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Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο

ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
ΕΚΠΑΙΔΕΥΣΗ ΚΑΙ ΔΙΑ ΒΙΟΥ ΜΑΘΗΣΗ
επένδυση στην κοινωνία της γνώσης
ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ & ΘΡΗΣΚΕΥΜΑΤΩΝ, ΠΟΛΙΤΙΣΜΟΥ & ΑΘΛΗΤΙΣΜΟΥ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ

ΕΣΠΑ
2007-2013
πρόγραμμα για την ανάπτυξη
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ

Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

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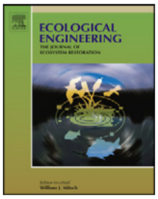

Geomorphology modification and its impact to anoxic lagoons

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ABSTRACT

Anoxia constitutes an important environmental problem, affecting coastal systems around the world. The physicochemical alterations on the water column of anoxic basins, caused by morphological modifications, were studied.

Deepening on the connecting sill between the permanent anoxic Aitoliko lagoon and Messolonghi lagoon was accomplished on May 2006. Seasonal variations of parameters like temperature, salinity and dissolved oxygen along the lagoon's water column were recorded and studied in a net of 14 stations, after sill's dredging. Wind speed and wind direction time series were used to estimate the wind's contribution to the hydrographical changes.

The water fluxes between the two environments increased, due to the sill's cross section increase. Salty water inflow into Aitoliko lagoon was recorded during the sampling period and was correlated with monimolimnion oxygenation throughout winter months. The meteorological conditions that prevailed during the sampling period could not create strong water inflows into the Aitoliko lagoon, and consequently it was not the reason for the recorded alterations in the lagoon's water body anoxia.

The limited deepening of the sill created a mild increase of water flow into the anoxic lagoon. This inflow of the saltier water resulted in a weak mixing of the water column, introducing oxygen into the bottom water for the first time in 55 years, without destroying the stratification.

1. Introduction

Anoxic environments have been of scientific interest since the early '30s (Skei, 1983). Nowadays, permanent or seasonal anoxic coastal basins, fjords and lakes constitute natural laboratories for oceanographers, chemists and biologists. Anoxia constitutes an important environmental problem. Bottom water anoxia/hypoxia for longer or shorter periods can be a natural phenomenon caused by vertical water stratification (Yao and Millero, 1995; Zopfi et al., 2001; Glazer et al., 2006; Ferentinos et al., 2010). However, it is usually human activities that result in the strengthening of stratification or in high loads of nutrients and organic matter into water bodies with poor circulation (Diaz, 2001; Pearl, 2006; Conley et al., 2007; Diaz and Rosenberg, 2008; Zillén et al., 2008). In marine systems with extremely limited water exchange and excessive anthropogenic input of nutrients and organic matter (e.g. Baltic, Black and Caspian Seas), bottom water has become permanently hypoxic/anoxic. The ecological consequences rapidly become perceptible (Josefson and Widbom, 1988; Nilsson and Rosenberg, 1997; Powilleit and Kube, 1999; Eden et al., 2003).

In transitional and coastal water bodies, morphology, nutrients load and salt/fresh water budget control anoxic conditions.

Morphology is the dominant factor responsible for permanent stratification of fjords, semi-enclosed seas and continental deep depressions. Shallow and narrow sills are accountable for bottom water stagnation and anoxia. Black Sea (Neretin et al., 2001; Glazer et al., 2006; Hiscock and Millero, 2006; Konovalov et al., 2006), Framvaren Fjord (Millero, 1991; Dyrsenn, 1999; Yao and Millero, 1995; Mandernack et al., 2003) and Cariaco Basin (Astor et al., 2003) are some characteristic examples of morphology-induced anoxia, while Adriatic Sea (Justić et al., 1987, 1993) and Danish coasts (Josefson and Hansen, 2004) are nutrient-induced anoxic environments.

In anoxic layers, hydrogen sulfide is producing through the reduction of sulfates, NH_4^+ is enhancing and PO_4^{-3} (over oxic conditions) is released from organic matter degradation. PO_4^{-3} is also released from sediments, reducing the N to P ratio and supporting the algal blooms. Thus, more organic matter is produced to fuel anoxia. All these processes are bacterially catalyzed and are more intense after spring surface photosynthesis when elevated rates of detritus materials reaching the anoxic layer.

Anoxia preconditions may be disturbed, affecting the characteristics of the anoxic environment in certain ways. Nutrients management (Boesch, 2006; Mitsch and Day, 2006) leads to the

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increase of dissolved oxygen concentrations mainly in seasonal stratified/anoxic environments such as NW continental shelf of Black Sea and numerous of estuaries in England (Balls et al., 1996; Bakan and Büyükgüng, 2000; Friedrich et al., 2002; Jones, 2006). Short term meteorological changes as storms and/or events of prolonged intensive winds have catastrophic results related to the advection of anoxic water to the surface, total anoxia and massive deaths (Dassenakis et al., 1994; Fallesen et al., 2000; Astor et al., 2003; Luther et al., 2004). Long-term meteorological changes (e.g. climate changes) deplete oceanic oxygen by increasing stratification and warming as well as by causing large changes in rainfall patterns, enhancing discharges of fresh water and agricultural nutrients to coastal ecosystems. Conversely, when climate becomes stormier and stratification decreases because of increased mixing, the risk of oxygen depletion declines (Tyson and Rearson, 1991; Diaz and Rosenberg, 2008).

Although there are many studies referred to impacts on water body anoxia caused by nutrients management and changes in meteorological or hydrological regimes, there is lack of information about the impacts on water column anoxia resulted by morphological modifications. This study aims to address these issues by examining the Aitoliko lagoon.

Human-induced morphological changes in the Messolonghi–Aitoliko lagoonal system during the last decades constitute a natural scale experiment and an excellent opportunity to record and understand the relationship between morphological modifications and changes in water column hydrography and anoxia, in such environments.

The main objective of this study is to investigate and correlate geomorphological changes in anoxic basins with physicochemical alterations in their water column. Deep water renewal and the consequently monimolimnion oxygenation, in meromictic systems, are the questions to be answered. Aitoliko lagoon constitutes the case study, as it is a semi-enclosed anoxic basin on which recent human-induced morphological changes have implicated in increased water exchange with its source basin (Messolonghi lagoon). Seasonal variations of parameters like temperature, salinity, and dissolved oxygen along Aitoliko lagoon water column were recorded and studied. It was attempted to associate the wind speed and direction, during the study period, with the recorded monimolimnion oxygenation, after 55 years of recorded anoxia (Hatzikakidis, 1951; Daneilidis, 1991; Psilovikos, 1995; Chalkias, 2006).

2. Materials and methods

2.1. Study area description

Aitoliko lagoon is a semi-enclosed basin in western Greece. It covers an area of about 16 km^2 and its maximum depth is 27.5 m. It is characterized as non-typical lagoon through its high depth and the fact that its longitudinal axis is perpendicular to the shoreline. Aitoliko basin communicates southerly with a typical shallow lagoon (Messolonghi lagoon) with mean depth of about 0.5 m. The lagoonal system communicates southerly with Patraikos Gulf (maximum depth 100 m) (Fig. 1).

The two lagoons are connected through two shallow and narrow openings, with a total cross sectional area of about 200 m^2, under the bridges of Aitoliko Island (Fig. 1). The mean depth of these openings is about 1.2 m, while their total length is 170 m. In Fig. 4 a detailed dimensional description of these two openings is presented as well as the changes made through time.

Table 1
Freshwater/nutrient point sources in Messolonghi–Aitoliko lagoons.

Source	Discharge (m^3/s)	PO_4-P (mg/l)	NO_3-N (mg/l)
		na	na
B1	3	na	na
B3	0.3	na	na
D1	1.3	na	na
D6	5	na	na
WWT	0.012	1.8	1.7

Sources location is shown in Fig. 3.
na, non-available values.

The region is characterized by typical Mediterranean climate, with mean annual precipitation of about 740 mm, whereas the output due to evaporation is approximately 1540 mm/year. High evaporation values during summer months affects dramatically mainly the physicochemical characteristics of the shallow Messolonghi lagoon.

The physicochemical characteristics of Aitoliko and Messolonghi lagoons differ significantly. Aitoliko lagoon is characterized of brackish surface water, while salinity values at the northern part of Messolonghi lagoon are not higher than 23–24 and 22–23 during winter and summer period, respectively. At the southern part of Messolonghi lagoon, salinity is as high as 49 during summer (Fig. 2B) and 36 during winter (Fig. 2A).

The Aitoliko lagoon is permanent stratified and its isolated bottom layer is characterized by constant temperature and salinity values of 13 °C and 27.5, respectively. The surface layers are characterized of high primary productivity with chlorophyll-a values seasonally varied from 10 and 60 μg/l (Daneilidis, 1991), whereas the average year concentrations of TP, PO_4-P, NH_3-N, NO_3-N and NO_2-N in this layer are approximately 0.03 mg/l, 0.02 mg/l, 0.2 mg/l, 0.1 mg/l and 0.012 mg/l, respectively (Daneilidis, 1991). High nutrient and primary productivity in the surface layer, led to oxygen depletion in the monimolimnion and the accumulation of H_2S with values up to 45 mg/l (Psilovikos, 1995).

The hydrographical network of the area is mainly anthropogenic. It is a network of canals which constitutes an irritation and/or drainage system, while a lot of the area's streams have been diverted into these canals. Water, from the drainage system, flows into the lagoonal system through four pumping stations (Fig. 3 and Table 1).

Water circulation in the study area is tidal-induced. The predominant astronomical tidal constituents are M2, K1 and K2 with amplitudes ±1.7 cm, ±0.9 cm and ±0.4 cm, respectively. Due to the absence of significant tides in the area water circulation in the lagoons is affected by meteorological conditions since, mainly by wind intensity and direction. The predominant meteorological tides Ssa and Sa in Aitoliko lagoon have amplitudes equal to ±6.5 cm and ±1 cm.

2.2. Historical analysis

The physicochemical parameters of the lagoon's water column have been the subject of only a few studies during the last decades. Some changes in the lagoon's characteristics have been recorded, but the common point was the permanent anoxic monimolimnion and the accumulation of sulfide in this layer. Physicochemical characteristics of the surface water layer in the permanent stratified Aitoliko lagoon, present the same seasonal variations during the last decades (since 1951), while changes in deep isolated water layer hydrography have been recorded.

In 1951, Aitoliko's monimolimnion (20 m-bottom) presented salinity values within the range of 31–32.5 (Hatzikakidis, 1951). During the years 1984–1985 the bottom layer was characterized of noticeable lower salinity values that were in the range 27.5–28.5 (Daneilidis, 1991). Ten years later, Psilovikos (1995) reported nearly the same values for the deep high salinity layer

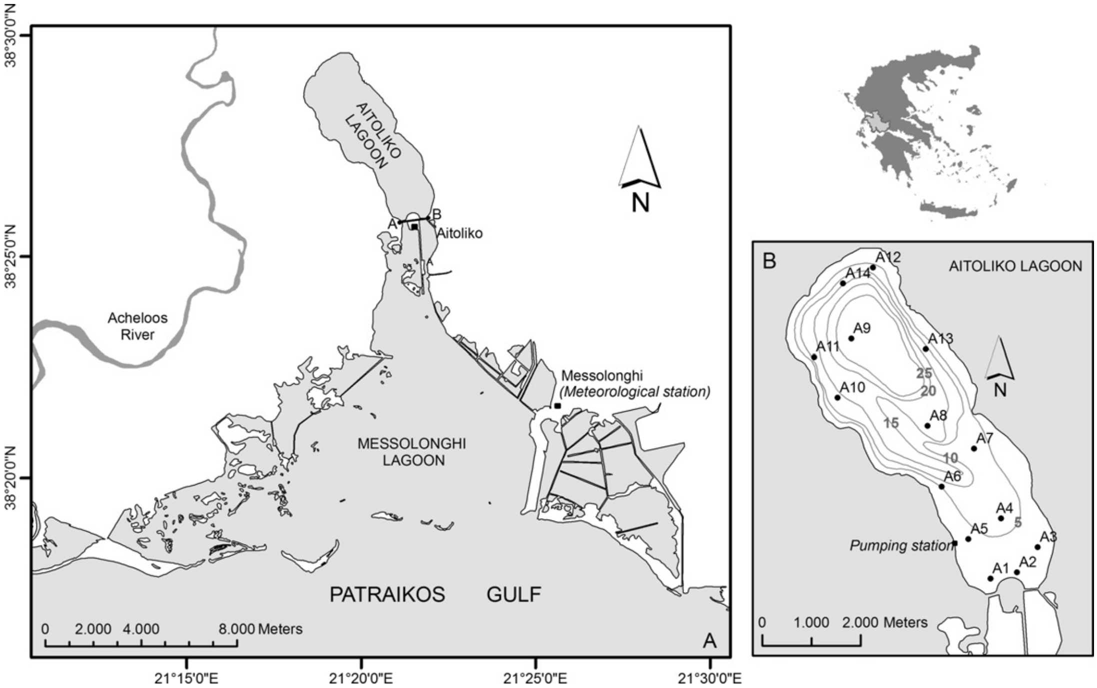

Fig. 1. (A) Map of the extended study area. (B) Sampling stations in Aitoliko lagoon.

(27–27.5). These changes in bottom water salinity are strongly related to morphological changes in Messolongi–Aitoliko lagoonal environment (Fig. 3) that altered the water column dynamics in the studied system. The bottom layer temperature was in the range of 15–16 °C, during the period 1951–2004 (Hatzikakidis, 1951; Daneilidis, 1991; Psilovikos, 1995; Chalkias, 2006).

The vertical distribution of dissolved oxygen and the depth of the oxic/anoxic interface were always of special interest in the Aitoliko lagoon. Oxic/anoxic interface was detected at 14 m and 19 m during the summer and the winter times in the year 1951, respectively (Hatzikakidis, 1951). Forty years later, these depths decreased to 10 m and 15 m (Daneilidis, 1991), respectively, while throughout the year 1995 anoxia recorded at the depth of 7 m (Psilovikos, 1995). Anoxic layer had its maximum thickness during 2003–2004, extending from a depth of 4 m down to the lagoon's bottom (Chalkias, 2006).

Several times, in the past years, the whole basin of Aitoliko lagoon, became anoxic. During these events, anoxic moni-

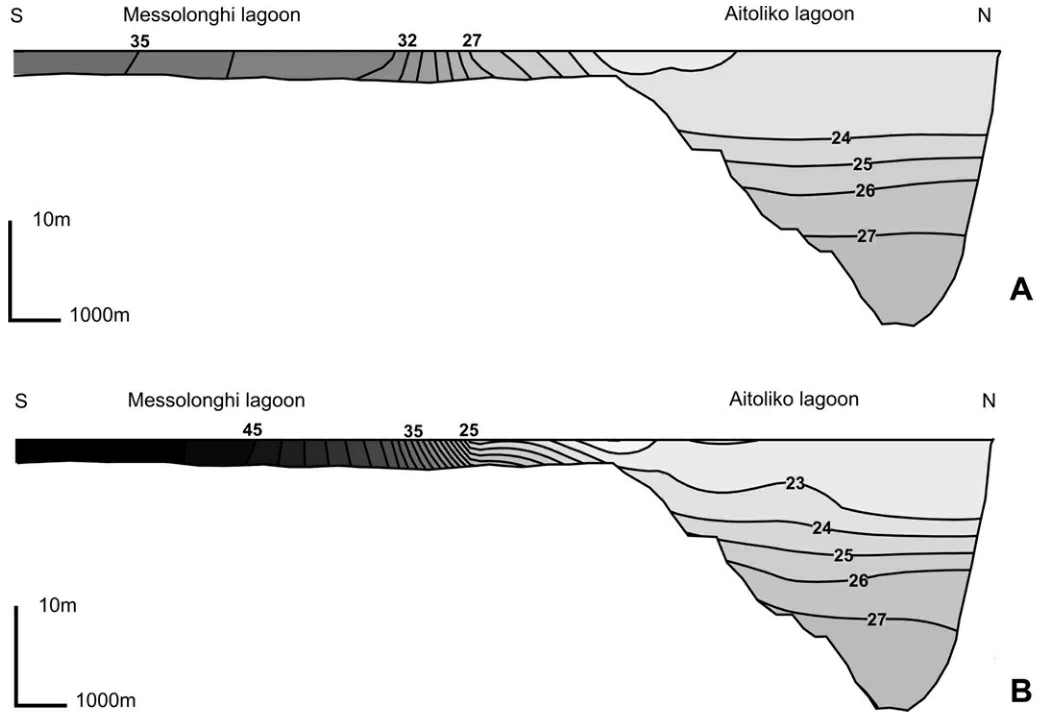

Fig. 2. Vertical salinity distribution along Messolonghi and Aitoliko lagoons. (A) Winter 2008, (B) Summer 2009.

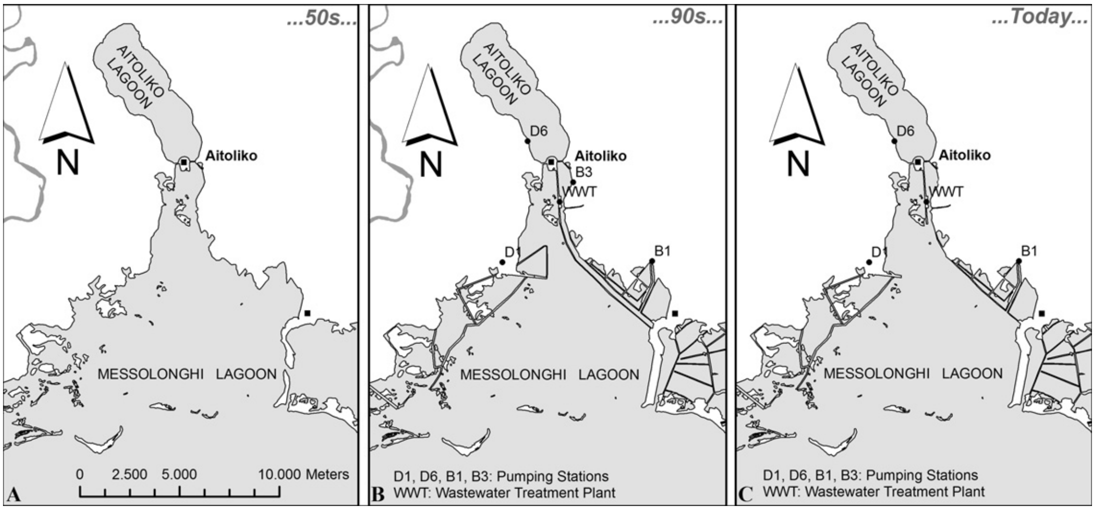

Fig. 3. Morphology of Messolonghi–Aitoliko lagoonal system through the time. The black straight lines represent human made banks in Messolonghi lagoon.

molimnion is advecting to the surface, releasing hydrogen sulfide and killing all the aquatic organisms. The mechanisms that contribute to these holomictic events are not totally understood. It is believed that these occur during autumn or winter months after intense southern winds (Leonardos and Sinis, 1997). The balance that keeps the anoxic water under the lighter, well oxygenated, surface layer is disturbed by the forcible enter of water from Messolonghi lagoon, which helps the anoxic water of the Aitoliko basin, to emerge.

The first reported mass mortality event in the Aitoliko lagoon is referred in 1881. Since then numerous of such holomictic events have been recorded in 1963, 1990, 1992, 1995 (Leonardos and Sinis, 1997), 2001 and 2008.

The progressive increase in the anoxic layer extent, as well as the increase of the holomictic events, was ascribed to the human interference on the Messolonghi/Aitoliko lagoonal system. During the last decades, nutrient load increased via primary wastewater treatment plants (Table 1). Fresh water discharges into the lagoons increased through the operation of drainage pumping stations, which drain the cultivated agricultural areas in the vicinity of the lagoons (Table 1). Moreover water exchange between the two lagoons limited through several technical works (Fig. 3A and B). All these factors gradually enforced anoxia in Aitoliko lagoon and the anoxic layer reached up to the depth of 4 m in 2004 (Chalkias, 2006).

During the latest years there was an effort to reverse the degradation of the system back to its previous natural state. The main objective was to facilitate water exchange between Messolonghi and Aitoliko lagoons, breaking up as many banks as possible. The reconstructions (Fig. 3C) completed on May 2006. Deepening of the connecting sill between the two lagoons was included in these works. After sill dredging in May 2006, the mean depth of the connecting channels increased about 10 cm, while a new opening, 3 m deep and 15 m wide was created, at the eastern part of the sill (Fig. 4). The total cross section increase by ~30%, in combination with the channel's maximum depth increase, facilitates the inflow of denser water from the saltier Messolonghi lagoon affecting Aitoliko lagoon hydrography.

In Table 2 basic morphometric parameters (Hakanson et al., 2007) of Aitoliko and Messolonghi lagoons through time are included and are related with the lagoonal system morphology during the different time periods (50s, 90s and present; Fig. 3).

2.3. Data collection and processing

Samplings were conducted on a monthly basis at fourteen (14) sampling sites for a period of 12 months (May 2006–April 2007). The location of the sampling sites can be seen in Fig. 1. During these samplings, continuous profiles of physicochemical parameters such as temperature, conductivity and dissolved oxygen were measured *in situ* using a Troll 9500 water quality multiparameter instrument. Instrument's accuracy is ±0.1 °C, ±2 μS/cm

Table 2
Morphometric parameters (Hakanson et al., 2007) of Aitoliko and Messolonghi lagoons through time, related with the morphological changes made in the lagoonal system.

50s			
Aitoliko lagoon		Messolonghi lagoon	
Area (km^2)	17	Area (km^2)	216
Mean depth (m)	12	Mean depth (m)	0.45
Max depth (m)	27.50	Max depth (m)	1.50
Section area (At)	120	Section area (At)	–
Form factor (Vd)	1.31	Form factor (Vd)	–
Dynamic ratio (DR)	1.19	Dynamic ratio (DR)	21.89
Exposure factor (Ex) × 10^{-3}	0.70	Exposure factor (Ex) × 10^{-3}	–
90s			
Aitoliko lagoon Sill's dredging at the western side		Messolonghi lagoon Levees construction (Fig. 3)	
Area (km^2)	17	Area (km^2)	209
Mean depth (m)	12	Mean depth (m)	0.45
Max depth (m)	27.5	Max depth (m)	1.50
Section area (At)	157.5	Section area (At)	–
Form factor (Vd)	1.31	Form factor (Vd)	–
Dynamic ratio (DR)	1.19	Dynamic ratio (DR)	21.50
Exposure factor (Ex) × 10^{-3}	0.93	Exposure factor (Ex) × 10^{-3}	–
Today			
Aitoliko lagoon Sill's dredging at the eastern side		Messolonghi lagoon Levees destruction (Fig. 3)	
Area (km^2)	17	Area (km^2)	214
Mean depth (m)	12	Mean depth (m)	0.45
Max depth (m)	27.50	Max depth (m)	1.50
Section area (At)	202.50	Section area (At)	–
Form factor (Vd)	1.31	Form factor (Vd)	–
Dynamic ratio (DR)	1.19	Dynamic ratio (DR)	21.80
Exposure factor (Ex) × 10^{-3}	1.20	Exposure factor (Ex) × 10^{-3}	–

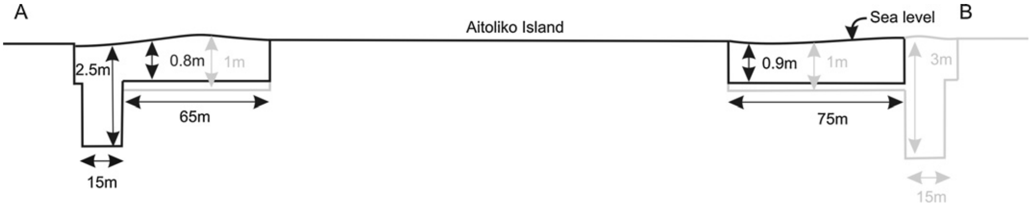

Fig. 4. Sill morphology before (black line) and after (light grey line) dredging.

and 0.2 mg/l for temperature, conductivity and dissolved oxygen, respectively. The temperature and conductivity data were corrected by a low pass filter to minimize sharp spikes in salinity for the short-term mismatch of the sensor responses between temperature and conductivity, using Matlab. Any spikes remaining in the salinity data were removed by calculating a 1 m running average. The despiked temperature and salinity data were used to construct density (sigma-*t*) profiles.

In practice, density is not measured; it is calculated from *in situ* measurements of pressure, temperature, and conductivity using the equation of state for sea water. For simplification, physical oceanographers often quote only the last 2 digits of the density, a quantity they call *density anomaly* or *Sigma* (s, t, p):

$$\sigma(s,t,p) = \rho(s,t,p) - 1\,\mathrm{g/cm^3} \tag{1}$$

When ocean surface layers are studying, compressibility can be ignored, and the sigma-*t* quantity (written σ_t) can be used:

$$\sigma_t = \sigma(s,t,0) \tag{2}$$

This is the density anomaly of a water sample when the total pressure on it has been reduced to atmospheric pressure (*i.e.* zero water pressure), but the temperature and salinity are *in situ* values.

In this study the *Brünt–Väisälä frequency* or the *static stability frequency* was used, evaluating the strength of density stratification in Aitoliko lagoon water column. The frequency quantifies the importance of stability, and it is a fundamental variable in the dynamics of stratified flow. In simplest terms, the frequency can be interpreted as the vertical frequency excited by a vertical displacement of a fluid parcel.

In the ocean where salinity is important, the *Brünt–Väisälä frequency* (N^2) is expressed by the equation:

$$N^2 = -\frac{g\,d\rho}{\rho\,dz} \tag{3}$$

where ρ, the potential density, depends on both temperature and salinity, and g the acceleration of gravity.

There were no direct meteorological observations within the Aitoliko lagoon, throughout the sampling period. Therefore, in order to assess the effect of the wind on the lagoon's hydrography, wind measurements from a station on the nearby Messolonghi town were used. This station is approximately 10 km southeast of Aitoliko town (Fig. 1). Wind speed and wind direction time series, with 10 min temporal resolution, were available. Daily means were calculated and studied for the analysis of the wind time series.

3. Results

The hydrography of Aitoliko lagoon waters varied, throughout the sampling period. Density, temperature, salinity and dissolved oxygen data from the deepest station A_9 are presented in Fig. 5, from May 2006 until April 2007.

3.1. Physico-chemical characteristics

Aitoliko lagoon appeared to be permanently stratified throughout the sampling period. Monimolimnion was extended always below 20 m depth and it was characterized of constant sigma-*t* (σ_t) values at 20–20.5 (Fig. 5A). To understand the factors that control stratification in Aitoliko lagoon, temperature and salinity were plotted with respect to the sampling time for the deepest station A_9 (Fig. 5B and C). During summer (June–August), stratification appeared dominated by temperature decrease with depth in the upper 10 m. From May to September seasonal thermocline combined with the lagoon's permanent halocline, resulted in an extensive strong metalimnion (from 6 to 20 m depth). In winter time (December–February), the surface layer was extended up to the depth of 12 m and the metalimnion's thickness was reduced while density changes were less sharp. Winter stratification is controlled exclusively by salinity gradient.

From June until October 2006, high salinity water was found at the upper metalimnion. Near the sill, it appeared as bottom current and was characterized by high values that reached 30 at station A_2 in August 2006 (Fig. 6). In the interior of the Aitoliko lagoon, the high salinity layer was expanded vertically through mixing, and its salinity was decreased as well. In August 2006, at the northern sampling station A_{14}, this layer was 6 m deep and its maximum salinity was 23.4 (Fig. 6). The maximum recorded salinity of the inflow water into the Aitoliko lagoon water body, as well as the depth at which this layer appeared inside Aitoliko lagoon varied during the sampling period. In June 2006, it extended from 4 to 10 m depth, while in October 2006 from 7 to 13 m depth with maximum salinity equal to 21.5 and 24, respectively (Fig. 5C).

This saltier water inflow from Messolonghi lagoon caused instabilities in the water column of Aitoliko lagoon. Some density inversions were found in the sigma-*t* profiles of Aitoliko lagoon water column. (Fig. 6 stations A_8, A_9 and A_{14}).

Water column stability on time is presented with static stability profiles (N^2) for the deepest sampling station (A_9) in Fig. 7. This describes the strength of density stratification in Aitoliko lagoon throughout the sampling period. In May 2006, high values up to $9 \times 10^{-3}\,\mathrm{s^{-2}}$ characterized the lagoon's water column down to 20 m depth, indicating the extensive and strong density gradient during that period. In June, instabilities of the static stability values were observed from 5 m depth down to 10 m. Particular high static stability values with alternating low negative values were recorded. This illustrated the depth of the saltier water inflow. Similar static stability profiles characterized Aitoliko's lagoon water column throughout the time period that the saltier water inflow was recorded (June 2006–October 2006). Instabilities, gradually from June to October 2006 were found at greater depths in the water column and were always in accordance with the depths on which the saltier water mass was recorded. After the thermal overturn, density stratification in Aitoliko lagoon water column was less strong and that was implied by the decreasing static stability values throughout the water column, in late autumn. Minimum static stability in Aito-

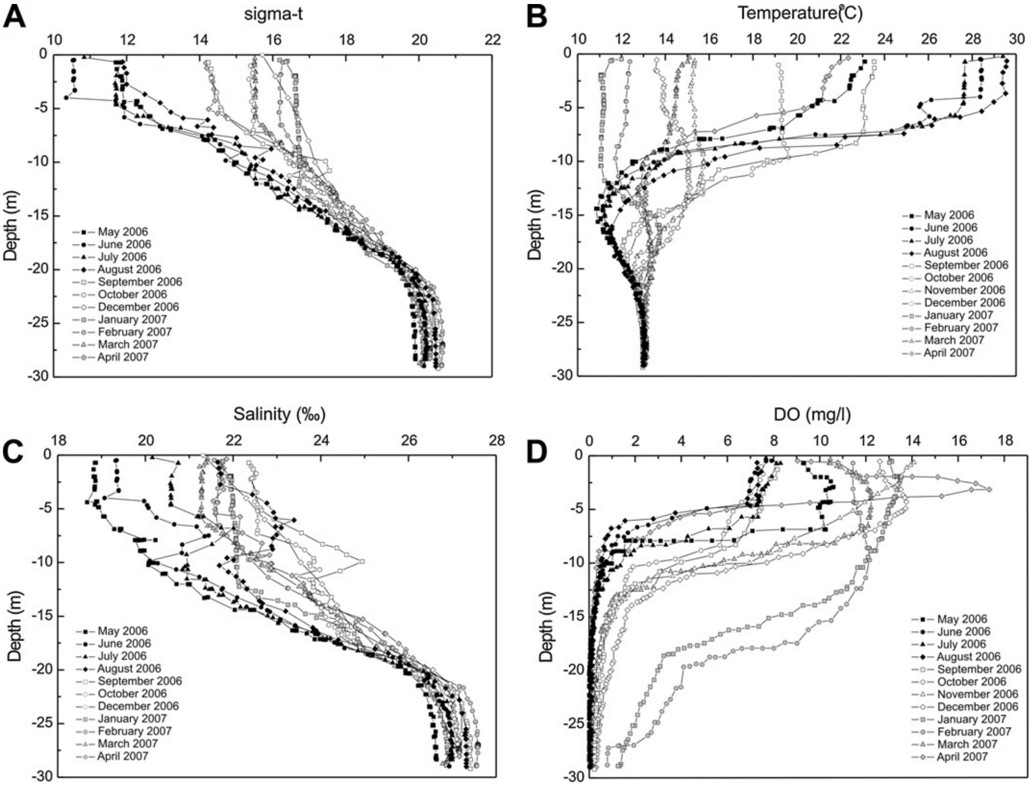

Fig. 5. Density (A), Temperature (B), Salinity (C) and Dissolved Oxygen (D) through the sampling period in the deepest sampling station A_9. In dissolved oxygen distribution (D) with black and grey are presented the anoxic and hypoxic conditions, respectively, in Aitoliko lagoon throughout the sampling period.

liko lagoon water column was presented during winter months (Fig. 7).

3.2. Oxygen distribution

The surface waters were always well oxygenated, with the percent saturation of dissolved oxygen frequently being higher than 100%, due to eutrophication and high primary productivity. The depth of this layer (>100% O_2) varied seasonally, from about 5 m during spring and summer to about 10 m during winter. Below this depth, oxycline was extended, with its lower limit being season-depended. From May to August 2006, the oxic/anoxic interface was located at 17–18 m depth and approximately the 11–13% of the lagoon's volume was characterized by zero oxygen concentration. This layer was reduced during the autumn months. In December 2006, anoxic conditions were observed only below the depth of 24 m (2% of the total volume), while during January and February 2007, dissolved oxygen was present in the lagoon's bottom layer. In particular, in January 2007, 3 mg/l dissolved oxygen was recorded in the upper limit of lagoon's monimolimnion (20 m depth). Oxygen concentration was gradually decreased with depth and values of about 1 mg/l characterized the maximum sampling depths. In February 2007, even higher DO (Dissolved Oxygen) concentrations were measured in the lagoon's bottom layer, with values of approximately 4 mg/l and 3 mg/l characterizing the depths of 20 m and 25 m, respectively. Values slightly lower than 1 mg/l, were recorded in water sediment interface. During March and April 2007 the anoxic layer was well developed below the depth of 20 m, occupying the 8% of the lagoon's total volume.

The presence of oxygen in the bottom layers of eutrophic lagoons, during winter time, is not uncommon. For the permanent stratified Aitoliko lagoon, the monimolimnion's ventilation is reported for the first time.

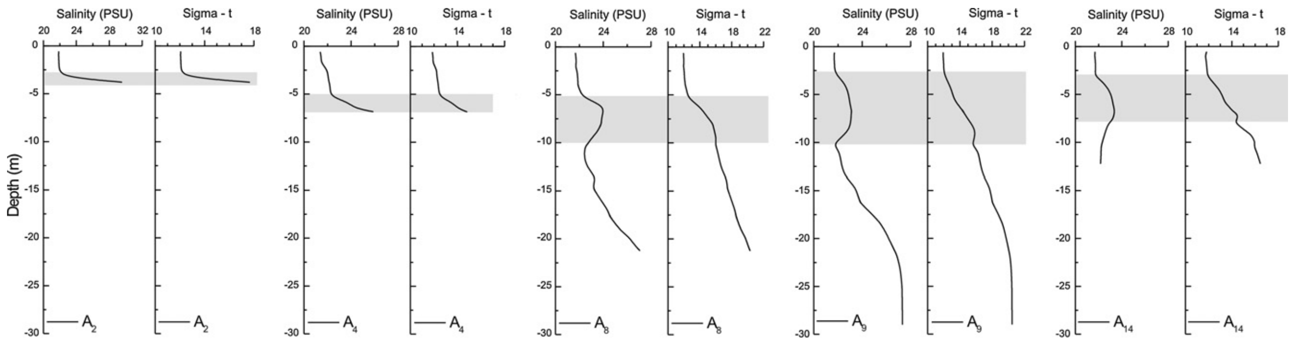

Fig. 6. Salinity (A) and Density (B) during August 2006 at the stations A_2, A_4, A_8, A_9, A_{14}.

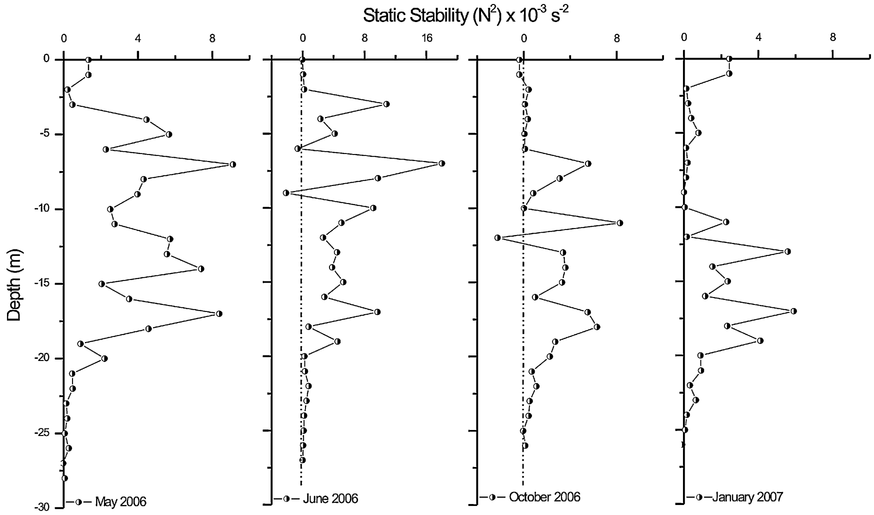

Fig. 7. Aitoliko lagoon static stability profiles. Station A_9.

3.3. Wind conditions

During the sampling period wind was predominantly northeastern (16%) and southern/southwestern (82%) (Fig. 8). Southernly southwesternly winds force water from Messolonghi into the Aitoliko lagoon. Intensive northeasterly winds cause an outflow of surface water, leading to a lowered sea level in the Aitoliko lagoon. When the wind decreases, water enters the lagoon again due to the pressure difference caused by low sea level in the lagoon.

Seasonal minimum values in scalar wind speed (mean daily values up to 6 m/s) characterized May and June 2006, while from December 2006 until March 2007 maximum values (greater than 10 m/s mean daily values) were recorded. Throughout the sampling period strong winds were always associated with northeast directions, while southern winds where always weak (up to 6 m/s) (Fig. 8).

Focusing on winter period, when lagoon's monimolimnion ventilation was recorded, strong (up to 12 m/s) northeastern winds are reported as the predominant wind regime during December 2006. January 2007 is characterized mainly by southwestern moderate winds. Southwestern winds up to 10 m/s were recorded in 24/1/2007, an intensive but short event (about 8 hours). In February 2007 northeastern winds blow up to the study area enhancing the outflow from the Aitoliko lagoon (Fig. 8).

4. Discussion

The permanent stratified Aitoliko lagoon constitutes an environment where anoxia is controlled predominantly by its morphology (large depth, small length), the morphology of Messolonghi lagoon (source basin) and the narrow and sallow sill. Salt/fresh water budget and nutrient load play supplementary roles. Aitoliko lagoon behaves like a typical anoxic basin such as many fjord type basins (e.g. Framvaren Fjord). Thus, human-induced morphological changes in the Messolonghi–Aitoliko lagoonal system constitute a natural scale experiment and an excellent opportunity to record and understand the relationship between morphological modifications and changes on water column hydrography and anoxia, in such environments.

Past studies report a permanent stratified anoxic environment on which the depth of anoxic-oxic interface decreases through the time, from 18 m in 1951 to 4 m in 2006. This reflects the progressive limitation between the source (Messolonghi) and sink (Aitoliko) lagoons throughout these years (Fig. 3). In the present study Aitoliko lagoon monimolimnion oxygenation during the winter months (January and February 2007), is reported for the first time.

Winter lagoon's oxygenation is ascribed to the salty water inflows from the adjacent Messolonghi lagoon. A bottom density current, at the southern part of Aitoliko lagoon was recorded from June until October 2006. This water mass entrained surrounding water and it was vertically expanded. When the water in the dense bottom current achieved the same density as the surrounding water, it was interleaved into the interior of Aitoliko lagoon promoting efficient vertical mixing within the basin. Vertical density instabilities in Aitoliko lagoon were recorded, demonstrating the mixing in its water column. Mixing processes, including breaking of interfacial waves during entrainment are related to the degree of density stratification.

From June to October 2006, salinity of the above-mentioned water mass in Aitoliko water column increased. This resulted from the salinity increase in the source basin (Messolonghi lagoon), which was caused from meteorological conditions and fresh/salt water budget. Density increase of the inflow water in combination with the weakness of density stratification in Aitoliko's water column after the autumn thermal overturn resulted in the depression of the saltier water mass at greater depths. That marks the mixing depth increase and it is probably the key to answer lagoon's bottom water oxygenation during winter time.

However, the question to be answered has to do with the reason behind the inflow of the saltier water into Aitoliko lagoon that led to the bottom water oxygenation.

In shallow systems, tidal currents may induce the appropriate turbulent energy to promote vertical mixing. In the deep Aitoliko lagoon the prevailing tidal amplitudes are not capable to renew the bottom water.

Intensive and prolonged southern winds can enforce denser water from Messolonghi to inflow Aitoliko lagoon and cause mixing of the water column. Furthermore, under strong and prolonged southern winds, water level will be raised in the downwind direction, inducing the pycnocline rise at the near-sill-area, thus allowing the better exchange of monimolimnion. North and northeasterly winds can cause an outflow of surface water, leading to a lowered sea level in the lagoon. When the wind decreases, water will enter the lagoon again due to the pressure difference caused by low sea level in the lagoon. The water that enters the lagoon

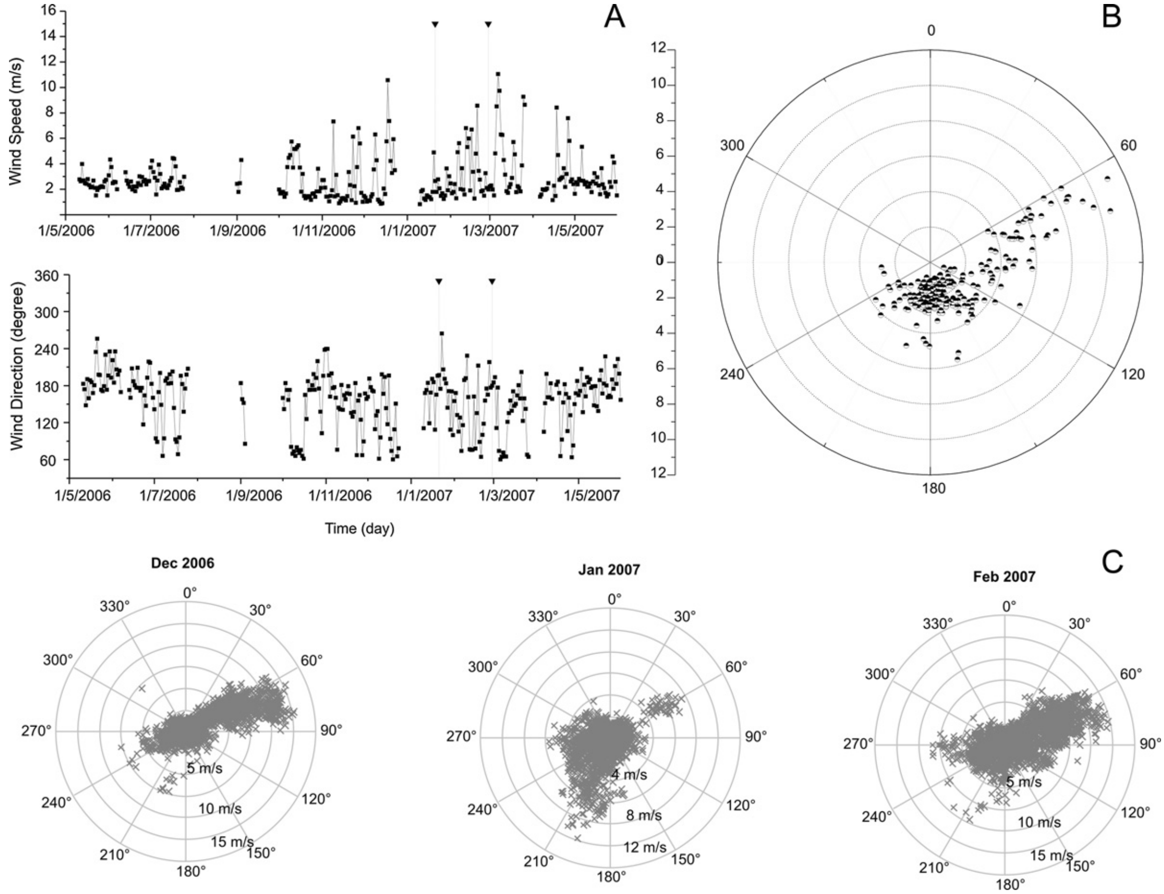

Fig. 8. (A) Daily mean wind speed and direction during the sampling period at the Messolonghi meteorological station. Reverse triangulars shows January (21/2/2007) and February (28/2/2007) samplings. (B) Dominant wind directions during the sampling period. (C) Wind roses during December 2006, January 2007 and February 2007.

is probably surface water mixed with saline Messolonghi water, meaning that it will be denser than the surface water and sink below that, ventilating the hypolimnion.

For these reasons wind contribution to lagoon's monimolimnion ventilation had to be investigated in this study. Throughout the sampling period strong winds (10–12 m/s) were always associated with northeast directions, while southern winds were always weak (up to 6 m/s). Focusing on the ventilation period (January and February 2007), wind speed and wind direction time series showed weak winds with variable direction and strong northern winds just before the samplings of 22/1/2007 and 28/2/2007, respectively.

Nevertheless, there are some reasons that we cannot ascribe Aitoliko lagoon bottom water ventilation in the strong northern winds. First of all, even though northeasterly winds were prevailed during December 2006, the monimolimnion of Aitoliko lagoon was anoxic. Neither the strong northern–northeasterly winds during spring 2007 result in bottom water ventilation. Besides, during January 2007, when for first time, the bottom water of Aitoliko lagoon is presented to be oxygenated; weak southern winds were prevailed in Aitoliko lagoon. Only, in February 2007, high dissolved oxygen concentrations in the monimolimnion of Aitoliko lagoon are combined with strong northeasterly winds.

Finally, in winter time, salinity values in Messolonghi lagoon is not higher than 36, at the southern part. The water that outflows Aitoliko lagoon during northern and northeasterly winds is mixing with the Messolonghi lagoon and inflows again in Aitoliko lagoon when wind decreases and pressure differences permit it. The mixing of the brackish surface water of Aitoliko lagoon with the Messolonghi water, with salinity values lower than 36, does not produce water, dense enough to dive in Aitoliko lagoon hypolimnion ventilating it. Conclusively, meteorological conditions prevailed in study area cannot alter water body anoxia, through vertical mixing, which means that wind was not the reason for the monimolimnion oxygenation.

Sill's dredging increased the channel's maximum depth in 3 m and the total cross sectional area about 30%. Consequently, water fluxes between Aitoliko and Messolonghi lagoons increased at about 30%. These morphological modifications allowed salty water from the source basin to flow in Aitoliko lagoon. Physicochemical characteristics of this water depend on meteorological conditions and fresh/salt water budget in Messolonghi lagoon, and therefore, present seasonal variability. In late autumn months the inflow water presents its maximum salinity value. Increased density, result to the depression of this layer in the water column of Aitoliko lagoon. At the same time (late autumn) lagoon's water column presents its minimum stability, after autumn thermal overturn. Moreover, dissolved oxygen saturation rates in surface layers increase as gradually temperature decreases during this period. The combination of low energy of Aitoliko water column with the increased salinity/density of the inflow water and the higher oxygen concentrations in the surface waters facilitated interfacial mixing processes and monimolimnion ventilation during winter months.

5. Conclusions

Morphological changes in coastal anoxic environments are particularly rare. Such changes affect directly the water exchange in lagoons and, consequently, the physicochemical balance on their water column. Morphological changes in the Aitoliko–Messolonghi lagoonal system affected Aitoliko's hydrography and water column anoxia twice during the last decades: in the, 90s when extensive human interference led to a wide anoxic layer from 4 m down to lagoon's bottom, and once recently when monimolimnion oxygenation resulted from the sill's deepening.

In conclusion, the limited deepening of a sill can create a mild increase of water flow into an anoxic lagoon. This inflow of oxygenated saltier water from the source basin results in a weak mixing of the water column. Such small scale mixing, can introduce oxygen into the halocline waters, without destroying the stratification. Such morphology modification can lower the anoxic-oxic interface and not destroy the anoxic character of the lagoon.

Reducing the connection between an anoxic coastal basin and its source basin water column, anoxia is amplified, while when morphological modifications facilitate water exchanges through these basins bottom water oxygenation can occur. Ventilation depth is dependent on the physicochemical characteristics of the source basin. Morphological modifications, when they are possible, could constitute a natural way of anoxic environment restoration.

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