline provides a robust framework for hydrodynamic modelling, sediment budget analyses, and long-term monitoring programs essential for detecting early warning signals of ecological regime shifts under projected climate change and anthropogenic pressures. These high-resolution datasets serve as critical inputs for adaptive management strategies aimed at preserving this first-degree natural protected area within one of the world's most intensively utilised maritime corridors.

Keywords: Coastal lagoon, bathymetry, benthic habitat mapping, GIS modelling, Çanakkale Strait, Turkish Straits System

Received: 13.01.2026, **Accepted:** 17.02.2026

Introduction

Coastal lagoons function as critical transitional zones between terrestrial and marine environments, providing indispensable ecosystem services while remaining highly susceptible to environmental stressors (Tagliapietra *et al.* 2009; Soria *et al.* 2022). These shallow, semi-enclosed systems are defined by restricted connectivity with open sea, a feature that profoundly governs their hydrodynamic regimes, water quality, and ecological functioning (Kjerfve 1994).

The morphometric attributes of these basins—most notably depth distribution and bathymetric geometry—exert a fundamental influence over their physical and biological dynamics. Due to their characteristic shallowness, such as lagoons exhibit minimal thermal inertia, rendering them exceptionally sensitive to atmospheric forcing (Anthony *et al.* 2009). Furthermore, benthic substrate composition plays a pivotal role in these systems, modulating both community assembly and key biogeochemical processes (Molinaroli *et al.* 2014).

According to their degree of exchange with the open sea, coastal lagoons are classified into leaky, restricted, or choked systems (Kjerfve and Magill 1989). Choked lagoons, defined by a singular narrow inlet, are characterized by attenuated tidal influence and extended water residence times. Such geomorphological configurations render these systems exceptionally vulnerable to eutrophication and anthropogenic environmental shifts (Lenzi and Cianchi 2022).

Recent assessments indicate that the lagoon remains relatively pristine, with key pollutants such as ammonium and anionic detergents consistently maintaining low concentrations (Ateş *et al.* 2025). Despite this, a comprehensive morphometric characterisation has hitherto been absent. Such baseline data are indispensable for elucidating the lagoon's hydrodynamic behaviour, residence times, and mixing patterns, which collectively govern nutrient cycling and ecological stability. Furthermore, high-resolution bathymetric data are critical for monitoring long-term variations in basin depth driven by sedimentation; such processes can fundamentally recognize ecosystem architecture and compromise resilience to environmental stressors.

The present study addresses this research gap by conducting a comprehensive bathymetric and benthic habitat mapping of the lagoon. The primary objectives are to: (i) quantify the bathymetric profile and volumetric capacity through systematic surveys integrated with GIS-based geospatial modelling; (ii) delineate the spatial distribution and extent of major benthic habitat types; and (iii) to establish a high-resolution morphometric baseline essential for future modelling and long-term environmental monitoring.

Materials and Methods

Study Area

The study was conducted in Çardak Lagoon (Figure 1), situated on the north-eastern coast of the Çanakkale Strait, approximately 15 km south-west of Lapseki district, Çanakkale Province, Türkiye. The Çanakkale Strait forms part of the Turkish Straits System (Öztürk and Öztürk 1996), which constitutes the sole hydrological corridor linking the Black Sea to the Mediterranean Sea via the Sea of Marmara and the Aegean Sea. This strategic waterway experiences some of the highest vessel transit densities globally, whilst its adjacent coastal zones support ecologically significant habitats. Previous scientific works mostly centred upon macrobenthos community, and relationships with environmental variables (Ateş *et al.* 2023; Dağlı *et al.* 2023).

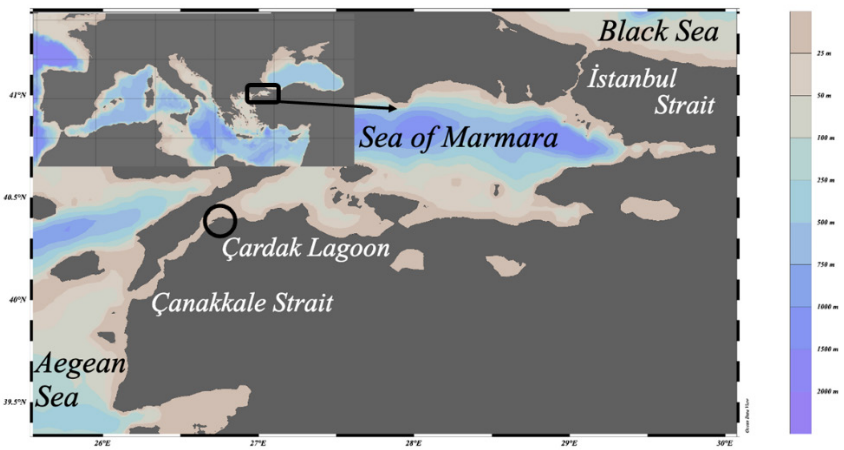

Figure 1. Geographical location of Çardak Lagoon (indicated by black circle) within the Turkish Straits System. The map delineates the lagoon's position along the northeastern coast of the Çanakkale Strait and its spatial proximity to the Sea of Marmara.

Morphometric Characteristics

The lagoon is aligned along a north-east–south-west axis, approximately parallel to the Strait, and maintains hydrological connectivity with the strait through 57.5 m in width a single outlet located its south-western margin (see Figure 2E). On the basis of its restricted exchange and morphological configuration, Çardak Lagoon can be classified as a choked lagoon, in which water exchange with the adjacent marine system is constrained a narrow inlet. The lagoon consists of one main and two sub-basins. The southern basin is connected to the main lagoonal reservoir through a single opening located along its southern boundary, whereas the northern basin is connected via two narrow channels situated along its southern margin. The two openings linking the northern basin to the main lagoon measure 2.2 m in width and 48.9 m in length (A), and 10.3 m in width and 122.4 m in length (B), respectively. The southern basin is connected through a single channel measuring 4.86 m in width and 18 m in length (C). In addition to its marine connectivity, the lagoon receives freshwater inputs from three distinct inflow points along its eastern shoreline (see Figure 2; I, II, III).

Figure 2. Cartographic delineation of the morphometry of Çardak Lagoon. The annotated regions (A, B, and C) highlight the transitional interfaces connecting discrete internal sub-basins, while Roman numerals (I, II, and III) designate the primary loci of terrestrial freshwater influx into the system, and Point E indicates the connection between the lagoon and the strait.

Bathymetric Sampling Design

To delineate the morphometric characteristics of the lagoon, systematic spatial sampling was conducted in April 2025, during which a 200 × 200 m sampling grid was generated across the study area using the open-source software QGIS (v3.42; QGIS.org, 2025). Within this spatial framework, 45 discrete nodes intersecting the water column were designated as bathymetric monitoring stations (Figure 3). Precise navigation to these predetermined coordinates was achieved *in situ* using a handheld GPS (Garmin eTrex 30; Garmin International Inc., Olathe, KS, USA). At each station, vertical depth profiles were quantified using a dual-method approach to maximise data accuracy: measurements obtained via a handheld hydrographic echo sounder (Plastimo Echotest II; Southampton, UK) were corroborated by manual sounding line measurements.

Figure 3. Cartographic representation of the systematic sampling design employed within Çardak Lagoon. The red squares illustrate the 200 × 200 m spatial grid nodes, delineating the locations targeted for bathymetric profiling and benthic habitat characterisation.

Benthic Habitat Characterisation

Concurrent with the bathymetric survey, benthic substrate characterisation was conducted at the same 45 spatial nodes to ensure methodological consistency. The classification of sedimentary facies and benthic habitat types was carried out through scientific diving operations. This approach enabled direct *in situ* visual inspection and ground-truthing of the seabed, allowing accurate identification of the dominant benthic habitat types at each sampling station.

Bathymetric Modelling and Volumetric Estimation

To achieve a high-fidelity quantification of the lagoon's aqueous capacity and to resolve the complex morphometry of the basin, a GIS-based volumetric analysis was executed using the QGIS platform. A Digital Elevation Model (Polidori and El Hage 2020) of the benthoscape was constructed by synthesising the discrete depth soundings with the lagoon's coastal boundary. To ensure an appropriate representation of the littoral interface and to reduce edge-effect interpolation errors, the shoreline vector was discretised into a high-density point cloud and assigned a hypsometric value of 0 m.

Subsequently, a Triangulated Irregular Network (TIN) interpolation algorithm (Peucker *et al.* 1978) was employed to generate a continuous, high-resolution bathymetric surface. This deterministic interpolation method was selected for its ability to preserve the exact values of the sampling nodes while representing the varying slope gradients extending towards the zero-depth boundary. The total volumetric capacity of the system was computed from the resultant surface using the Raster Surface Volume geoprocessing toolset.

Geospatial Interpolation and Cartographic Modelling
To reconstruct the lagoon's benthic morphometry, a TIN interpolation algorithm was employed. Given the systematic, grid-based acquisition of depth data at 45 sampling nodes, the TIN method was selected for its ability to preserve local hypsometric variability. Unlike smoothing algorithms, TIN maintains abrupt morphological transitions, making it suitable for generating bathymetric surfaces from regularly distributed vector point data.

For the spatial delineation of benthic habitats, Voronoi tessellation (Thiessen polygons; Thiessen 1911; Okabe *et al.* 2000) was applied to the same sampling grid. This method partitions the study area into proximal regions based on the nearest-neighbour principle, thereby assigning the categorical habitat attributes of each sampling node to its surrounding area. This approach was chosen to represent discrete benthic units without introducing artificial gradients, ensuring that the spatial representation remains consistent with the *in-situ* observations (Burrough *et al.* 2015).

Result and Discussion

Bathymetry and Lagoon Morphometry
The bathymetric profile of Çardak Lagoon was constructed using high-resolution *in situ* depth soundings recorded at 45 stations (Figure 3). Analysis of the vertical profile indicates a heterogeneous basin morphology, characterised by pronounced depth variations over short spatial scales. Recorded depths ranged from a minimum of 0.14 m in the shallow peripheral zones to a maximum of 3.10 m within localised deeper basins, with an arithmetic mean depth of 1.09 m (Figure 4). Rather than exhibiting a uniformly flat floor, the lagoon is characterised by discrete deep depressions surrounded by extensive shallow flats, indicating the presence of distinct hydrodynamic zones where water residence times and vertical mixing potential likely differ between shallow margins and deeper pockets.

GIS-based bathymetric modelling enabled quantitative description of the lagoon's physical dimensions. The analysis indicates that Çardak Lagoon has a total surface area of 1.39 km^2, closely aligning with the earlier estimate of 1.2 km^2 reported by Ateş *et al.* (2025). Volumetric integration of the TIN model yielded an estimated total water volume of approximately 1.22×10^6 m^3.

An important methodological observation emerged with respect to the lagoon's average depth. Whilst the simple arithmetic mean calculated directly from sampling points was 1.09 m, the GIS-based volumetric integration produced a spatially weighted mean depth of 0.88 m. This 0.21 m differential reflects the substantial volumetric contribution of extensive shallow littoral zones, which are often underrepresented in conventional point-based hydrographic surveys. The GIS-based volumetric approach provides more accurate representation by integrating the spatial extent of depth values, offering enhanced precision for water budget calculations and hydrodynamic modelling. This discrepancy highlights systematic bias in conventional point-based assessments and demonstrates the added value of the geospatial modelling approach applied in this study.

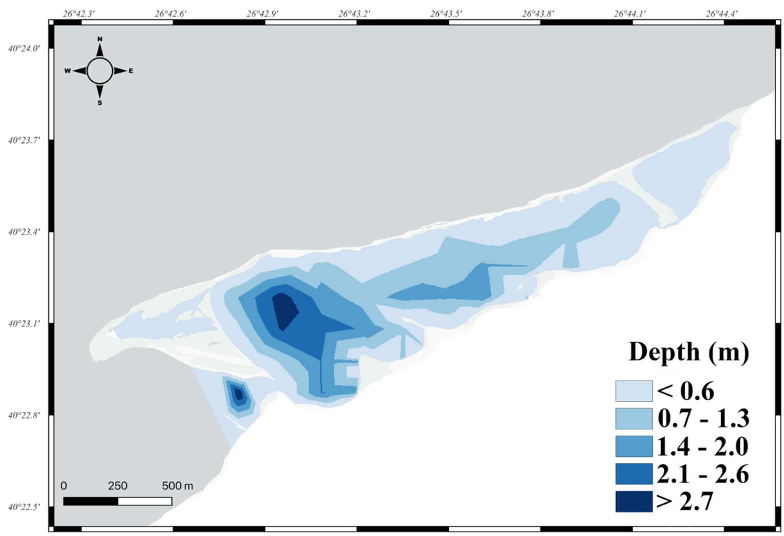

Figure 4. Bathymetric map of Çardak Lagoon derived from *in situ* depth measurements. The colour gradient illustrates the spatial variation in water depth, highlighting the contrast between the extensive shallow flats (minimum: 0.14 m) and the localised deep basins (maximum: 3.10 m).

The morphometric characteristics position Çardak Lagoon amongst the shallowest documented systems in the Mediterranean region, with morphometry comparable to systems such as Homa Lagoon in the eastern Aegean Sea (Can *et al.* 2009). The pronounced shallowness (mean depth 0.88 m) has important implications for the lagoon's physical and ecological functioning. Shallow systems possess limited heat storage capacity and thermal inertia, rendering them highly responsive to atmospheric forcing and susceptible to rapid temperature fluctuations (Anthony *et al.* 2009). This sensitivity influences biogeochemical processes, primary production, and habitat suitability for aquatic biota.

Benthic Habitat Distribution and Sedimentological Patterns

Benthic habitat distribution was delineated using a Voronoi tessellation (Fortune 1987; Molinaroli *et al.* 2014) model (Figure 5) based on sedimentological observations from the sampling stations (Figure 3). This approach resolved the lagoon floor into six discrete benthic habitat types: sand–gravel, fine sand, algae–gravel, mixed *Zostera*–shell substrates, mud/silt, and silt–clay. The resulting habitat map reveals a pronounced spatial mosaic, reflecting the interaction between basin morphology and prevailing hydrodynamic energy gradients.

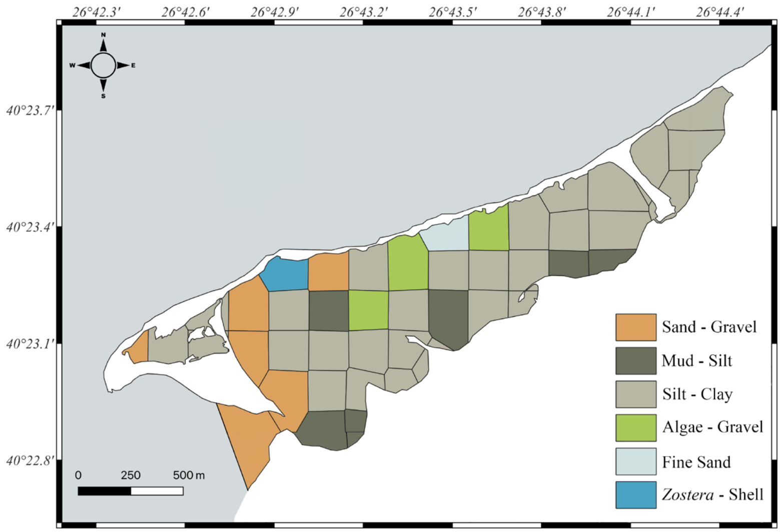

Figure 5. Spatial distribution of benthic habitat types across Çardak Lagoon derived from Voronoi tessellation modelling. The map delineates the lagoon floor into six discrete sedimentary types: sand–gravel, mud/silt, silt–clay, algae–gravel, fine sand, and mixed *Zostera*–shell substrates.

Coarser sediment facies, including sand–gravel and algae–gravel substrates, were largely confined to the western inlet zone and adjacent channelised areas, where higher hydrodynamic energy associated with marine exchange dominates. In contrast, fine-grained mud/silt and silt–clay substrates were preferentially accumulated within the central and inner basin areas, corresponding to more quiescent hydrodynamic conditions. Fine sand and mud–silt facies occupied intermediate positions between these end-member environments, forming transitional zones across the lagoon floor. This sedimentary organisation is consistent with patterns observed in other Mediterranean coastal lagoons, where restricted circulation and shallow depths promote the retention of fine particles in low-energy sectors (Molinaroli *et al.* 2014).

Cymodocea sp. and *Cystosria* sp. were found to be abundant seagrass type of Çardak Lagoon. These were detected as main food item for dominant crab of Çardak Lagoon, *Carcinus aestuarii* (5.94% IRI) (Acar and Ateş 2021). Mixed *Zostera*–shell substrates were identified in limited areas near the inlet, indicating the presence of seagrass-associated habitats within the lagoon. Although spatially restricted, these habitats are ecologically significant, as seagrass meadows contribute to primary production and support elevated biodiversity (Duarte *et al.* 2013) and role as refuge areas for juvenile fish (Franco *et al.* 2006). At the same time, their occurrence in proximity to higher-energy and better-flushed zones is consistent with the sensitivity of *Zostera* beds to light availability and water quality conditions (Ralph *et al.* 2007). The spatial distribution of benthic habitats therefore mirrors the lagoon's hydro-geomorphic structure, with substrate type closely aligned with depth, energy regime, and basin compartmentalisation.

Conclusions

This study presents the first comprehensive bathymetric and benthic habitat characterisation of Çardak Lagoon. The lagoon is an exceptionally shallow water body, with a spatially weighted mean depth of 0.88 m, maximum depth of 3.10 m, and total volumetric capacity of 1.22×10^6 m^3. Six principal sedimentary facies were identified, reflecting hydrodynamic energy gradients across the system.

Integration of systematic field measurements with GIS-based analytical frameworks provides a robust baseline for future monitoring. Recent assessments indicate the lagoon remains relatively unimpacted by severe pollution, yet its shallow morphometry renders it vulnerable to environmental pressures. The bathymetric and benthic data constitute essential inputs for hydrodynamic modelling and adaptive management strategies. Future research should focus on water quality monitoring, hydrodynamic simulation, and temporal dynamics of sediment accumulation.

Acknowledgements

This work was supported by The Scientific and Technological Research Council of Türkiye (Project no: 124O118). The authors thank Prof. Dr. Abdullah Suat Ateş for his help in characterisation of seagrass and to Samet İşcan for his help during fieldwork.

Competing interest: No potential conflict of interest was reported by the authors.
Ethics committee approval: There is no necessity for ethical approval for this research.
Author contributions: R.K.G.: Writing-Original draft, methodology, data analyses; İ.B.D.: Sampling, laboratory works, visualisation, editing; Y.Ş.: Sampling, laboratory works, visualisation, editing.

Türk Boğazlar Sistemi'ndeki, Çardak Lagünü'nün batimetrik ve bentik karakterizasyonu

Öz

Bu çalışma, Çanakkale Boğazı'na bitişik bir kıyısal lagün olan Çardak Lagünü'nün ilk bütünleşik batimetrik ve bentik habitat karakterizasyonunu sunmaktadır. Yüksek çözünürlüklü haritalama, düzenli 200 × 200 m CBS ağı üzerinde düzenlenmiş 45 istasyonda sistematik arazi çalışmaları ile gerçekleştirilmiştir. Her istasyonda derinlik ölçümleri çift yöntemli doğrulama ile elde edilmiş, bentik substratlar ise yerinde bilimsel dalış yoluyla karakterize edilmiştir. Batimetrik yüzeyler TIN enterpolasyonu kullanılarak yeniden yapılandırılmış, bentik habitatlar ise Voronoi mozaiklemesi ile mekânsal olarak sınırlandırılmıştır. Lagün 1,39 km^2 yüzey alanına, 1,22 × 10^6 m^3 toplam su hacmine ve hacimsel ağırlıklı 0,88 m ortalama derinliğe (maksimum derinlik: 3,10 m) sahiptir. Altı bentik habitat tipi sisteme hâkimdir: kum–çakıl, ince kum, alg–çakıl, karışık *Zostera*–kabuk substratları, çamur/silt ve silt–kil. Kaba taneli sedimentler ağırlıklı olarak yüksek enerjili giriş bölgesiyle sınırlı iken, ince taneli fasiyesler tercihen merkezi ve iç havzalarda birikmekte ve bu durum belirgin hidrodinamik enerji gradyanlarını yansıtmaktadır. Belirgin sığlık ve kısıtlı deniz bağlantısı (tek bir 57,5 m genişliğinde bağlantı), lagünü atmosferik zorlamaya ve termal dalgalanmalara karşı özellikle duyarlı kılmaktadır. Bu fiziksel temel çizgi, öngörülen iklim değişikliği ve antropojenik baskılar altında ekolojik rejim kaymaların erken uyarı sinyallerinin tespit edilmesi için gerekli olan hidrodinamik modelleme, sediman bütçesi analizleri ve uzun vadeli izleme programları için sağlam bir çerçeve sunmaktadır. Üretilen yüksek çözünürlüklü mekânsal veri setleri, dünyanın en yoğun kullanılan deniz koridorlarından biri içinde yer alan bu birinci derece doğal koruma alanının korunmasına yönelik uyarlanabilir yönetim stratejileri için kritik girdiler oluşturmaktadır.

Anahtar kelimeler: Kıyısal lagün, batimetri, bentik habitat haritalama, CBS modelleme, Çanakkale Boğazı, Türk Boğazlar Sistemi

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