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EXTENDED ABSTRACT 341

Assessment of Geo-environmental Status of Trichonis Lake, Greece: Mineralogy, Sedimentology, and Chemistry

Vasilatos C.[1], Megremi I.[1], Gkioka Z.[1], Theori N.[2], Cuida Lopez E.[3], Stoica A.I.[3], Economou-Amilli A.[2]
(1) Faculty of Geology & Geoenvironment, National and Kapodistrian University of Athens, Athens, Greece, vasilatos@geol.uoa.gr (2) Faculty of Biology, National and Kapodistrian University of Athens, Athens, Greece (3) Department of Landscape, Water and Infrastructure, University of Natural Resources and Life Sciences, Vienna

Research Highlights

Sediments of Trichonis Lake are dominated by quartz and calcite, reflecting the lithological influence of surrounding limestone and flysch formations.

Reduced nutrient levels in lake water since the late 1990s highlight the positive ecological impact of decreased agricultural pressures, providing a foundation for sustainable lake management strategies.

Introduction / Background

European Union countries have evaluated all freshwater habitats larger than 50 hectares to comply with the Water Framework Directive 2000 (European Commission, 2000). To support biological, hydromorphological, and physico-chemical monitoring, a range of indicators and multimetric indices has been developed. These include factors such as morphology, hydrology, nutrient levels, thermal conditions, salinity, pollutants, and priority substances. Geochemical indicators such as pH, sediment mineralogy, and the concentrations of ions, nutrients, and potential pollutants in soil and water, are normally used to assess habitat quality and quantify the environmental stress affecting ecosystems (ecological status) (e.g. Vasilatos et al., 2019).

Trichonis Lake, located in western Greece, is the largest and one of the deepest natural freshwater lakes in Greece, with a maximum depth of 58 m and a surface area of approximately 98 km² (Figure 1). On the northeastern side of the lake the steep slope of Panaitoliko Mountain is visible, while the southwestern side is bounded by the ridge of Arakinthos Mountain. The wider "Trichonis basin" is a neo-tectonic graben approximately 30 km in length and 10 km in width (Doutsos et al., 1987); its hydrological basin extends to an area of 402 km^2 (Koutsoyiannis et al., 2008) and its southern boundary is defined by a prominent WNW-ESE trending normal fault. Geologically, the area belongs to the External Hellenides, specifically the Pindos and Gavrovo geotectonic units (Figure 2). Trichonis Lake occupies the eastern margin of a fractured tectonic trough at a semi-circular shape. This trough was formed primarily due to the intense tectonic activity of the region and partially by the collapse of limestone masses into existing underground caverns, which constitute an extensive karstic network. These karsts are continually enlarged by the erosive and solvent action of water, leading to the collapse of overlying layers and contributing to ongoing changes in the morphology of the region (Evangelidis et al., 2008; Kiratzi et al., 2008, Benekos et al., 2013). Trichonis Lake main geomorphological characteristics are summarized in Table 1.

Table 1. Geomorphological characteristics of Trichonis Lake (cf. Tafas et al., 1997).

Max. length	18.2 km
Max. width	7.5 km
Max. depth	58 m
Mean depth	30.45 m
Lake volume	2.99 x 10^9 m^3
Shore length	52.1 km
Surface area	98.2 km^2
Drainage area	215 km^2

The water level of the lake is artificially controlled by a dam being constructed to regulate its discharge at an average altitude of 15.5 m with a fluctuation of ±1 m. This dam communicates by means of a 2.8 km long Trichonis-Lysimachia Unifying Trench with Lysimachia Lake, to which its excess water potential is channeled.

The lake is recognized for its rich biodiversity, including endemic fish (e.g. Vardakas et al. 2022), freshwater hydrobiids (e.g. Radea et al. 2017), and algae species (Economou-Amilli 1979, 1982); and generally, for the presence of unique aquatic plants, as well as its role in local hydrology and as a water source for nearby communities. However, like many freshwater ecosystems globally, Trichonis faces environmental pressures due to agricultural activities, urban runoff, and sedimentation processes, potentially threatening the health of its ecosystem. In previous studies (e.g., Kehayias & Doulka, 2014; Overbeck et al., 1982; Tafas et al., 1997) due to its limnological and biological characteristics Trichonis was classified as a carbonate-type, low-conductivity lake ("class II, low salinity" warm lake) with an oligotrophic to mesotrophic ecosystem. Furthermore, Kehayias & Doulka (2014), using zooplankton as a biotic indicator, suggested that Trichonis Lake is undergoing a transitional shift toward a eutrophic state, emphasizing the need for continuous monitoring and inspection of the ecosystem.

Figure 1. Location map of the study area (Perivolioti et al., 2021).

Objectives

The objective of this study is to assess the geo-environmental status of Trichonis Lake by analyzing the mineralogical and sedimentological characteristics of its sediments along with the physicochemical parameters of lake water. This analysis aims to identify changes in sediment composition, assess nutrients concentrations, and evaluate the impact of anthropogenic activities, offering a comprehensive assessment of current environmental condition of the lake and helping guide future management efforts.

Methods

Study Area and Sampling Sites

Bottom sediment and water samples were collected from various sites throughout Trichonis Lake in September 27-28, 2024, to capture a representative profile of the lake's sedimentary environment (Figure 2). Sampling sites were selected to encompass areas near potential pollution sources, such as agricultural runoff zones and areas adjacent to urban settlements, as well as deeper, central lake locations to account for natural sediment deposition.

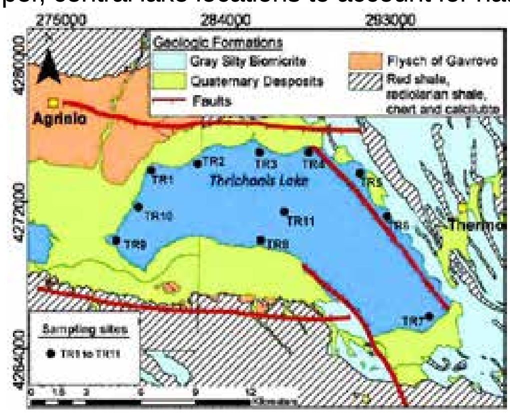


Figure 2. Simplified geological map of the study area (modified after Benekos et al., 2013) with the sampling sites.

Sediment Sampling, Preparation and Analysis

Sediment was retrieved from each site using a stainless-steel dredge bottom sludge sediment grab sampler

(Figure 3). Sediment samples were collected in 2 L plastic bags. Before the experimental procedure, the coarse organic matter was removed from the samples. In the laboratory they were air-dried, homogenized, and sieved to remove particles larger than 2 mm. Fine fractions were preserved for further mineralogical, sedimentological, and chemical analyses. The granulometric characterization was conducted according to Folk's methodology and classification (Folk, 1974). Mineralogical analysis was carried out by using an X-Ray Siemens D 5005 Diffractometer, equipped with a Cu tube and a graphite monochromator, in combination with the DIFFRACplus software package at NKUA, Department of Geology and Geoenvironment. The organic matter (OM) content was determined using dry combustion, involving drying at 105°C for 24 hours and combustion at 380°C for 6 hours in a muffle furnace (Vasilatos et al., 2019). The $CaCO_3$ (%) content was estimated by combusting the above samples at 950°C for 1 hour.

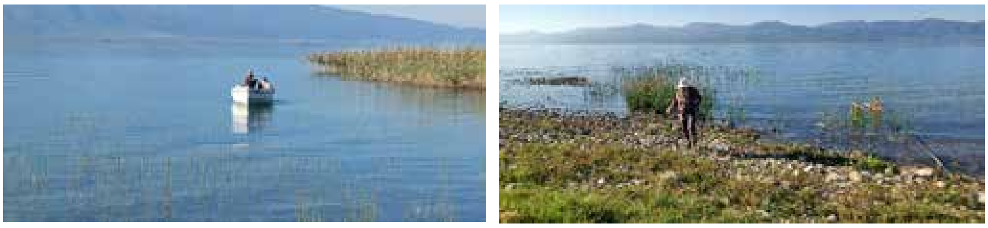


Figure 3. Sampling in Trichonis Lake. Photographs have been captured from sampling site TR4 (Figure 2).

Water Sampling, Preparation and Analysis

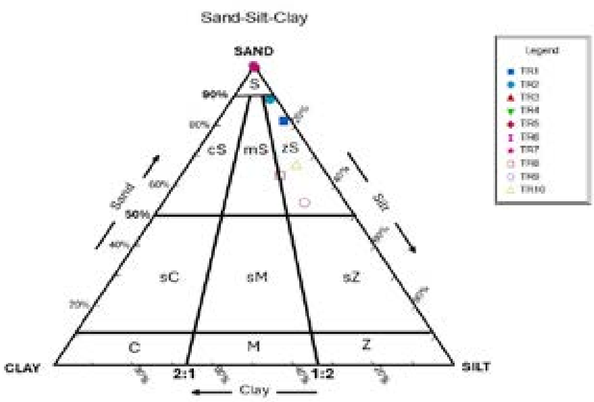
pH, redox potential (Eh), conductivity, total dissolved solids (TDS) and dissolved oxygen (DO) measurements were performed *in situ*, using a portable Multiparameter Analyzer (CyberScan Series 600, EUTECH). Water samples (Figure 3) were filtered through 0.45 μm membrane filters, collected and stored in polyethylaine containers. They were divided into two groups; the first group was persevered for the measurements of anions while the second was acidified by addition of concentrated HNO_3 for the measurements of cations. Then they were all stored at cooling conditions (~ 4°C) into a portable refrigerator.

Chemical analyses for NO_2^-, NO_3^-, NH_4^+, PO_4^{3-} and SO_4^{2-} were performed using a HACH DR/2400 spectrometer. The detection limits of the methods were 0.007 mg·L^{-1}, 0.05 mg·L^{-1}, 0.013 mg·L^{-1}, 0.01 mg·L^{-1}, and 3 mg·L^{-1}, respectively.

Results and Discussion

Sedimentology

Particle size data (Figure 4) can reveal sediment transport patterns and indicate environmental conditions impacting sedimentation, such as changes in water flow or anthropogenic disturbances.



S: sand
s: sandy
Z: silt
z: silty
C: clay
c: clayey
M: mud
m: muddy

Figure 4. Bottom sediments granulometry according to Folk's (1974) classification scheme.

Sedimentological analysis indicated that sites near limestone formations are classified as sand while samples nearby flysch formations are silty sand, dominated by finer sediment fractions (Figure 4). This distribution suggests that sedimentation processes in the lake are controlled by the mineralogical composition of the adjacent lithologies and rock erosion.

Sediments Mineralogy and Chemistry

Quartz and calcite were confirmed in all samples originated from the surrounding flysch and limestone formations (Table 2). Clay minerals (chlorite and muscovite) and feldspars have been identified in samples adjacent to the flysch and related Quaternary deposits (Figure 2). These findings align with typical mineral assemblages expected in freshwater lake sediments within flysch and limestone-rich areas.

Table 2. Mineralogical composition of the bottom sediments (qualitative).

	TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	TR9	TR10
Quartz	+	+	+	+	+	+	+	+	+	+
Calcite	+	+	+	+	+	+	+	+	+	+
Aragonite								+		
Orthoclase		+					+			
Albite	+	+						+	+	+
Anorthite		+						+		
Muscovite	+	+						+	+	+
Chlorite	+	+						+	+	+

+ referring to the presence of the mineral phase

The organic matter content in the bottom sediments ranged from 0.1% to 6.2% (Table 3). The maximum value (6.2%) was observed at sampling site TR9, located near the opening of the Trichonis-Lysimachia Unifying Trench, pointing out the ecological importance of this trench. The high value of organic matter content at that site is a strong indicator of ecological processes like increased biological productivity or enhanced sediment accumulation. Samples with the lowest organic matter content showed the highest quartz content based on their X-ray diffraction (XRD) patterns

Table 3. Quantitative analysis of the Organic Matter and $CaCO_3$ content of the samples.

	TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	TR9	TR10
Organic Matter (%)	1.7%	1.2%	1.0%	0.1%	1.2%	0.6%	1.0%	5.3%	6.2%	2.6%
$CaCO_3$ (%)	19.4%	23.0%	39.0%	39.8%	11.6%	69.4%	19.3%	52.4%	67.3%	42.3%

Water Chemistry

Physicochemical parameters, concentration and chemical composition of the major anions of water samples from Trichonis Lake are presented in Table 4. All measured water parameters comply with the standards for water intended for human consumption (European Commission, 2000).

The measured pH values range from 6.52 to 7.90, falling within the typical range for lake water associated with limestone or flysch lithologies. The observed high concentrations of NH_4^+, NO_3^-, and PO_4^{2-} in the sample TR8, as well as of NO_3^-, NO_2^-, and PO_4^{2-} in the sample TR4 suggest a tangible impact of agricultural and urban runoff on Trichonis Lake. The consistent SO_4^{2-} levels (27.1–28.4 mg/L) across sampling sites indicate minimal influence from human activities, which would cause greater variability near potential sources. Instead, these concentrations may stem from natural processes, such as the presence of evaporitic formations in the wider area.

Nutrient levels are much lower than in 1980–1997 (Koutsoyiannis et al., 2008) but similar to 2000–2002 (Koutsoyiannis et al., 2008) presumably due to the late-1990s abandonment of extensive tobacco cultivation around the lake, which had caused ecological strain.

Table 4. Measurements of the water physical and chemical parameters.

	Units	TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	TR9	TR10	TR11
pH		7.83	7.83	7.35	6.52	7.74	7.64	7.13	7.13	7.89	7.90	7.16
Eh	mV	113	117.4	107	92.2	129.8	105.9	115.8	162.7	90.7	79.4	154.5
DO	mg/l	5.68	6.91	5.72	7.99	6.67	5.4	6.69	6.69	7.02	6.39	6.88
EC	μS/cm	347	334	312	323	324	318	289	334	298	310	330
TDS	mg/l	232.49	223.78	209.04	216.41	217.08	213.06	193.63	223.78	199.66	207.7	221.1
NH_4^+	mg/l	<0.013	<0.013	0.030	<0.013	0.040	0.013	0.040	0.050	<0.013	0.030	0.064
NO_3^-	mg/l	0.886	4.43	1.77	11.96	3.54	5.32	1.33	14.61	5.76	0.87	0.89
NO_2^-	mg/l	<0.007	<0.007	0.01	0.06	0.02	<0.007	0.033	0.01	0.023	0.016	0.009
PO_4^{3-}	mg/l	0.03	0.03	0.03	0.06	0.07	0.01	0.06	0.04	0.01	0.06	0.04
SO_4^{2-}	mg/l	27.7	27.7	27.9	28.4	27.1	28.3	27.9	28.3	27.3	27.2	26.3

Comparison with Other Mediterranean Lakes

Even though Trichonis Lake has been classified as a typical warm lake, it resembles more closely to temperate lakes than tropical ones (Tafas et al., 1997) exhibiting shallow metalimnia that characterize lakes of higher latitudes.

The bottom sediments of Trichonis Lake are primarily composed of quartz, calcite, and clay minerals such as chlorite and muscovite, reflecting the geological influence of surrounding flysch and limestone formations. This composition is characteristic of carbonate-type lakes in limestone-dominated regions (Tafas et al., 1997; Kehayias & Doulka, 2014). In contrast, many Mediterranean lakes exhibit more diverse sediment compositions depending on local geology, including higher proportions of volcanic materials (e.g., in volcanic lake basins) or organic-rich sediments in eutrophic systems (Karathanasis & Hajek, 1993; Gkenas et al., 2012; Michaloudi et al., 2013; Köprücü & Polat, 2017).

The relatively low organic matter content (ranging from 0.1% to 6.2%) in Trichonis sediments aligns with its oligotrophic to mesotrophic status, whereas highly eutrophic Mediterranean lakes often exhibit significantly higher organic matter concentrations due to increased biological productivity and nutrient input (Overbeck et al., 1982; Tafas et al., 1997; Kehayias & Doulka, 2014). The high $CaCO_3$ content (up to 69.4%) further distinguishes Trichonis as a carbonate-rich system, a feature not universally observed in Mediterranean lakes, where sediment composition varies widely.

Nutrient levels (e.g., NH_4^+, NO_3^-, and PO_4^{3-}) in Trichonis Lake water are relatively low compared to heavily impacted Mediterranean lakes, although localized agricultural and urban runoff has resulted in elevated nutrient concentrations in specific sites, indicating ongoing anthropogenic pressure (Petaloti et al., 2004). When compared to other Mediterranean lakes, Trichonis exhibits nutrient levels and chemical parameters indicative of a transitional ecosystem, less impacted by eutrophication than many lakes in the region.

Conclusions

Comprehensive assessment of the geo-environmental status in Trichonis Lake revealed insights into its sedimentological, mineralogical, and chemical characteristics, as well as into the impact of natural and anthropogenic factors.

Key conclusions include:

- The sediments are predominantly composed of quartz and calcite, reflecting a lithological influence of the surrounding flysch and limestone formations. Variations in sediment texture, ranging from sand to silty sand, highlight localized sediment transport and deposition processes.
- Organic matter content ranged from 0.1% to 6.2%, with higher values near areas of enhanced biological productivity, such as at the Trichonis-Lysimachia trench. This differentiation signifies the ecological importance of sedimentary organic matter accumulation in assessing ecosystem "health".
- Physicochemical parameters, including pH, Eh, and TDS, are consistent with those expected in freshwater systems influenced by limestone and flysch. Elevated nutrient levels at specific sites point to agricultural runoff and urban influences, although the overall nutrient concentrations declined since the late 1990s, likely due to reduced agricultural pressures, including the cessation of tobacco cultivation.
- While some localized contamination is evident, such as elevated NH_4^+, NO_3^-, and PO_4^{3-} levels near agricultural areas, the consistent SO_4^{2-} levels across sites suggest limited anthropogenic influence on this parameter. The mineralogical composition of the lake sediments also emphasizes the dominance of natural geochemical processes in shaping its chemistry.
- Overall, Trichonis Lake shares some commonalities with other Mediterranean lakes in terms of its sensitivity to anthropogenic impacts and nutrient dynamics. However, its distinct carbonate-rich sediment composition and relatively stable water chemistry highlight its unique geological and ecological context. This underscores the importance of tailored conservation efforts to preserve the lake's ecological balance amidst regional anthropogenic pressures.

This study provides a baseline for understanding the geo-environmental dynamics of Trichonis Lake and offers valuable guidance for future conservation and management strategies aimed at maintaining the health of this vital freshwater ecosystem. Findings underscore the need for continued monitoring and sustainable land-use practices to mitigate anthropogenic pressures and preserve the ecological integrity of the lake.

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