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A newly formed lagoon under eutrophication on the coast of Kumlubent-Gelibolu, Çanakkale Strait (Dardanelles), Sea of Marmara

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Abstract

Lagoons are semi-enclosed and dynamic water bodies that are highly vulnerable to coastal dynamics and environmental stressors associated with anthropogenic activities and climate change. We investigated a pristine lagoon, hereafter referred to as Kumlubent Lagoon, located on the coast of Gelibolu in the Çanakkale Strait in the Sea of Marmara. The evolution of coastal morphology and Kumlubent Lagoon's formation was investigated by using satellite images collected between 2006 and 2020. In addition, water samples were collected from the lagoon and the shore on April 15 and 16, 2022 for nutrient (NO_3, NO_2, NH_4, PO_4, and Si), chlorophyll-a (chl-a) and total organic carbon (TOC) analyses in order to determine the trophic status of the lagoon. Our results showed that the nearshore deposition of coastal sediments gradually formed a sand barrier that isolated the lagoon from the sea in the year 2013. The nutrient analyses showed a clear indication of eutrophication of the lagoon. Accordingly, 29.784 µm/L of NH_4, 1.168 µm/L of PO_4, 34.15 (±1.54) µg/L of chl-a and 40.50 mg/L of TOC were measured in the water samples from the Kumlubent Lagoon. Our study suggests that the deposition of longshore drifted sediments in a southwesterly direction along the Çanakkale Strait plays a dramatic role in the development of coastal morphology in the Gelibolu-Kumlubent region. The rapid eutrophication of the Kumlubent Lagoon may be related to the high nutrient input from agricultural activities in the region.

Keywords: Lagoon, Kumlubent-Gelibolu, Çanakkale Strait, coastal morphology, long-shore drift, eutrophication

Introduction

Lagoons are water bodies that are separated from the sea by a natural sand barrier (Boynton et al., 1996), and are estimated to cover the 13% of coastal areas on a global scale (Nixon, 1982). However, the lagoons on the coasts of the Sea of Marmara are not very well documented. Increasing anthropogenic pressure from eutrophication, rapid urbanization and tourism is affecting the pristine nature of the coastal areas of the Sea of Marmara. Moreover, the coasts are extremely dynamic environments that are constantly changing due to the erosion and deposition of sand by waves and currents over time periods as short as a decade (Khawfany et al., 2017). Therefore, time series of morphological changes such as lagoon closure, shrinkage and changes in biogeochemical properties are important.

The Marmara Sea is an inland sea, separating the peninsulas Thrace and Anatolia and connects the Black Sea–Mediterranean marine realms through the Turkish Strait System (The Strait of Istanbul: Bosphorus, The Strait of Çanakkale: Dardanelles). It consists of a very complex morphology including shelves, slopes, basins, sub-basins and ridges, with an area of about 11 110 km^2 (Fig. 1) (Gazioğlu et al., 2002). It is a unique body of water located between one of the most eutrophic seas, the Black Sea, and one of the most oligotrophic seas, the Mediterranean Sea. The Sea of Marmara together with the straits is called the Turkish Strait System (TSS). There is a two layered water circulation in TSS due to the salinity differences between the Black Sea (~18‰) and the Mediterranean Sea (~38‰) and the shallow strait depths of the Istanbul and Çanakkale Straits (-35 m and -55 m, respectively) (Beşiktepe et al., 1994; Polat and Tugrul, 1995; Ünlüata et al., 1990). Brackish Black Sea waters enter in the Istanbul Strait as a surface current and form strong clockwise jet in the Sea of Marmara, while saltier Mediterranean waters enter the Çanakkale Strait as deep currents (Beşiktepe et al., 1994). The Çanakkale Strait has the one of the highest currents velocities in the Marmara Sea. High-resolution ocean current modeling revealed that the highest surface current velocities are found in the Çanakkale Strait and in the southern part of the Sea of Marmara due to the Bosporus jet (0.4-0.5 m/s) (Ilicak et al., 2021) (Fig. 1b).

In 2020-2021, a massive marine mucilage outbreak (gelatinous colloidal organic material) occurred in the Sea of Marmara (Savun-Hekimoğlu and Gazioğlu, 2021; Tuzcu-Kokal et al., 2022). The mucilage also reached the Çanakkale Strait via surface currents and affected the marine life (Özalp, 2021). After the mucilage outbreak, the Sea of Marmara and the straits were declared some special environmental protection areas by the Republic of Türkiye Ministry of Environment, Urbanization and

Climate Change. Chlorophyll-a is a common parameter used as an indicator of phytoplankton abundance (also known as primary productivity) and water quality (Boix et al., 2005; Vollenwieder et al., 1998). The Chl-a values in seawater increase in the spring and summer seasons. Based on the Sentinel-3 satellite data exampled for the date 16 April 2022, the distribution of chl-a showed that the chl-a values were higher in the southern section and especially in the Gulf of Gemlik with values as high as 45 µmol/L and relatively lower values in the northern section and in the Çanakkale Strait (Fig. 2). Chl-a concentrations in the Sea of Marmara between 2010 and 2013 ranged from 2.16-7.18 µg/L (Yalçın et al., 2017). Higher chl-a values, as high as 15.16 µg/L, were measured in the Gulf of Bandırma and Gulf of Erdek (Balkis et al., 2012). The highest nutrient levels were generally found in the Black Sea entrance region in the strait of Istanbul. The nitrate concentrations ranged from 4.14-6.15 µmol/L, and the phosphate concentrations ranged from 1.77-4.82 µmol/L based on the data between 2010 and 2013 (Yalçın et al., 2017; Çelik et al., 2022).

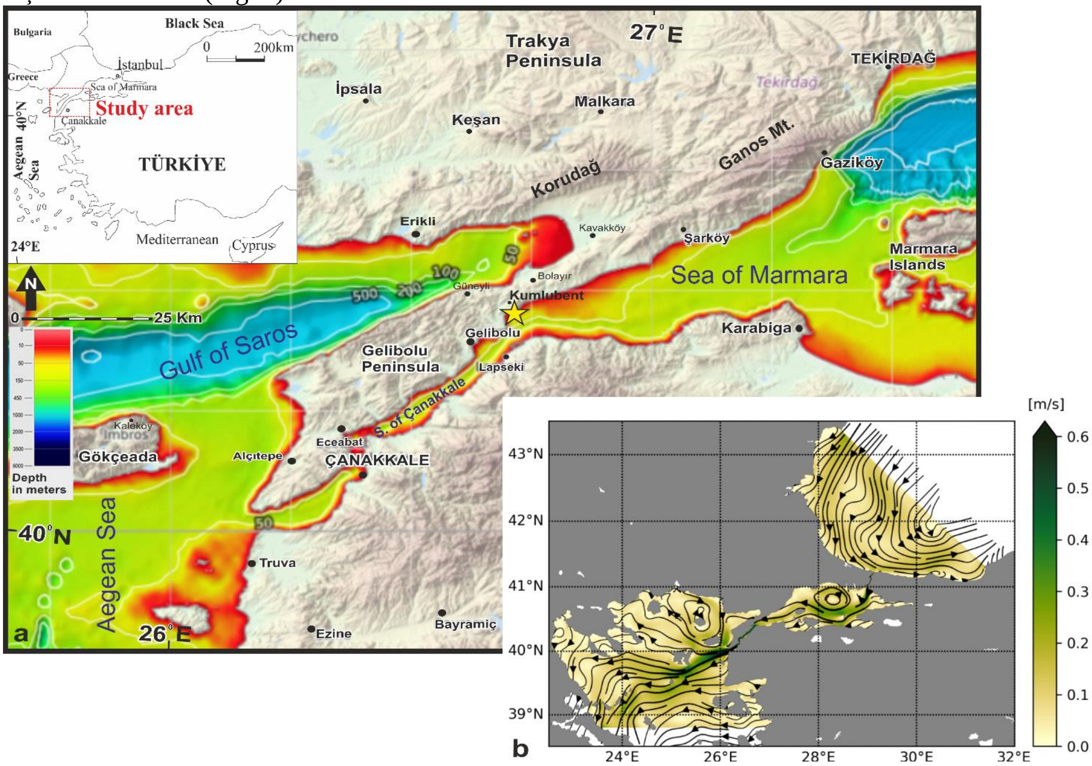

Fig. 1. (a) Location map of the Sea of Marmara with the location of the Kumlubent Lagoon (indicated as a yellow star) in Gelibolu in the Strait of Çanakkale, Türkiye (the bathymetry map from the EMODNet dataset, https://tiles.emodnetbathymetry.eu), and (b) averaged sea surface speeds in the Turkish Strait System (Ilicak et al., 2021).

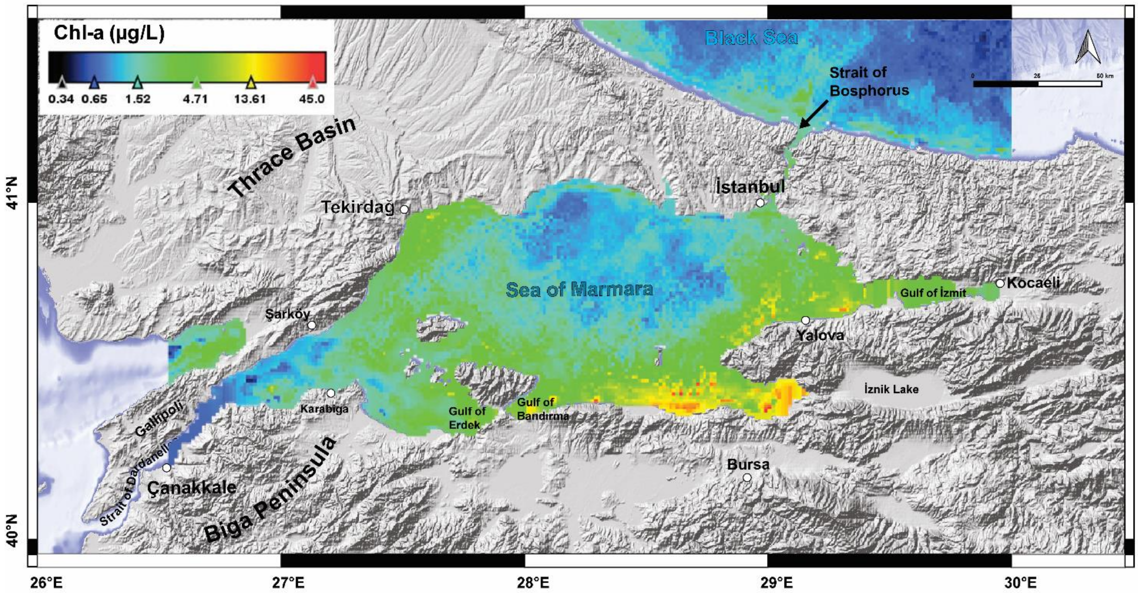

Fig. 2. Chl-a concentrations in the Sea of Marmara created by using the Sentinel-3 data and Copernicus SNAP software, for the date 16 April 2022 (daily mean data). A base map with a 5 × 5-meter resolution DEM was generated by The General Directorate of Mapping of the Republic of Türkiye.

The study area is located in the Kumlubent region of Gelibolu in the Çanakkale Strait and is still a relatively pristine (untouched) coastal strip (Fig. 1). The Çanakkale Strait is about 70 km long, and 55 m deep and is part of the TSS. The Çanakkale Strait acts as a biological corridor for marine species of the Black Sea and the Mediterranean (Tekeli and Aslan, 2023). The Kumlubent region was first reported in a paleontological study on the marine terraces found in the region (Sakınç and Yaltırak, 1997). Notably, increasing scientific attention has been given to the Kumlubent location for paleoclimatic (e.g., relative sea-level change) and tectonic investigations (Tarı et al., 2023; Tarı et al., 2024a), as the region is located in the tectonically active western Marmara region. This tectonic activity is controlled by the North Anatolian Fault Zone (NAFZ), which played a crucial role in the development of the coastline during different time periods (Tarı et al., 2024b). Moreover, the pristine nature of the Kumlubent coast also allows paleoclimate research (Tülümen et al., 2024). The coastal areas in the Çanakkale Strait are susceptible to dynamic morphological changes due to erosion and sedimentation processes associated with the strong currents in the strait and also anthropogenic changes due to rapid urbanization. The purpose of this study is (i) to demonstrate the evolution of the coastal morphology and formation of a young lagoon in the Gelibolu-Kumlubent region in the Çanakkale Strait and (ii) to determine the nutrient, chl-a and TOC levels in the Kumlubent lagoon in order to understand the trophic status of the lagoon.

Samples and Methods

Study Site

The study area, referred to here as 'Kumlubent', is located in Gelibolu in the Çanakkale Strait, about 4.6 km northeast of Gelibolu Hamzaköy beach and 2.4 km from Gelibolu-Eğritaş beach (Fig. 1). The lagoon of Kumlubent has an elliptical shape that runs parallel to the coast. It is about 250 m long and 65 m wide and has an area of about 13.5 km^2 (Fig. 3). The depth of the water is not known, but it is probably very shallow at 2-3 m. Beach grass *(Ammophila breviligulata and Salicornia)* were present at the edge of the lagoon. Also patches of algae mats on the water surface and accumulation of organic foam and odor were also observed in the lagoon (Fig. 3). The beach between the lagoon and the sea consists of gray to beige sand and gravel (Fig 3). There are a few residential houses in the region and the land behind the coast is used for agricultural activities such as clover cultivation (Fig. 3). In order to determine the development of the coastal morphology at the Kumlubent shoreline, Google Earth Pro™ images were analyzed for fourteen years between 2006 and 2020 A time-lapse image was created using the Adobe Illustrator program to illustrate the sediment transport and deposition along the coastline and the timing of the isolation of the Kumlubent Lagoon (Fig. 4).

Fig. 3: Photographs of field studies conducted on 15 and 16 April 2022 in Gelibolu-Kumlubent in the Sea of Marmara showing; (a) a wide-view aerial photo of Kumlubent Lagoon (from TripinView©), (b) and (c) a view of the shore and (d) and (e) the lagoon water with the green algal mats and accumulated organic foams.

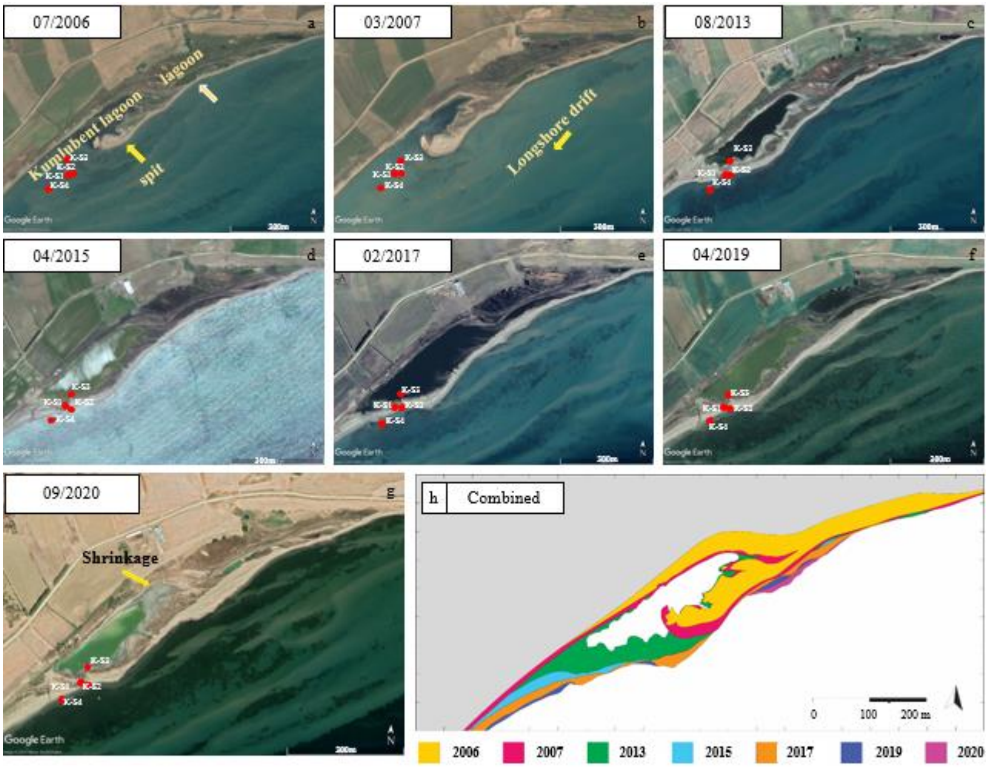

Fig. 4: Formation of Gelibolu-Kumlubent lagoon shown by (a-g) Google Earth Pro^{TM} images collected from 2006-2020 in the Gelibolu-Kumlubent region and (h) a combined map.

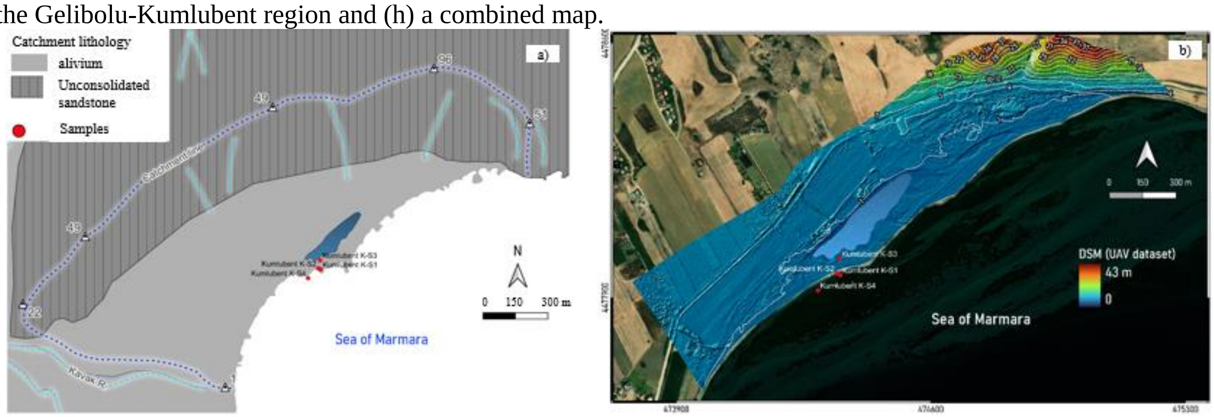

Fig. 5: (a) Lithology within the catchment of the lagoon and the associated near-shore environment. The red rectangle indicates the study area. The numbers next to the triangles denote the elevations. (b) DBM data of Kumlubent Lagoon (5 cm/px) produced by an unmanned aerial vehicle (UAV) dataset and sample locations (in red circles). Note the 3-m elevation contour around the lagoon. The base map is taken from the Bing™ Maps satellite image.

Digital Surface Model

During the field study, the Gelibolu coastal area was surveyed using an unmanned aerial vehicle (UAV) to generate high-resolution digital surface models (DSMs) and orthomosaics. Then, the modern lagoon boundary is produced by using the UAV dataset (Figure 5).

Water sampling

Water samples were collected during the field campaign on 15-16 April 2022 on the Kumlubent-Gelibolu shoreline (Fig. 3). Seawater samples K-S1, KS-2, and KS-4 were collected from the shore, while K-S3 was collected samples from the Kumlubent Lagoon. Before sampling, the bottles were rinsed with sample water three times. For the water samples for chl-a analyses, 0.75 of seawater and 0.1 L of lagoon water were filtered through 0.7-micrometer pore-size GF/F glass fiber filters. The dissolved content of the K-S3 from the lagoon was so high that the filters were clogged very shortly; therefore, only 0.1 L of the sample could be filtered. The filter was then folded and deep-frozen until the analysis. For nutrient analyses, water samples were filtered through 0.2 µm polycarbonate Whatmann filters. All the seawater samples were kept cool and dark until the analysis.

Nutrients and TOC

Dissolved NO_3, NO_2, NH_4, PO_4, and Si concentrations in the water samples were measured by using a Bran+Luebbe Model Auto analyzer at the Institute of Marine Sciences, Middle East Technical University. Total organic carbon (TOC) concentrations in the seawater samples were analyzed in the Environmental Engineering Chemistry Laboratory at Istanbul Technical University following standard procedure of SM5310 B.

Chl-a measurements

Chlorophyll-a concentrations in the water samples were determined by spectrophotometry via 90% acetone filter pigment extraction following the APHA 10200H standard method (APHA, 1999). One liter of seawater was filtered through the 0.7 µm glass fiber filters and the filters were immediately coated with aluminum folio to protect the sample from light and then deep frozen for preservation. The filters were cut into small pieces by using a scissors and 5 ml of 90% acetone was added to the 50 ml centrifuge tubes. The samples in the centrifuge tubes were further mixed by using an IKA brand vortex for one minute. The samples were stored in a refrigerator at 4 °C for 16 hours for extraction. After the extraction, the debris filter was removed with tweezers, and the remaining solution was cool centrifuged for 5 minutes at 3500 rpm. All the processes were performed in the dark or with dim indirect lighting as much as possible. Chlorophyll-a measurements were performed by using an INESA 722 N VIS spectrophotometer at the Biogeochemistry Laboratory, Eurasia Institute of Earth Sciences, ITU.

The absorbance at wavelengths of A630 nm, A647 nm, A664 nm and A750 nm was measured and the calculations were done by using the following the formula:

$$\text{Chlorophyll} - a\left(\frac{\mu g}{L}\right) = \frac{11{,}85(A664-A750)-1{,}54(A647-A750)-0{,}08(A630-A750)xv}{VxZ}$$

where; v=volume of the extract (ml), V=volume of the sample filtered (L), and Z= Path length of the cuvette (cm). The standard deviations were calculated by using the replicate measurements.

Results and Discussion

Development of the Kumlubent coastal morphology

The erosion of sedimentary material by surface currents, the transport of the this drifted material and the deposition processes determine the morphology of the coastline (Davidson-Arnott, 2011). Google Earth Pro™ images collected between 2006 and 2020 revealed a rapid evolution of the coastal morphology of the Kumlubent coastal region (Fig. 4). Also, a smaller lagoon was observed in the pictures from 2006 before the closure of the Kumlubent Lagoon (Fig. 4).

The oldest available Google Earth Pro™ images were from 2006 and 2007 and showed the initiation of a small ‘sand-spit’ in the form of a narrow curved finger of sand (Fig. 4a, b). ‘Spit-type’ deposition occurs when sharp changes in the shape of the coastline occur and subsequently, ‘recurved sand’ (Fig. 4b) is formed resulting in changes in wind and current activity (Carter et al., 1989; King and Cullagh, 1971). Spit deposition could be related to the location of the Kumlubent region. Gelibolu-Kumlubent is on to the entrance region of the Çanakkale Strait where the coastline changes sharply (Fig. 1). This resulted in a decrease in the surface current and provided low-energy conditions for the suspended material to be deposited in the Gelibolu region.

The deposition of sediment along the spit sand continued between the years 2006 and 2013 and the barrier sand was fully developed which stopped the connection of the lagoon with the seawater in 2013 (Fig. 4c). The closure of the sand barrier can be considered as the birth of the Kumlubent barrier lagoon (Fig. 4c). After the closure, the biogeochemical properties of the lagoon may have changed rapidly due to the lack of exchange with seawater. The water input to the lagoon started to be dominated by the small streams mostly from the agricultural fields (Fig. 5). Further deposition of drifted sand from the sea continued along the southwestern portion of the lagoon between 2013 and 2017 (Fig. 4). Kumlubent Lagoon reached its largest surface area as seen in the images from 2017 (Fig. 4e). In 2019, some additional sand was also deposited in the southwestern section (Fig. 4f).

In 2020, shrinkage of the lagoon in the eastern section was observed, probably due to high levels of evaporation in the shallow sections of the lagoon (Fig. 4g). Lagoons are vulnerable to climate change due to their shallow depths (Shalby et al., 2021). Considering the stages of coastal lagoons, the shrinkage could lead to the formation of saline ponds (brine type) and the deposition of evaporitic minerals such as gypsum and halite (Khawfany et al., 2017). Changes in the salt balance may also alter the chemical and the biological composition of the lagoon.
Layers of high suspended material in the sea that were quasi parallel to the coast were recognized in the aerial photograph (Fig. 3) and the Google Earth Pro™ images (Fig. 4). In the coastal regions, a wave releases a surge of energy that creates a current that runs parallel to the coastline which is called a “longshore current” (Fig. 3a). This sand material in the sea, which is also the reason for the barrier sand formation, was sourced from the other coastal regions that were eroded by the ‘longshore drift’ activity. The evolution of the Kumlubent coastal region showed that the region is one of the depositional areas in the Sea of Marmara with particles probably originating from several resources by eroded by the long-shore drift. Additionally, Kumlubent is a barrier- lagoon and barrier-lagoons are generally found in the wave dominated regions (Davidson-Arnott, 2011), indicating a strong influence of wave activity in the region.

The southwesterly direction of deposition of sand material, and the suspended sediments in the sea also correlate with the direction of the main surface current of the Çanakkale Strait (Ilicak et al., 2021). Therefore, we conclude that coastal morphology of the Kumlubent was developed by deposition of longshore drifted sand particles that were likely eroded from the shorelines of the eastern sections. Based on the surface currents in the Sea of Marmara (Fig 1b), we can speculate that the suspended fine clay material eroded from even the southern coasts of the Sea of Marmara can be long-range transported and finally deposited in the Kumlubent region. Therefore, the sediment succession in the region is expected to represent a chaotic origin of reworked material from different erosional regions in the Marmara coastlines. Notably, protection of pristine wave dominated Kumlubent shore is also important for deposition of suspended material to prevent marine mucilage outbreaks in the Sea of Marmara.

Eutrophication of the lagoon

Eutrophication is a trophic state that occurs when a water body is excessively enriched with nutrients as a result of nitrogen and phosphorus inputs, leading to an overabundance of phytoplankton. In terms of trophic state classification, chl-a concentrations ranging from 0-2.6 µg/L are oligotrophic (very low primary productivity, nutrient deficiency), 2.6-7.3 µg/L are mesotrophic (intermediate primary productivity), 7.3-56 µg/L are eutrophic (high primary productivity, excess nutrients) and 56-155+ are hypertrophic or hypereutrophic (hyper primary productivity, severe algal blooms) (Carlson, 1977).

In the Kumlubent Lagoon, the analyses of the water samples revealed that the dissolved nutrient concentrations ranged between 0.115 and 0.314 mg/L for NO_3^-, between 0.121 and 2.394 µm/L for NO_2^-, between 0.143 and 29.784 µm/L for NH_4^+, between 0.030 and 1.668 µm/L for PO_4, and between 0.773 and 1.671 µm/L for Si (Table 2). The Chl-a concentrations ranged between 3.09 and 34.15 µg/L, and the seawater TOC concentrations ranged from 3.55-40.50 mg/L (Table 1).

Table 1: GPS coordinates, dates and hours of seawater sampling from Kumlubent located in Gelibolu, Çanakkale. Water samples K-S1, K-S2, and K-S4 were taken from the sea and K-S3 was taken from the lagoon.

Station	Date	Time	Latitude (ºN)	Longitude (ºE)
Kumlubent S1	15.04.2022	13:45	40.451923	26.697522
Kumlubent S2	16.04.2022	10:30	40.451967	26.697395
Kumlubent S3- Lagoon	16.04.2022	10:45	40.452330	26.697495
Kumlubent S4	16.04.2022	14:45	40.451542	26.696798

The highest chl-a, TOC, PO_4 and NH_4 were measured in the lagoon sample K-S3, indicating high productivity in the lagoon. The dissolved NO_3 and Si concentrations were lower in the lagoon water compared to the seawater samples. Chl-a concentrations in the Kumlubent lagoon waters indicate the eutrophication of the lagoon, while the seawater samples showed a mesotrophic state with moderate levels of primary productivity. Eutrophication in the Kumlubent Lagoon was also strongly supported by the high concentrations especially of NH_4 (29.784 µm/L), PO_4 (1.168 µm/L) and total organic carbon (TOC) (40.5 mg/L) (Table 2). Hypoxic or anoxic conditions in the lagoon could occur because of the shallow depths and limited exchange with other water bodies (Boynton et al., 1996). The accumulation of organic foams and algal mats (Fig. 3) and the strong odor in the Kumlubent Lagoon also indicated eutrophication and also possibly high bacterial activity due to the anoxic conditions.

Table 2: Results of nutrient, chl-a, and TOC concentrations in the water samples from the Kumlubent Shoreline (K-S1, K-S2, K-S4) and from the Kumlubent Lagoon (K-S3).

Sample	NO_3 (µm/L)	NO_2 (µm/L)	NH_4 (µm/L)	PO_4 (µm/L)	Si (µm/L)	Chl-a (µg/L)	TOC (mg/L)
Kumlubent S1	0.194	0.266	0.143	0.030	1.651	4.99 (±0.3)	3.60
Kumlubent S2	0.988	2.394	0.176	0.060	1.630	6.04	3.55
Kumlubent S3-Lagoon	0.115	0.162	29.784	1.668	0.773	34.15 (±1.54)	40.50
Kumlubent S4	0.314	0.121	0.336	0.096	1.671	3.09 (±1.21)	3.65

The Gelibolu-Kumlubent coastal region is still pristine (untouched) with a few residential areas. The lithology in the catchment area is dominated by unconsolidated sandstone (Fig. 5a). However, the region is heavily used for agriculture, e.g., clover cultivation (Fig. 5b). The water enters the lagoon via small streams, which are probably enriched with nutrients due to fertilizers. The excessive input of nitrogen and phosphorus from the fertilizers may have led to an increase in the primary productivity and organic content of the lagoon. In the near future, there may also be an increase in residential areas, human population and anthropogenic pollution, as the new Çanakkale Bridge connecting the Gelibolu and Lapseki districts of Çanakkale will be completed in 2022. Therefore, it is important to investigate the geomorphologic, oceanographic and biodiversity features in the pristine coastal zone in Gelibolu-Kumlubent.

Conclusions and Recommendations

- Gelibolu-Kumlubent coast in the Sea of Marmara is a depositional area and coastal region dominated by the wave activity.
- The progressive deposition of longshore drifted sand caused an initial sand spit that was later recurved and a sand-barrier was formed that isolated the Kumlubent Lagoon in year 2013.
- The Kumlubent Lagoon exhibited shrinkage in 2020 and eutrophication with high NH_4, PO_4, Chl-a and TOC concentrations.
- Eutrophication may be related to the excessive nutrient loading from agricultural activities in the region.
- Further oceanographic and biological studies in the region are proposed to understand the impact of the

Kumlubent Lagoon on the environment and human health.

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