

Article

Climate Change and Its Potential Impact on the Conservation of Wooden Pole Dwellings in Lake Bolsena: Insights from Climate Proxy Data and High-Frequency Water Monitoring

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Abstract

This study examines the impact of recent climatic trends on the preservation of submerged wooden structures at the Gran Carro archaeological site in Lake Bolsena, Italy. Climatic data from the Bolsena Meteorological Station were analysed alongside in situ water quality measurements collected near the archaeological remains at a depth of 4 m. The key parameters included water temperature (T_w), redox potential (E_h), dissolved oxygen (DO), and total dissolved solids (TDS). Trend analyses using the Mann–Kendall test and Sen's slope revealed significant increases in air and water temperatures, which were strongly correlated. Although precipitation exhibited an upward trend, its negative correlation with temperature suggests greater variability rather than a stable water supply. Despite increased rainfall, lake levels showed a significant decline, likely due to intensified evaporation and water extraction for irrigation. UAV surveys confirmed recent lowering of the lake's water surface during drought periods. Among the limnological parameters, dissolved oxygen saturation declined significantly, while redox potential increased, indicating shifts toward more anaerobic conditions. These environmental changes could promote the activity of erosive bacteria that degrade submerged wood. Conversely, increased evaporation might also enhance oxygen penetration at depth, potentially activating decay agents such as soft rot fungi and wood-boring bacteria. Overall, the findings suggest that ongoing climatic changes are adversely affecting the preservation of submerged wooden structures, highlighting the need for adaptive management strategies to protect both the lake ecosystem and its archaeological heritage.

Keywords: waterlogged archaeological wood; environmental chemistry; UAV; sediments; wood bacteria



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1. Introduction

Climate change exerts multifaceted impacts on terrestrial and aquatic ecosystems, with lakes functioning as sensitive sentinels of environmental change [1]. In particular, extreme

events such as heatwaves and prolonged droughts are altering water availability, thermal regimes, and hydrochemical balances, threatening both ecological functioning and the preservation of cultural heritage [2]. Lakes respond rapidly to anomalies in air temperature, precipitation, and radiation inputs, as evidenced by global mapping of lake dynamics that highlights the role of small- to medium-sized basins in amplifying climate signals [3]. Regional modeling further demonstrates how shifts in climate variables propagate through catchment–lake systems, affecting both water quantity and quality [4,5].

The limnological outcome of extreme climatic events is strongly modulated by local physical drivers. Solar radiation and reduced convective mixing during hot, dry periods favor strong thermal stratification and hypolimnetic oxygen depletion [6], while wind-driven turbulence intermittently counteracts stratification, promotes vertical exchange, and can mobilize sediment-bound constituents. Changes in wind regimes therefore act as a key control on whether a lake remains stably stratified or experiences episodic mixing events that reintroduce nutrients and redox-active elements to the photic zone. Under calm, warm conditions, buoyant cyanobacteria and other bloom-forming taxa can accumulate at the surface, producing harmful algal blooms whose timing and spatial extent are shaped by the coupled interactions among temperature, light, wind forcing, and nutrient availability [7–11].

Droughts complicate this picture by reducing lake volume and increasing sediment exposure and resuspension, thereby altering porewater chemistry and releasing bound nutrients and contaminants to the water column [12]. These hydrochemical shifts—reflected in increases in conductivity, changes in redox state, and episodic oxygen depletion—affect both ecosystem functioning and the geochemical environment in which buried organics persist [5,13]. In volcanic basins, geogenic inputs and volcanoclastic sediments further modulate ionic strength, buffering capacity, and the concentrations of Fe–Mn–S species, producing site-specific diagenetic pathways that can influence both water chemistry and early mineralization of organic remains.

Submerged cultural heritage in lacustrine environments is particularly sensitive to such coupled physical–chemical–biological dynamics. Waterlogged archaeological wood and other organics are typically preserved where saturated, anoxic sediments limit microbial attack; however, fluctuations in water level, oxygen penetration, and sediment geochemistry can quickly compromise these protective conditions. Microbial activity, driven by shifts in redox and nutrient regimes, accelerates decay; sediment resuspension and shoreline recession can physically destabilize deposits; and mineral uptake during early diagenesis can either aid preservation or promote mechanical weakening depending on mineral type [14,15]. Studies on wooden foundation elements and waterlogged timbers demonstrate the variety of degradation pathways and emphasize the importance of combining micro-morphological, chemical, and thermogravimetric analyses to assess preservation state [16–18].

Lake Bolsena (central Italy) offers a unique case study for exploring these coupled dynamics. It is the largest volcanic lake in Europe, characterized by basaltic–trachytic geology, complex stratification, and high cultural significance. Its submerged archaeological site of Gran Carro, dated to the Villanovian culture (9th–8th century BCE), preserves wooden poles and settlement structures that provide a rare archive of protohistoric lifeways in central Italy [17–19]. Earlier studies have described the mineralization processes affecting waterlogged wood and highlighted the vulnerability of these remains to hydrochemical changes [20]. However, despite this growing awareness, integrated assessments that connect climatic forcing, limnological variability, sediment mineralogy, and archaeological preservation remain scarce, especially in volcanic lake contexts.

This study addresses this gap by investigating the interplay between climate extremes, limnological dynamics, and conservation conditions at Gran Carro. Using a 30-year climatic dataset, high-resolution in situ measurements collected during 2022—an exceptional year marked by severe drought and record-breaking heatwaves—along with UAV-based shoreline surveys and sediment analyses, we evaluate how multiple stressors converge to influence both lake dynamics and heritage preservation. By adopting a multidisciplinary perspective that incorporates climate diagnostics, limnology, geochemistry, and archaeology, the research contributes new insights into the vulnerability of submerged cultural heritage in the volcanic lake of Bolsena.

For clarity, the results are organized as follows: Sections 3.1 and 3.2 describes the seasonal and long-term climate variation in the study area, using ETCCDI (frost days, hot days, tropical nights). Sections 3.3 and 3.4 presents in-lake measurements of water parameters (temperature, dissolved oxygen, pH, electrical conductivity) also near the archaeological site, in particular, Section 3.4 analyzes shoreline fluctuations in relation to drought events. Section 3.5 explores correlations between climatic and aquatic variables. Finally, Section 3.6 examines sediment composition and its implications for preservation.

2. Materials and Methods

2.1. Site Description

Lake Bolsena is located in central Italy, in the province of Viterbo, within the Upper Lazio region (Figure 1). It is well known as the largest volcanic lake in Europe, with a water volume of approximately 9.2 km³. The lake occupies a caldera formed by the collapse of the magma chamber roof following the cessation of volcanic activity from the Vulsinian apparatus. Lake Bolsena serves as a vital resource for the local population, providing water for domestic use, agriculture, and supporting tourism. Approximately 22,000 people reside within its watershed, with the population increasing to around 35,000 during the summer months [21].

The lake is subject to pollution risks, particularly from agricultural runoff containing high levels of nitrogen (N) and phosphorus (P) from fertilisers. The first limnological studies of Lake Bolsena were conducted between 1966 and 1971 by the National Research Council [22], and data collection has continued regularly since. In 2004, the lake's water renewal time was estimated at approximately 120 years [21], but more recent assessments suggest an increase to around 300 years [23]. In addition to the lake's intrinsic vulnerability—due to the absence of inflowing tributaries and the presence of only a single outflow—this shift is attributed to factors such as intensified agricultural practices, inadequate maintenance of sewage infrastructure, increasing urbanization, and climate-related stressors [21,23].

The ecological status of the lake has been monitored over several decades, with annual reports documenting progressive eutrophication, particularly in the deeper layers [21]. From an archaeological perspective, the Gran Carro site within the lake has been extensively studied. It was discovered in 1959 by Alessandro Fioravanti [19,24] and dates to the beginning of the Early Iron Age (9th century BCE). The settlement is located at a depth of 4–5 m, approximately 100 m offshore from the lake's eastern shore (42°35' N, 11°59' E, Figure 1). Wooden structural remains from the site show variable states of preservation, ranging from well-preserved to heavily degraded wood [17]. Notably, these remains tend to accumulate heavy metals, reflecting both biotic and abiotic degradation processes [18].

As for the climate, according to the Köppen–Geiger climate classification [25], Lake Bolsena falls within the Csa category, which means a Mediterranean climate with hot dry summers. However, due to its specific altitude (~350 m a.s.l.) and lake influences, local conditions are attenuated. In fact, winters are mild, typically lasting from October through May, with the mean minimum temperature of the coldest month dropping slightly

below 0 °C (−0.3 °C). Summers are moderately warm, with mean maximum temperatures remaining below 29 °C. Annual precipitation is moderately high, ranging from 954 to 1166 mm, with summer rainfall events contributing between 103 and 163 mm. Summer aridity is not particularly pronounced and is confined to July and August (Figure S1), supporting the classification of Bolsena’s climate as mesotemperate, sub-humid to humid ombrotypes and lower supramediterranean thermotype [26].



Figure 1. Location and spatial organization of the study area in Lake Bolsena, central Italy. The right panel displays a high-resolution aerial view of the eastern shore of the lake, highlighting key features including the base camp, multiparametric probe deployment site, the “Aiola” submerged structure, and the underwater archaeological site.

2.2. Dataset Presentation

This study analysed climate data provided by the Civil Protection Department (PC) [27] and the Regional Agency for the Development and Innovation in Agriculture of Lazio (ARSIAL) [28], along with water quality data from the Regional Agency for Environmental Protection of Lazio (ARPA) [29]. Daily mean, (T_{med}), maximum (T_{max}) and minimum (T_{min}) air temperatures, as well as daily precipitation (PRCP), were collected from 1990 to 2023, covering a 34-year period. These raw climatic data were used to derive a series of standard climatic indices relevant to ecological and hydrological processes

(see Section 2.3 Methods) and were aggregated to monthly and yearly means to facilitate comparison with limnological datasets.

To better understand the lake's water conditions, data from ARPA were examined with particular reference to water temperature (Tw), pH, dissolved oxygen concentration (DO), and electrical conductivity (EC). These parameters are widely recognized as key indicators of water quality and ecosystem health particularly for tracking seasonal or long-term changes. The ARPA dataset spans a shorter period (2014–2019), with a frequency of 1–2 samples per season. Monthly averages were computed for consistency with other datasets.

To complement this information and contextualise the lake's biogeochemical dynamics, it is important to consider the vertical structure of the water column. The epilimnion—the upper, well-mixed and warmer layer—extends to a depth of approximately 25 m, and the most recent full water column turnover, which enables exchange between epilimnion and hypolimnion, occurred in spring 2019 [30]. Monitoring parameters such as temperature, dissolved oxygen, and nutrient levels in this layer provides critical insight into the ecological status of the lake.

Since the ARPA monitoring probe is positioned on the western shore—nearly opposite the Gran Carro archaeological site—this study further integrated high-resolution data from a multiparameter probe installed near the archaeological remains. Unlike the low-frequency ARPA dataset, this in situ probe records hourly measurements on a continuous daily basis. The parameters analysed include Tw, pH, DO, oxygen saturation (O_{sat}), redox potential (Eh), salinity (Sal), EC, and total dissolved solids (TDS). These high-frequency data, covering the period from July 2022 to September 2023, were aggregated to monthly means and used to capture short-term variability and dynamic shifts in water quality.

Hydrological data were also considered, including daily water level records (minimum, mean, and maximum) from ARSIAL for the year 2022, which were averaged to a monthly scale.

All datasets underwent standard quality control procedures. Obvious outliers were removed, and missing values were treated either through interpolation (for time series) or exclusion (for sparse sampling), depending on context. An overview of the dataset attributes—including temporal coverage, source, resolution, and processing level—is presented in the metadata table below (Table 1).

2.3. Methods

Figure 2 provides a concise visual summary of the workflow, illustrating the operations of data collection, data processing, and the generation of final analytical outputs. The initial step of the analysis involved calculating average values of the climatic parameters and examining their temporal variations over the observation period. To evaluate extreme climatic conditions, the climatic dataset was further processed to derive a set of climate indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) of the World Meteorological Organization (WMO) and the United Nations (UN), which are specifically designed to characterise extreme climate events [31]. The selected indices are listed in Table 2; in Table S1 are reported additional climatic indices related to the Supplementary Materials.

Table 1. Overview of the environmental parameters used in the study, including their abbreviations, data sources, data resolution, observation periods, derived indices, and the final temporal resolution.

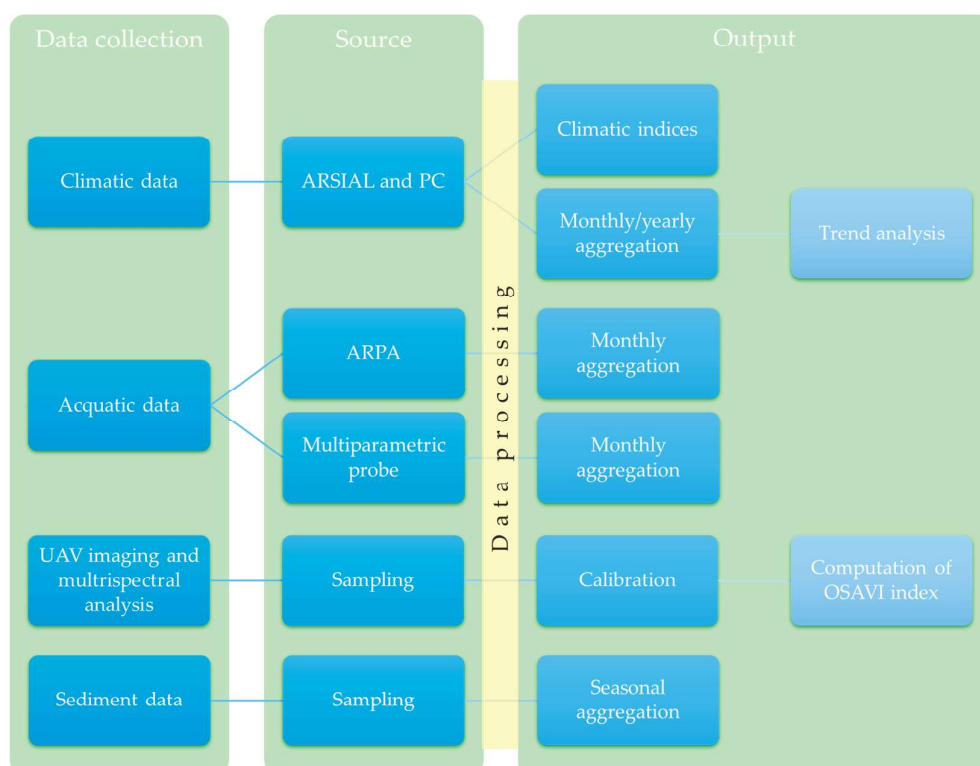
Parameter	Abbreviation (Measurement Unit)	Source	Acquisition Type	Original Temporal Resolution	Spatial Resolution	Period	Derived Indices *	Final Resolution
Air temperatures	Ta (°C)	PC, ARSIAL	Weather station	Daily mean, max and min	Point	1990–2023	FD0, SU30, TR20, CDD	Monthly / yearly mean
Precipitation	P (mm)	PC, ARSIAL	Weather station	Daily total	Point	1990–2023	R0, R1, R10, R20, R50 CWD	Monthly / yearly mean
Water temperature	Tw (°C)	ARPA	Randomized sampling	1–2 sampling per season	Point	2014–2019	–	Monthly mean
pH	pH (pH)	ARPA	Randomized sampling	1–2 sampling per season	Point	2014–2019	–	Monthly mean
Dissolved oxygen	DO (mg/L)	ARPA	Randomized sampling	1–2 sampling per season	Point	2014–2019	–	Monthly mean
Electrical conductivity	EC (µS/cm)	ARPA	Randomized sampling	1–2 sampling per season	Point	2014–2019	–	Monthly mean
Water level	L (m)	ARSIAL	Randomized sampling	Daily mean, max and min	Point	2022	–	Monthly mean
Water temperature	Tw (°C)	Probe	In situ sensor	Hourly	Point	Jul 2022–Sep 2023	–	Monthly mean
pH	pH (pH)	Probe	In situ sensor	Hourly	Point	Jul 2022–Sep 2023	–	Monthly mean
Dissolved oxygen	DO (mg/L)	Probe	In situ sensor	Hourly	Point	Jul 2022–Sep 2023	–	Monthly mean
Electrical conductivity	EC (µS/cm)	Probe	In situ sensor	Hourly	Point	Jul 2022–Sep 2023	–	Monthly mean
Redox potential	Eh (mV)	Probe	In situ sensor	Hourly	Point	Jul 2022–Sep 2023	–	Monthly mean
Salinity	Sal (g/kg)	Probe	In situ sensor	Hourly	Point	Jul 2022–Sep 2023	–	Monthly mean
Global horizontal irradiation	GHI (kWh/m ²)	EU PV-GIS	Satellite-derived dataset	Hourly	Gridded, 0.05° (~5 km)	2005–2023	–	Monthly / yearly mean
pH	pH (pH)	Probe	Randomized sampling	1 sampling per season	Point	May 2021–Aug 2023	–	Seasonal mean
Redox potential	Eh (mV)	Probe	Randomized sampling	1 sampling per season	Point	May 2021–Aug 2023	–	Seasonal mean
Available Phosphorous	AP	Probe	Randomized sampling	1 sampling per season	Point	May 2021–Aug 2023	–	Seasonal mean
Total Phosphorous	TP	Probe	Randomized sampling	1 sampling per season	Point	May 2021–Aug 2023	–	Seasonal mean

* The explanation of these indices is reported in Table 2.

Table 2. Analysed climatic indices from the Expert Team on Climate Change Detection and Indices (ETCDDI) of the World Meteorological Organization (WMO) and United Nations (UN).

ID	Indicator Name	Definitions
FD0	Frost days	Number of days when $T_{min} \leq 0\text{ }^{\circ}\text{C}$
SU30	Hot days *	Number of days when $T_{max} \geq 30\text{ }^{\circ}\text{C}$
TR20	Tropical nights	Number of days when $T_{min} \geq 20\text{ }^{\circ}\text{C}$
R0	Dry days	Number of days when $PRCP < 1\text{ mm}$
R10	Heavy precipitation days	Number of days when $PRCP \geq 10\text{ mm}$
CDD	Consecutive dry days	Maximum number of consecutive days with $PRCP < 1\text{ mm}$
CWD	Consecutive wet days	Maximum number of consecutive days with $PRCP \geq 1\text{ mm}$

* The ETCDDI mainly uses the summer days, i.e., the number of days when $T_{max} \geq 25\text{ }^{\circ}\text{C}$ (SU25), however in this study, SU30 are more suitable for the explanation of extreme climatic events.

**Figure 2.** Workflow of the integrated environmental analysis at Lake Bolsena. The diagram illustrates the different stages of data acquisition, processing, and the final results.

Climate indices were also analysed over the same time frame as the climatic data to evaluate their variation throughout the study period.

To explore monotonic relationships among the measured environmental variables, we applied Kendall's tau correlation [32], a non-parametric method also referred to as a filter method. This measure is based on concordance between observation pairs. This approach identifies the most influential variables by assessing the strength and direction of the relationship between each variable and the response of interest. Correlations were examined between daily air temperature data—maximum (T_{max}) and minimum (T_{min})—and various water quality parameters, including T_w , pH, DO, $Osat$, Eh , Sal , EC , and TDS , as measured by the probe (Multiparameter Probe Tripod, Aqualabo, Champigny-sur-Marne, France) near the archaeological site. Additionally, we quantified long-term temporal trends

in these environmental variables applying the Mann–Kendall trend test [33], a widely used non-parametric method for detecting monotonic trends in time series data. To estimate the rate of change over time, we also calculated the Sen’s slope estimator [34], which provides a robust estimate of the median trend per unit time. In addition to the Mann–Kendall trend test, we also considered the Rescaled Adjusted Partial Sums (RAPS) and Innovative Trend Analysis (ITA) methods [35]. The first method allows for the detection of systematic or anomalous fluctuations in the time series, highlighting turning points and random variations that may not be detected by traditional tests. The second method allows the trend to be analysed without rigid statistical assumptions, through a direct comparison between the first and second halves of the series. This technique is particularly useful for identifying positive, negative, or no trends, even in short or noisy series.

Importantly, the analysis also accounted for potential lagged effects of climatic variables on water quality. In addition to same-day correlations (Lag 0), the influence of Tmax and Tmin one (Lag 1), two (Lag 2), and three days (Lag 3) prior to water parameter measurements was evaluated to capture delayed responses in the lake system.

Global Horizontal Irradiation (GHI) data were retrieved from the European Commission’s PV-GIS database (SARAH3, [36]) for the period 2005–2023. Monthly and annual means were calculated in order to characterize the long-term variability of incoming solar energy, which was used as a proxy for insolation-driven processes affecting lake thermal dynamics and hydrological balance.

All dataset, i.e., climate, water, and sediment were processed using the statistical software R (v. 4.5.1, R Core Team, Viena, Austria). The analyses were performed using the R packages trend, Kendall, and ggplot2 for visualization.

2.3.1. UAV Imaging Analysis and Multispectral Analysis

To investigate spatial patterns in the lakeshore vegetation and assess environmental changes in the vicinity of the archaeological site, a UAV-based remote sensing survey was conducted during the summers of 2022 and 2023. Two aerial platforms were used: a DJI Phantom 4 RTK (Da-Jiang Innovations Co., Ltd., Shenzhen, China) for high-accuracy photogrammetric mapping, and a DJI Phantom 4 (Da-Jiang Innovations Co., Ltd., Shenzhen, China) equipped with a MAPIR Survey 3 OCN (Mapir Inc., San Diego, CA, USA) multispectral camera for vegetation and surface analysis.

The Phantom 4 RTK was deployed at an altitude of 100 m, achieving a Ground Sampling Distance (GSD) of 2.74 cm. It operates with an RTK GNSS correction system and TimeSync technology, ensuring centimeter-level positioning accuracy through NTRIP-provided RTCM 3.2 corrections. This system is compliant with ASPRS Class III accuracy standards for digital orthophotos.

The multispectral survey was conducted at 70 m altitude to improve spatial detail, capturing images in three spectral bands (Orange, Cyan, and Near-Infrared—OCN filter, Mapir Inc., San Diego, CA, USA). The camera integrates a reflectance calibration target and ambient light sensor to enable post-acquisition radiometric correction. The acquired images were processed using MAPIR Camera Control software (MCC v. 20250605, Mapir Inc., San Diego, CA, USA), which applies reflectance calibration and computes a range of vegetation indices. In this study the Optimized Soil Adjusted Vegetation Index (OS-AVI) was applied to detect riparian vegetation, aquatic plants, and potential indicators of environmental disturbance or pollution. The OSAVI is less sensitive to soil brightness than the Normalized Difference Vegetation Index (NDVI)—another widely used index in this field—due to the incorporation of the correction factor L. This characteristic is particularly relevant in the present study, as the submerged nature of the area results in high reflectance disturbances.

All multispectral datasets were calibrated using in-field reflectance targets and then georeferenced to the RTK-based orthomosaic. The resulting outputs were visually enhanced using LUTs (Look-Up Tables) to facilitate interpretation and overlaid with archaeological and environmental data layers for contextual analysis.

This UAV-based workflow allowed for the detection of vegetation health patterns and subtle environmental disturbances in proximity to the submerged structures, supporting the integration of spatial and environmental data in the interpretation of site dynamics.

2.3.2. Sediment Analysis

Sediment samples were seasonally and randomly collected from Spring 2021 to Summer 2023 as reported in detail in Moscatelli et al. [37]. Sediment cores were collected discriminating between WSed, 12 replicates were taken in the vicinity of WAW, at 10 cm depth, and Sed, 12 replicates taken, at the same depth, within the archaeological area but not in contact with WAW. The following properties were measured: pH, redox potential (Eh), and both available and total phosphorus content. Soil pH was determined potentiometrically in a 1:2.5 (*w/v*) soil-to-deionized water suspension using a pH meter (Hanna Instruments Inc., Woonsocket, RI, USA), following the protocol described by Van Reeuwijk [38]. Redox potential (Eh) was measured in a 1:5 (*w/v*) soil-to-deionized water suspension using a commercially available oxidation-reduction potential (ORP) combination electrode connected to a millivoltmeter (Mettler-Toledo International Inc., Greifensee, Switzerland).

The total metal content was analysed using inductively coupled plasma optical emission spectroscopy (ICP-OES) with an Optim 8000 DV instrument (PerkinElmer Inc., Shelton, CT, USA) according to the method described in Sidoti et al. [18]. Total phosphorus content was quantified at its specific emission wavelength of 213.617 nm.

3. Results and Discussions

3.1. Description of Seasonal Climate in Bolsena

Table 3 provides an overview of the climatic conditions in the Bolsena area, which can be classified as sub-Mediterranean due to a brief dry period typically occurring in July and August. During the reference period 2014–2019, the mean annual temperature was 14.8 °C, with a maximum of 40.9 °C recorded in August 2017 and a minimum of −8.3 °C in February 2018. The average total annual precipitation was 840.4 mm, ranging from a maximum of 1140.4 mm in 2014 to a minimum of 531.2 mm in 2017.

With regard to extreme climatic events, it is possible to draw insights into their seasonal distribution. Nearly 70% of days during the summer months (June to August) record maximum temperatures exceeding 30 °C (Figure 3a). Tropical Nights are observed particularly in August, aligning with the elevated temperatures recorded during this period. Precipitation is scarce, or even absent, especially in July (Figures 3b and S2). The number of Consecutive Dry Days (CDD) peaks during the summer, reaching a maximum in August, with 58.97% of days classified as dry (Figure 3c). In contrast, extreme rainfall events are more frequent between September and November and again from March to April, with notable concentrations in November (Figure S2). It is important to note that the wide error bars in Figure 3 reflect substantial interannual variability in the data from 1990 to 2022.

3.2. Temporal Analysis of Bolsena Climate

The time series reveals a clear increase in the total annual number of hot days over the study period. The lowest values were recorded in 2000 (5.5%) and again in 2014 (6.3%). A marked rise in the SU30 is observed after 2014, with peak values reached in 2022 (27.1%) and 2023 (27.7%). In fact, the 2023 data suggest that maximum temperatures exceeded

30 °C for nearly three months (Figure 4a). These results indicate a clear upward trend in the frequency of hot days, with SU30 values reaching their highest levels in recent years, particularly in 2022 and 2023. The SU30 pattern closely mirrors that of Tropical Nights (TR20). Notably, in 2022, the highest percentage of hot days coincided with the peak occurrence of tropical nights (6%). Tropical nights were absent before 1992 and remained infrequent until 2008. The highest recorded values occurred in 2015 (7.7%) and again in 2022.

Table 3. ¹ Monthly cumulative mean of precipitation (P) in the years 2014–2019 in Bolsena; the dataset is from the Italian Service of Civil Defence (PC) and Regional Agency for the Development and Innovation in Agriculture in Lazio (ARSIAL). ² Monthly mean air temperature (Ta) in the years 2014–2019 in Bolsena; the dataset is from PC and ARSIAL.

2014–2019	P (mm) ¹	Ta ² (°C)
Jan	74.5	6.5
Feb	82.8	6.6
Mar	92.1	9.4
Apr	49.9	13.4
May	65.1	16.9
Jun	47.6	21.3
Jul	38.4	24.4
Aug	32.3	24.3
Sep	67.3	20.0
Oct	83.8	15.8
Nov	123.0	11.3
Dec	83.7	7.7
Cumulative	840.4	-
Mean	70.0 ± 24.5	14.8 ± 6.4

In contrast, the number of frost days shows a declining trend (Figure 4a). From 2013 to 2023, frost days consistently remained below 5%, equating to fewer than 20 frost days per year. In 1999, there were 68 frost days (18.6%), whereas in 2023, only five (1.4%). Frost days are closely linked to winter lake turnover, which typically occurs in January–February [21,39], and their reduction is likely attributable to changing climatic conditions that influence this process.

Statistical analysis using the Mann–Kendall trend test confirms these observed patterns, indicating a statistically significant upward trend in the number of summer days ($\tau = 0.469$, $Z = 3.89$, $p < 0.001$) with a Sen’s slope estimate of 0.37 days year^{−1}. Tropical nights exhibit an even stronger positive trend ($\tau = 0.684$, $Z = 5.68$, $p < 0.001$), with a Sen’s slope of 0.12 days year^{−1}, reflecting their recent emergence and increasing frequency. In contrast, frost days show a marked and statistically significant negative trend ($\tau = -0.582$, $Z = -4.82$, $p < 0.001$), with a Sen’s slope of -0.38 days year^{−1}. While the 95% confidence intervals for all Sen’s slope estimates include zero—indicating some uncertainty in the exact magnitude of change—the direction and statistical significance of the Mann–Kendall results provide robust evidence of warming-related changes in seasonal temperature extremes over the study period.

The SU30 curve in Figure 4a indicates not only increased temperature intensity but also an extension of the hot season. After 2015, hot days began to occur in September; after 2020, they were also recorded in May. By 2023, the hot season appears to extend into October. Figure 4b further illustrates the intensification of temperature extremes, reflected in the rising SU30 values, suggesting both more frequent and more intense hot days. This shift may have implications for various ecological and climatic processes in the region.

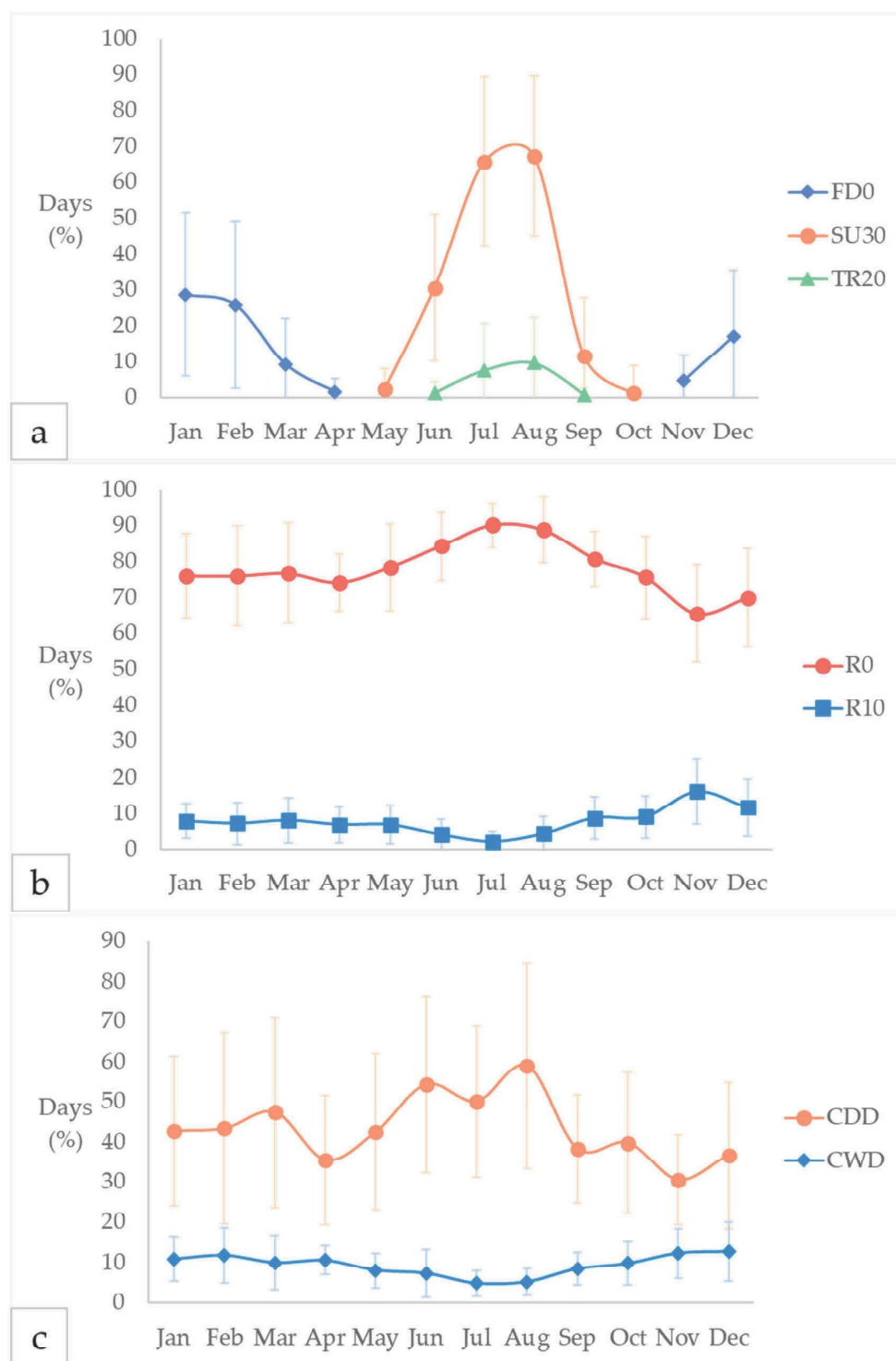


Figure 3. Seasonal climatic analysis of the Bolsena area for the period 1990–2023 (based on ARSIAL and PC datasets). The results are expressed as the monthly percentage of days. **(a)** FD0: Frost days, number of days when $T_{min} \leq 0^{\circ}\text{C}$; SU30: Hot days, number of days when $T_{max} \geq 30^{\circ}\text{C}$; TR20: Tropical nights, number of days when $T_{min} \geq 20^{\circ}\text{C}$. **(b)** R0: Dry days, number of days when $PRCP < 1\text{ mm}$; R10: Heavy precipitation days, number of days when $PRCP \geq 10\text{ mm}$. **(c)** CDD: Consecutive dry days, maximum number of consecutive days with $PRCP < 1\text{ mm}$; CWD: Consecutive wet days, maximum number of consecutive days with $PRCP \geq 1\text{ mm}$.

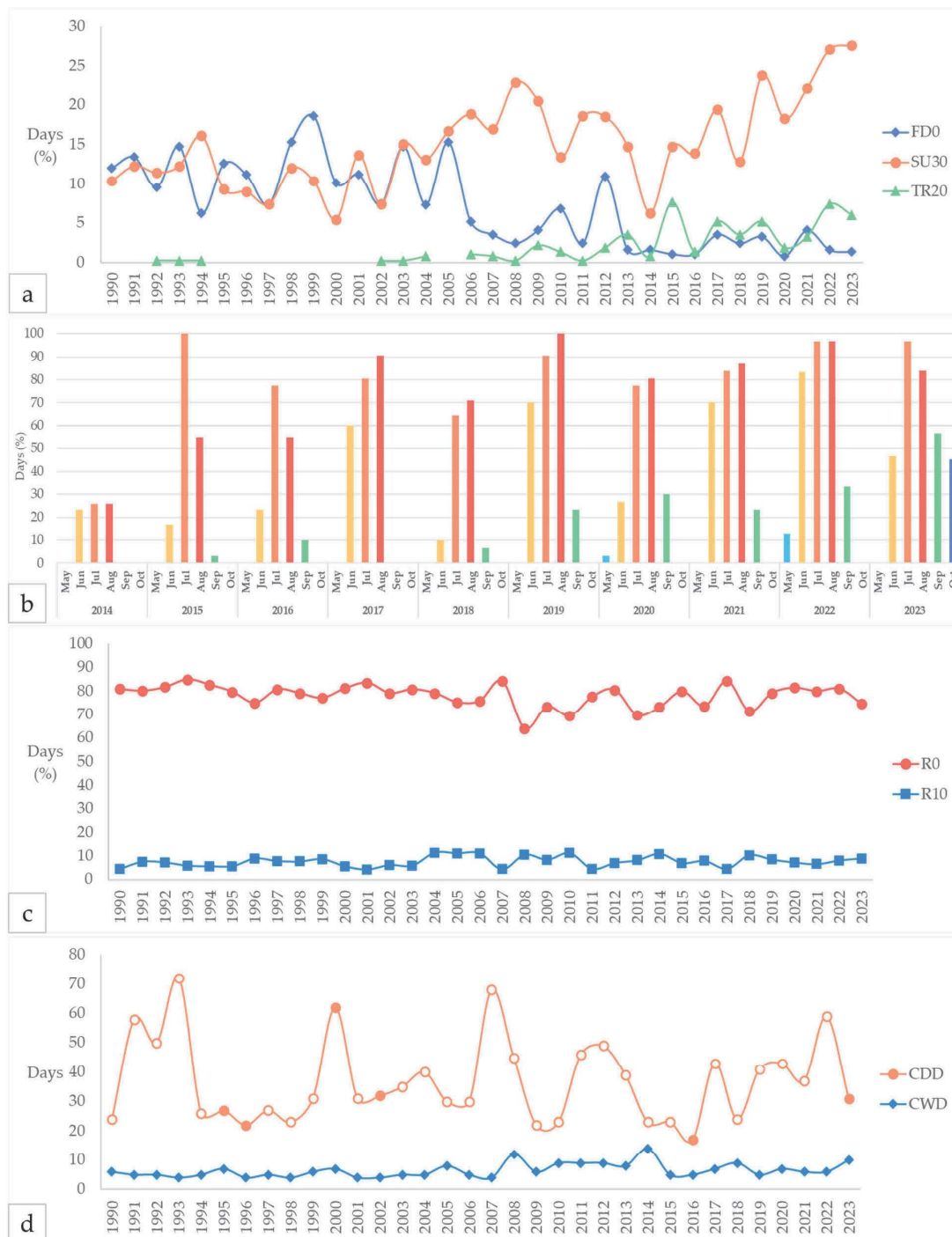


Figure 4. Climatic analysis of the Bolsena area for the period 1990–2023 (based on ARSIAL and PC datasets). The results are expressed as the annual percentage of days. (a) FD0: Frost days, number of days when $T_{min} \leq 0^\circ\text{C}$; SU30: Hot days, number of days when $T_{max} \geq 30^\circ\text{C}$; TR20: Tropical nights, number of days when $T_{min} \geq 20^\circ\text{C}$. (b) Consecutive dry days per month (May–October) in the period 2014–2023. (c) R0: Dry days, number of days when $PRCP < 1\text{ mm}$; R10: Heavy precipitation days, number of days when $PRCP \geq 10\text{ mm}$. (d) CDD: Consecutive dry days, maximum number of consecutive days with $PRCP < 1\text{ mm}$; CWD: Consecutive wet days, maximum number of consecutive, maximum number of consecutive days with $PRCP \geq 1\text{ mm}$; filled circles indicate that the maximum number of consecutive dry days (CDD) occurred during winter, whereas open circles indicate that the maximum occurred during summer.

Despite the broader trend of increasing storm and flood events globally, the study area has not experienced significant extreme events of this type to date [31]. Both the R0 and R10 remain relatively stable, showing no clear increasing or decreasing trend. This suggests that, up to the present, the area has not undergone significant changes in total or extreme rainfall patterns (Figure 4c).

CDD are commonly observed during the summer months, as indicated by open circles in Figure 4d. In some years, CDD also occur during the winter season, represented by filled circles (Figure 4d). A high number of CDD during summer is of particular concern due to elevated temperatures, which pose greater stress on ecosystems and living organisms. Moreover, CDD index has slightly increased since 2014 (Figure S3), contributing to an extension of the hot season, as previously observed for SU30. This stress is further exacerbated by increased evaporation, particularly when prolonged dry periods coincide with tropical nights [8].

In contrast, CWD have remained relatively stable at around seven consecutive days over the past three years. However, there is an indication of an increase in 2023, with up to ten consecutive wet days recorded.

The observed variability in both CDD and CWD may have significant implications for local ecosystems, particularly in terms of thermal stress and water availability, which are critical factors for ecosystem resilience and the survival of aquatic and terrestrial organisms.

The analysis of Global Horizontal Irradiation (GHI) from 2005 to 2023 (Figure 5) reveals the expected seasonal cycle with summer maxima above 220 kWh/m² per month and winter minima around 50 kWh/m² per month. The Mann–Kendall test indicates a weak positive trend (Sen's slope = +0.27 kWh/m² yr^{−1}), though not statistically significant ($Z = 1.33$, $p > 0.05$). Interannual variability, likely linked to short-term meteorological fluctuations such as cloud cover and heatwaves, appears stronger than any long-term directional change in insolation. Years with elevated summer irradiation (e.g., 2011, 2017, 2020, 2022) coincide with warm and dry summers (Figure 4a), higher water temperatures, and reduced dissolved oxygen near the Gran Carro settlement (Section 3.4), highlighting the role of solar input in modulating both atmospheric demand and lake surface energy balance [40,41]. Although the trend is not significant, the persistence of high-irradiance summers has direct implications for lake evaporation and subsequent hydrological and ecological dynamics [42,43].

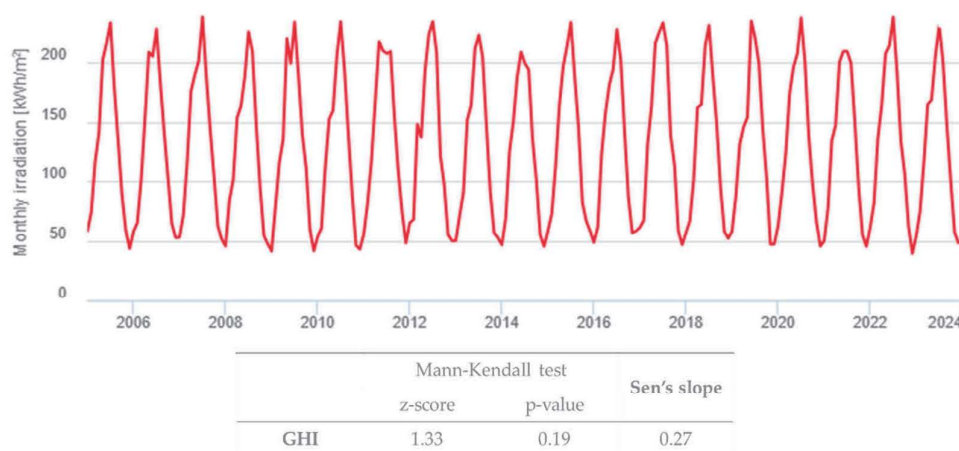


Figure 5. Monthly solar irradiation for Bolsena lake in the period 2005–2023 and relative Mann–Kendall analysis for trend evaluation.

Episodes of intense solar radiation enhance evaporation and stratification, thereby amplifying hypoxia in bottom waters and altering redox-sensitive processes, as reflected in

sediment phosphorus dynamics (Section 3.6; [44,45]). The observed increase in electrical conductivity and salinity during the most irradiated years further supports the role of evaporation in concentrating solutes and modifying lake chemistry. Solar radiation governs the partitioning of energy between sensible and latent heat fluxes [42], and in lacustrine systems up to 60% of incoming shortwave radiation can be converted into latent heat, sustaining evaporation and atmospheric demand [40]. Such irradiance-driven feedbacks not only alter nutrient dynamics and lake metabolism [43] but also accelerate the decomposition of organic matter, including submerged archaeological wood. Periods of strong evaporation and fluctuating water levels expose wooden remains to alternating oxic–anoxic conditions that stimulate microbial and fungal activity capable of degrading lignocellulosic material [46]. Thus, even in the absence of a significant long-term increase in solar radiation, recurrent high-irradiance summers contribute to hydrological imbalance, biogeochemical instability, and increased risks for the preservation of cultural heritage in lacustrine settings.

3.3. Water Data Analysis

Lake Bolsena is classified as a monomictic lake [21], meaning it undergoes a single mixing event of the water column annually. This overturn typically occurs in January or February, during which vertical mixing reaches its greatest depth, usually between late winter and early spring (Figure 5). Thermal stratification begins in April and persists until December [30]. The highest temperatures are recorded in July and August, ranging between 24 and 26 °C. The warmest surface water conditions occur in August, when average temperatures reach approximately 26.5 °C.

Throughout the year, the pH of the epilimnion remains consistently alkaline, never falling below 8—even during the mixing period in early February, which is typically associated with changes in water chemistry. This persistent alkalinity contrasts with other systems where elevated pH has been attributed to high bicarbonate concentrations [47]; however, bicarbonates were not detected in the water column or sediments of Lake Bolsena. The pH remains high—up to 8.8—until December. Notably, Matthiesen et al. [15] reported a surface pH of 7.6 in December, indicating interannual variability.

DO concentrations show distinct seasonal variation. The lowest DO values, around 6 mg/L, are observed during the summer stratification period (July, Figure 6), coinciding with thermal stability and limited vertical mixing. From October to May, DO concentrations are frequently above 9 mg/L, reflecting good oxygenation throughout the water column. According to Björdal and Elam [48] and Salmaso et al. [39] values above 6 mg/L are considered sufficient to support aquatic life, including fish species. These findings suggest that Lake Bolsena maintains generally favorable oxygen conditions during the mixing period, while experiencing oxygen depletion during periods of strong stratification in summer. Indeed, even it is not easy to identify specific trends for the type of data acquisition, as these are spot analyses referring to different periods. A slight upward trend in DO can be observed during the summer months of May, June, July, and August, probably due to a total mixing of the water column between the end of 2018 and beginning of 2019 (Figure 6).

3.4. Water Analysis Close to Archaeological Settlement

The multiparameter probe installed in July 2022 at a depth of 4 metres recorded slightly different conditions compared to the corresponding surface water values measured by the ARPA monitoring unit located on the opposite side of the lake (Figure 7). The analysis of these differences provides insights into the vertical stratification of water properties in proximity to the archaeological settlement.

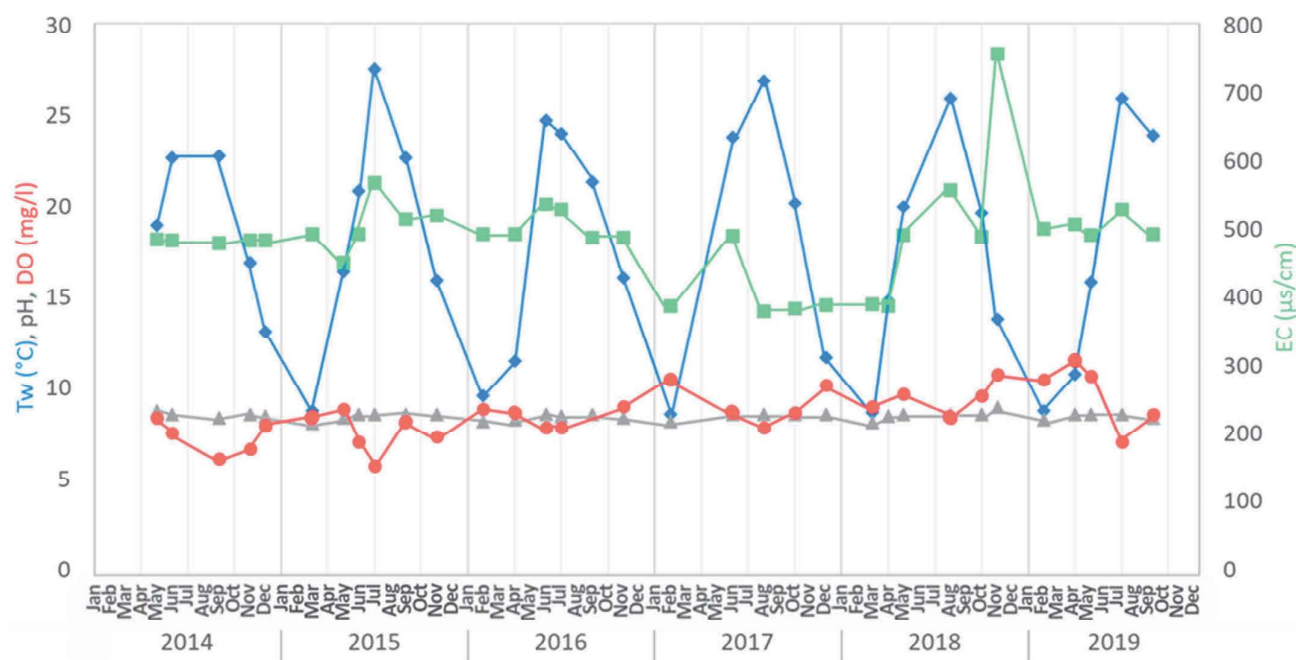


Figure 6. Dataset of water temperature (Tw), dissolved oxygen (DO), pH, and electrical conductivity (EC) for the period 2014–2019, provided by the Regional Agency for Environmental Protection of Lazio (ARPA). All parameters refer to measurements taken in the epilimnion layer.

Figure 7b shows a high redox potential (Eh), which is typical of lentic environments such as lakes [49]. Since the probe is positioned within the epilimnion at 4 m depth, Eh values remain consistently positive. This indicates an oxidizing environment, as oxygen concentrations in the epilimnion are generally higher than in deeper water layers [50].

The year 2022 has been reported as exceptional from a climatic perspective [34]. In that year, Lake Bolsena registered a water level of only 35 cm above the silt layer, compared to the expected minimum of 70 cm required during the same period to prevent water stagnation [51]. The combined effects of extreme heat and prolonged drought are clearly evident in aerial imagery of the Aiola structure, captured by an Unmanned Aerial Vehicle (UAV). Previously interpreted as a ritual platform, Aiola is now hypothesized to be closely associated with nearby hot spring activity. Figure 8b related to UAV acquisition, allows for the identification of various elements within the water using multispectral imagery. Dark green areas correspond to travertine deposits, while light green tones indicate the presence of algae. The shoreline appears yellow due to a reduced algal presence. On the top of the Aiola structure, algae are absent because the water is too shallow; as a result, this area appears red in the OSaVI rendering. In both images of Figure 8b, the upper left corner appears red despite being covered by trees, which should normally appear green. This discrepancy is due to water coverage affecting the reflectance signal and, consequently, the index. However, since the primary aim of this analysis is focused on aquatic features, this issue can be corrected by applying a reclassification of the spectral data. By the interpretation of the UAV imagery (Figure 8a) it can be deduced that Aiola was significantly more exposed in July 2023 than in July 2019. An even greater portion of its upper surface emerged by late July 2022 and early August 2023. On 21 August 2022, a substantial part of Aiola's summit was clearly above water level (the black coloration of the surface corresponds to the stones composing the uppermost layer). Due to strong evaporation, the shoreline appears noticeably closer, indicating substantial water retreat.

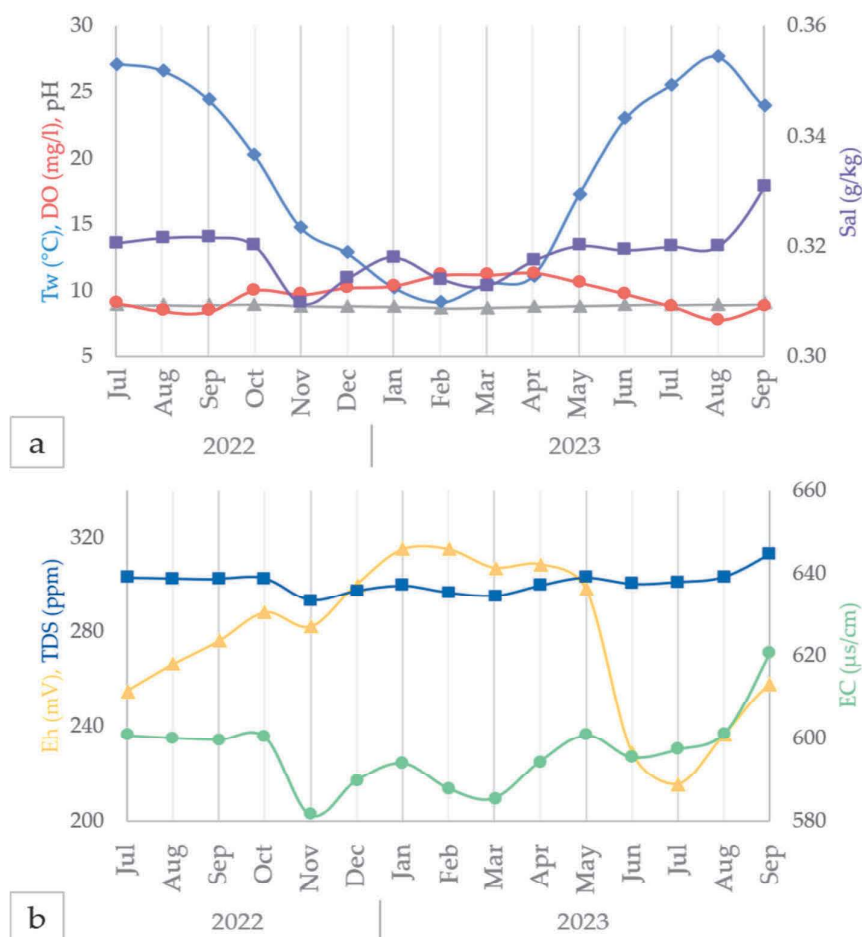


Figure 7. Monthly mean of the analysed parameters monitored by the multiparametric probe. (a) Tw: Water temperature; DO: dissolved oxygen; pH; Sal: Salinity. (b) Eh: Redox potential; TDS: total dissolved solids; EC: electrical conductivity.

Between July 2022 and September 2023, pH values near the archaeological site remained alkaline (Figure 7), with an average above 8 and peak values exceeding 9.10 during the summer, extending through to October 2022. This persistent alkalinity is attributed to elevated water hardness, which was measured at 36.7 °F. In 2002 Mosello et al. [21] reported a mean EC of 400 µS/cm in Lake Bolsena; however, our measurements from 2022 and early 2023 recorded values exceeding 600 µS/cm in the area adjacent to the archaeological settlement (Figure 7), indicating a higher concentration of dissolved ions, likely influenced by some localized hydrothermal inputs but we cannot exclude it might be related to a higher mineralization or anthropogenic input such as agriculture.

Water temperatures were anomalously high, reaching 26 °C in July. DO levels remained above 6 mg/L, indicating satisfactory oxygenation conditions. The winter overturn was evident between January and March 2023, as demonstrated by the combination of high DO levels and low water temperatures (Figure 7).

Figure 9 presents a comparison between temperatures recorded in July and August 2023. On average, temperatures in July are higher than August which are more stable except for the decrease recorded during the last five days of the month. In July there are more pronounced extremes as warm temperatures (with peaks exceeding 40 °C), while in August temperatures were more tightly clustered between 35 °C and 39 °C. To determine whether this difference is statistically significant, we apply the non-parametric Wilcoxon Rank-Sum Test. It confirms the absence of a statistically significant difference between the

two months, indicating no relevant variation in the central tendency of the distributions ($W = 514$; $p\text{-value} = 0.6421$) in 2023. The result is consistent with the abnormal hot and prolonged period in 2023. However, to identify meaningful patterns, it may be beneficial to monitor the behavior of July and August temperatures over a longer time horizon, to detect potential trends or seasonal effects

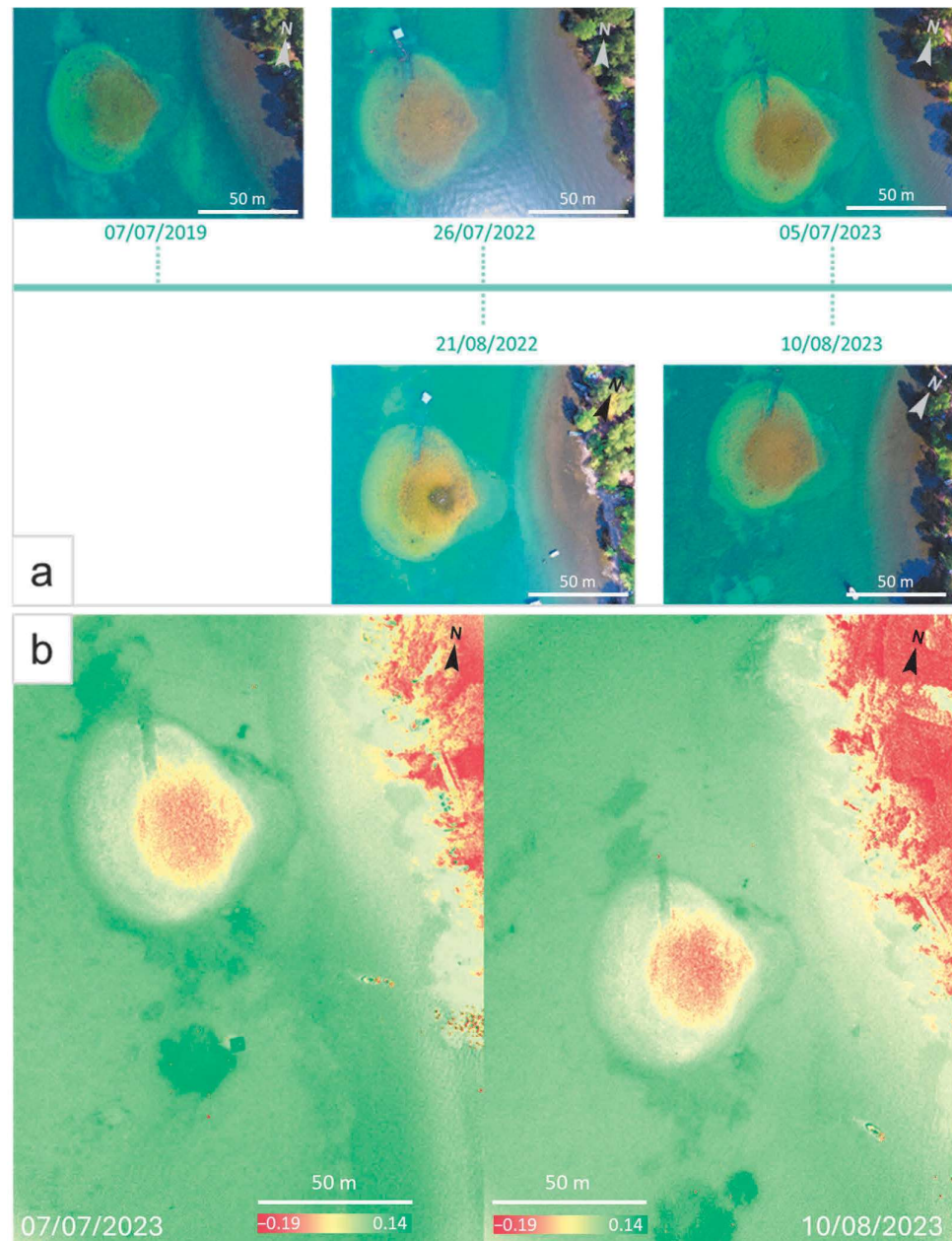


Figure 8. (a) The UAV images illustrate the shoreline fluctuations in the “Aiola” area during the summer seasons from 2019 to 2023. (b) Comparison of multispectral aerial imagery (OSAVI) acquired in July and August 2023, highlighting changes in surface conditions and vegetation stress around the site.

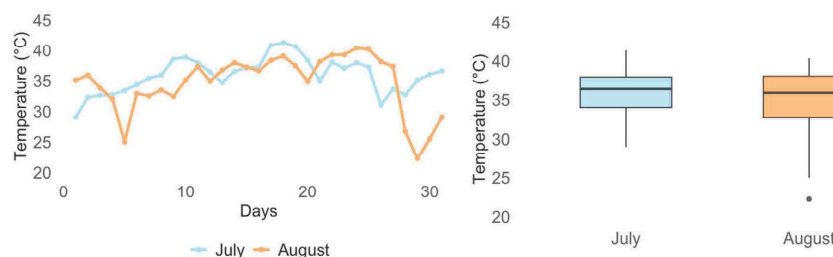


Figure 9. Time series plots and boxplots of daily temperatures recorded in July and August 2023.

The extreme heat events of 2022 likely induced a strong thermal stratification and enhanced water column stability. Increased light availability and phosphorus release from sediments may have favored the proliferation of cyanobacterial blooms [52]. Notably, elevated pH levels during this period may facilitate the mineralization of organic phosphorus. At high pH, hydroxyl ions can displace organic or metal–organic phosphate complexes, promoting phosphorus bioavailability (nutrients availability for organisms) [52]. While these pH changes may not directly harm aquatic organisms, they significantly affect the solubility and availability of key nutrients, potentially exacerbating eutrophication. For instance, increased phosphorus solubility may stimulate excessive algal growth, thereby raising long-term oxygen demand in the system [53].

Di Matteo et al. [54] previously linked water level decline in Lake Bolsena (between the 1980s and mid-1990s) primarily to reduced precipitation. Regarding our analysis, the results of the Mann–Kendall trend test indicate a positive trend with a Sen’s slope of 6.44 mm/year, suggesting a possible increase in precipitation during the period analysed. However, the statistical significance is marginal (z -score = 1.75, p -value = 0.080), and the 95% confidence interval for the slope (−1.06, 14.49) includes zero, indicating that the trend cannot be considered with certainty to be different from zero. This confirms which precipitation is not the main cause of the observed decline in water levels in Lake Bolsena in recent decades, because they do not change significantly. However, it is important to note that even in the absence of a decreasing trend, interannual variability in rainfall can still exert a significant influence on annual changes in lake level, and therefore the correlation between the two phenomena remains relevant. Moreover, the decline in lake level could result not only from climatic factors, such as rising temperatures and evaporation, but also from anthropogenic pressures, such as increases in water withdrawals. In particular, the summer drought of 2022, characterized by an uninterrupted period of 59 days without rain between May and July, reinforces the importance of processes related to rising temperatures in reducing the lake level.

3.5. Correlation Between Climatic and Water Properties

In this section, we analyse the correlation among the inputs listed in Table 4, which encompass different types of data including meteorological parameters, water quality indicators, and water level measurements. Understanding the relationships between these diverse variables is essential to assess the factors influencing lake dynamics. To quantify the strength and direction of the relationships between variables, we use Kendall’s tau correlation coefficient. Unlike Pearson’s correlation, which assumes linearity and normally distributed data, Kendall’s tau method is not parametric and is less affected by outliers and generally more robust with non-normal data. It offers a clearer interpretation as the probability of concordance. It is also less sensitive to ties, providing more stable estimates when many repeated values occur. For small to medium sample sizes, Kendall’s tau tends to be statistically more reliable. In addition, it is particularly suitable for dataset

that includes variables of different natures and units as well as potentially nonlinear or monotonic relationships.

Table 4. Description of variables used in the analysis, including meteorological parameters (temperature and precipitation), water quality indicators, and water level measurements with respective lagged values. Units of measurement are specified for each variable. Lag terms represent values from previous days (lag1 = 1 day before, lag2 = 2 days before, etc.).

Variable	Description	Unit
Tmax	Daily maximum temperature	°C
Tmin	Daily minimum temperature	°C
Tmed	Daily mean temperature	°C
Tmax_lag1	Daily maximum temperature with 1-day lag	°C
Tmin_lag1	Daily minimum temperature with 1-day lag	°C
Tmed_lag1	Daily mean temperature with 1-day lag	°C
Tmax_lag2	Daily maximum temperature with 2-day lag	°C
Tmin_lag2	Daily minimum temperature with 2-day lag	°C
Tmed_lag2	Daily mean temperature with 2-day lag	°C
Tmax_lag3	Daily maximum temperature with 3-day lag	°C
Tmin_lag3	Daily minimum temperature with 3-day lag	°C
Tmed_lag3	Daily mean temperature with 3-day lag	°C
P	Total daily precipitation	mm
P_lag1	Total daily precipitation with 1-day lag	mm
P_lag2	Total daily precipitation with 2-day lag	mm
P_lag3	Total daily precipitation with 3-day lag	mm
Lmed	Daily mean water level	cm
Lmed_lag1	Daily mean water level with 1-day lag	cm
Lmed_lag2	Daily mean water level with 2-day lag	cm
Lmed_lag3	Daily mean water level with 3-day lag	cm
Tw	Water temperature	°C
Osat	Oxygen saturation	%
DO	Dissolved oxygen	mg/L
pH	pH of the water	pH
Eh	Redox potential	mV
EC	Electrical conductivity	µS/cm
Sal	Salinity	g/kg
TDS	Total dissolved solids	Ppm

As expected, the increase in air temperatures is positively correlated with the rise in water temperatures. This effect persists for up to two days after the initial air temperature measurement (day *t*), indicating a thermal inertia of the water body. In fact, thanks to the high specific heat capacity of water, the water absorbs and releases heat more slowly than the surrounding air. Both atmospheric and water temperatures exert a negative influence on dissolved oxygen availability. Notably, minimum air temperatures appear to play a relevant role, potentially linked to climatic stress associated with the Tropical Nights Index. High nighttime temperatures intensify lake water stratification, further restricting oxygen circulation. Indeed, increasing thermal stress is associated with a decline in DO levels and, more prominently, with a reduction in Eh. Redox potential is a measure of the system's capacity to engage in oxidation-reduction reactions. Under extreme conditions, diminished oxygen availability and lower redox values may lead to hypoxia, with detrimental effects on aquatic organisms. During anaerobic phases, stable thermal stratification can inhibit vertical mixing, thereby reducing oxygen penetration into deeper water layers.

The relationship between redox potential, electrical conductivity, and turbidity is complex and context-dependent, governed by the chemical and physical properties of the aquatic system. In general, a positive correlation is observed between redox potential

and conductivity (Figure 10). Oxidizing conditions (high Eh) promote the dissolution of specific ionic species—such as sulphates, nitrates, and metal ions (e.g., Fe^{3+} , Mn^{2+})—thereby enhancing conductivity. Conversely, under reducing conditions (low Eh), processes such as sulphate reduction to sulphide increases ionic concentrations and alter conductivity.

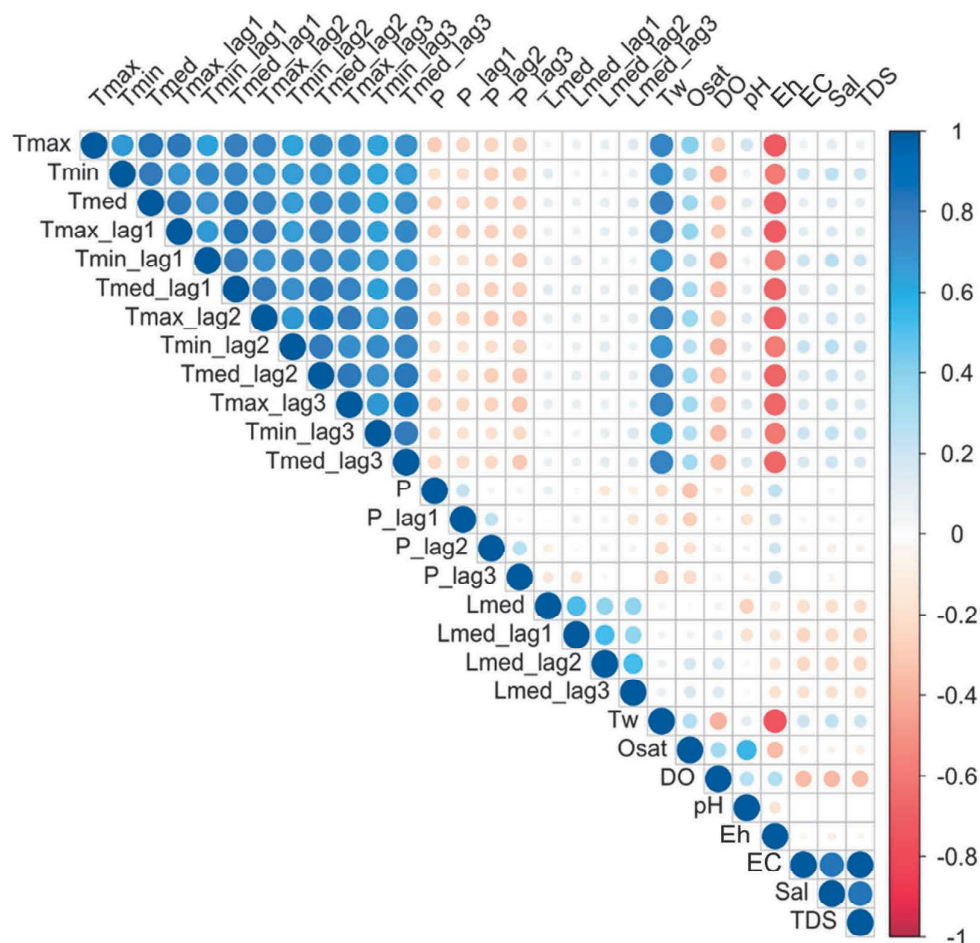


Figure 10. Kendall's tau correlation coefficients for the analysed parameters described in Table 1.

In Lake Bolsena, sulphide species are believed to play a key role in arsenic immobilization through the precipitation of arsenic into insoluble forms [18]. Furthermore, redox dynamics indirectly influence turbidity by affecting the precipitation of compounds. For instance, oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) can lead to the formation of insoluble ferric hydroxides, contributing to increased turbidity. Similar mechanisms may occur for other metals and organic matter.

Changes in redox conditions also regulate microbial community composition, as different taxa dominate under specific redox environments. These microbial processes modulate biogeochemical cycling and can generate organic matter and particulates, further influencing turbidity. Dissolved oxygen is moderately correlated with redox potential—higher DO levels generally support more oxidising conditions. Additionally, DO is negatively correlated with conductivity, salinity, and total dissolved solids (TDS), all of which show strong mutual positive autocorrelation, as expected given the interdependence of these parameters (e.g., conductivity being derived from TDS and salinity).

It is crucial to note that the ecological consequences of redox potential variations depend on both their magnitude and persistence, as well as the limnological characteristics of the lake and its watershed. Prolonged periods of elevated temperature, especially in

summer, should be considered a major environmental stressor. Numerous studies have demonstrated that increases in air temperature can significantly alter lake circulation dynamics due to differential warming of surface and deep layers [55,56].

As observed in Lake Bolsena, these effects may be amplified in lakes with limited hydrological inflows and long water residence times. Therefore, in assessing lake trophic evolution, it is necessary to consider not only catchment-derived nutrient loads but also broader climatic drivers. A long-term trend has already been identified in Bolsena, where alternating drought and flood periods since the early 1990s have disrupted the lake's hydrological regime, leading to reduced inflows [57]. Monitoring redox potential fluctuations is thus essential for evaluating water quality, managing aquatic ecosystems, and anticipating the ecological consequences of climate change.

Table 5 presents the results of the trend analysis based on the Mann–Kendall test and Sen's slope estimation. The findings reveal a statistically significant decline in all temperatures, including $T_{\max}$, $T_{\min}$, T_{med} , and T , as well as for the respective lags up to three days. Negative z scores and consistent slopes (e.g., -0.18 for $T_{\max}$) indicate a steady cooling trend over the period analysed. Daily precipitation (P) and its lags show a slight but significant increasing trend (z -scores between 3.15 and 3.82), albeit with a slope of zero, indicating a possible trend towards more frequent but not necessarily more intense events. The average water level (L_{med}) shows a decreasing trend, with increasing significance in subsequent lags (up to z -score = -3.41), suggesting a progressive reduction over time. Water temperature (T_w) also shows a strong negative trend (z -score = -14.37), consistent with the trend in atmospheric temperature variables. As for oxygen, there is a decrease in saturation (O_{sat} , z -score = -5.80), but a slight increase in DO, (z -score = 5.67), which could reflect a greater capacity of the system to retain oxygen in colder conditions. The Eh shows a clearly positive trend (z -score = 15.07), suggesting increasingly oxidizing conditions over time, while the pH shows a slight but significant decrease. Finally, EC and TDS do not show significant trends, while salinity shows a slight decrease (z -score = -2.14), albeit with a slope close to zero. These results suggest significant climatic and hydrological changes, with potential ecological implications.

The Mann–Kendall trend test and Sen's slope estimator are well-established methods widely used in environmental and climatological research to identify long-term trends in climate variables. These techniques allow for the identification and quantification of consistent directional changes over time. However, these approaches assume a monotonic trend and may be less sensitive in the presence of sudden changes, local fluctuations, or nonlinear behavior. To overcome these limitations and obtain a complete view of the variables under examination, the analysis included two additional methods: RAPS and ITA. In the analyses conducted, the lagged variables (lag1, lag2, and lag3—corresponding to one-, two-, and three-step time lags) were excluded from the RAPS and ITA plots, as the results obtained show trends that are substantially similar to those of the respective original variables (lag0).

Figure 11 shows the results obtained with the RAPS method for the variables under study. Temperatures ($T_{\max}$, $T_{\min}$, T_{med} , T_w , and their corresponding lagged versions at lags 1, 2, and 3) exhibit a pronounced bell-shaped curve, with a peak in the middle of the series (corresponding to the summer months), highlighting a strong seasonality consistent with the annual cycle. This trend is regular, indicating a relatively stable system from a thermal point of view. Precipitation (P and its corresponding lagged versions at lags 1, 2, and 3) is highly fluctuating, with no regular pattern. This suggests dry periods alternating with short rainy events, consistent with an irregular climate. The water level (L_{med} and its corresponding lagged versions at lags 1, 2, and 3) shows a systematic decline, indicating a possible progressive drought, reduced water supply, or

intensification of withdrawals. The behavior of DO (dissolved oxygen) appears as an U-shaped curve, indicating anoxic conditions in the central part of the series (summer), followed by a recovery in cooler periods. In contrast, Osat shows cyclical fluctuations, potentially influenced by photosynthesis or oxygen crises. The variables pH, Sal, and TDS show a consistent upward trend, indicating a progressive shift in water quality marked by increasing alkalinity, salinity, and total dissolved solids. Finally, the redox potential (Eh) follows a U-shaped curve, with the lowest values observed during the summer and the highest in winter, suggesting a seasonal reduction in oxidative conditions during the warmer months.

Table 5. Results of the Mann–Kendall trend test and Sen’s slope estimation for each variable in the analysed period (May–December 2022).

Variable	Mann–Kendall Test		Sen’s Slope
	z-Score	p-Value	
Tmax	−12.54	0	−0.18
Tmin	−10.8	0	−0.1
Tmed	−12.54	0	−0.14
Tmax_lag1	−12.7	0	−0.18
Tmin_lag1	−10.89	0	−0.1
Tmed_lag1	−12.47	0	−0.14
Tmax_lag2	−12.58	0	−0.18
Tmin_lag2	−10.91	0	−0.1
Tmed_lag2	−12.34	0	−0.14
Tmax_lag3	−12.37	0	−0.18
Tmin_lag3	−11	0	0
Tmed_lag3	−12.23	0	0
P	3.55	0	0
P_lag1	3.15	0	0
P_lag2	3.24	0	0
P_lag3	3.82	0	0
Lmed	−2.58	0.01	0
Lmed_lag1	−2.82	0	0
Lmed_lag2	−3.11	0	0
Lmed_lag3	−3.41	0	0
Tw	−14.37	0	−0.11
Osat	−5.8	0	−0.11
DO	5.67	0	0.01
pH	−2.08	0.04	0
Eh	−15.07	0	0.04
EC	−1.48	0.14	0
Sal	−2.14	0.03	0
TDS	−1.45	0.15	−0.18

Figure 12 shows the results obtained with the ITA method for the variables under study. Temperatures (Tmax, Tmin, Tmed, Tw, and their corresponding lagged versions at lags 1, 2, and 3) clearly show a positive trend, with the second half of the series characterized by higher values than the first. This suggests a probable seasonal or climatic effect, consistent with a progressive warming of the period observed. As regards the parameters Osat, DO, pH, Eh, Sal, TDS, there is a clear increase, indicating that the aquatic system underwent significant changes in the second part of the time series. On the contrary, the average water level (Lmed and its corresponding lagged versions at lags 1, 2, and 3) shows a negative trend, highlighting a possible decline in water resources during the period considered, perhaps linked to a reduction in precipitation or increased evaporation. Finally, it should be noted that the precipitation variable (P and its corresponding lagged versions at lags 1,

2, and 3) behaves erratically and does not show a clear trend, due to its high variability and concentration in a few extreme events.

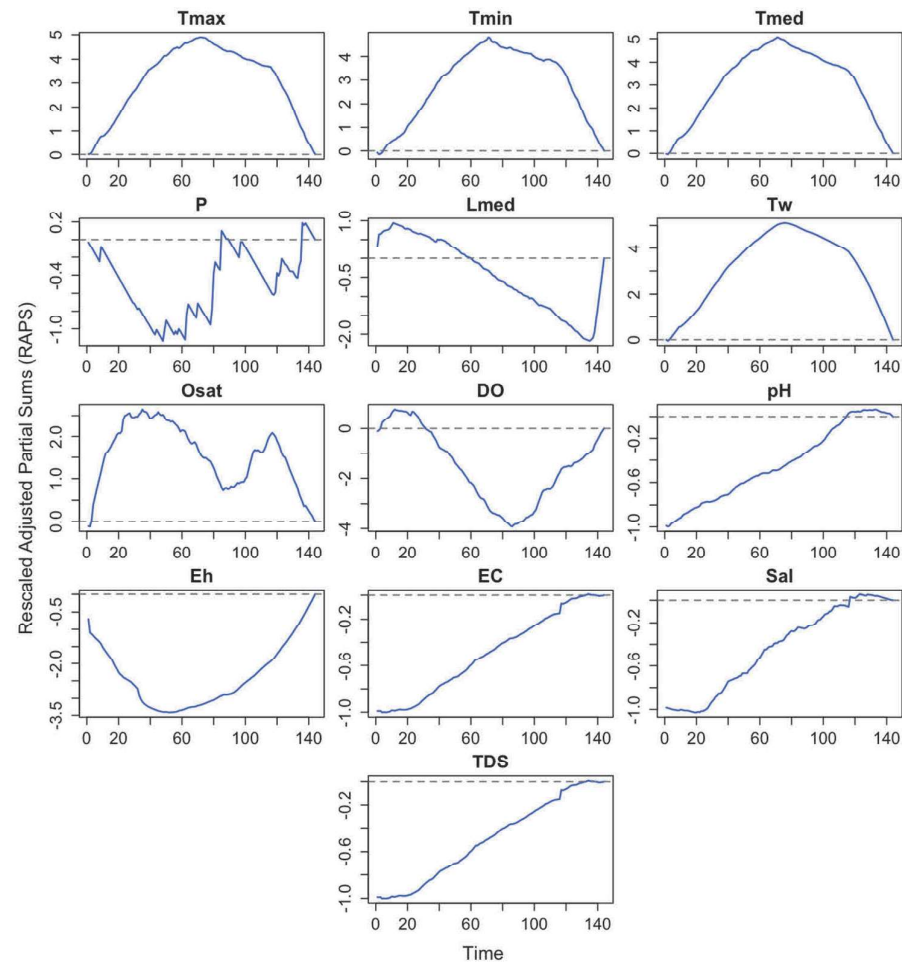


Figure 11. Results of the RAPS analysis for the variables under study.

3.6. Sediment

Sediment quality plays a critical role in the conservation of cultural heritage, as the physical, chemical, and biological characteristics of sediments—particularly in conjunction with the surrounding water—can significantly influence the preservation of archaeological materials [58,59]. Sediments surrounding waterlogged archaeological wood (WAW) often exhibit distinct features in terms of decay evidence, microbial activity and diversity, and chemical composition when compared to sediments unaffected by the presence of WAW. Moreover, sediment properties may undergo alterations due to both natural factors (e.g., climate change) and anthropogenic influences (e.g., overtourism, pollution), which can ultimately impact the rate of WAW degradation. At Gran Carro, sediment sampling was discriminated into WSed and Sed and the hypothesis to be tested was that the sediment surrounding archaeological wood (WSed) showed evidence of decay in terms of chemical composition which differed from the sediment not interested by the presence of WAW (Sed) [37].

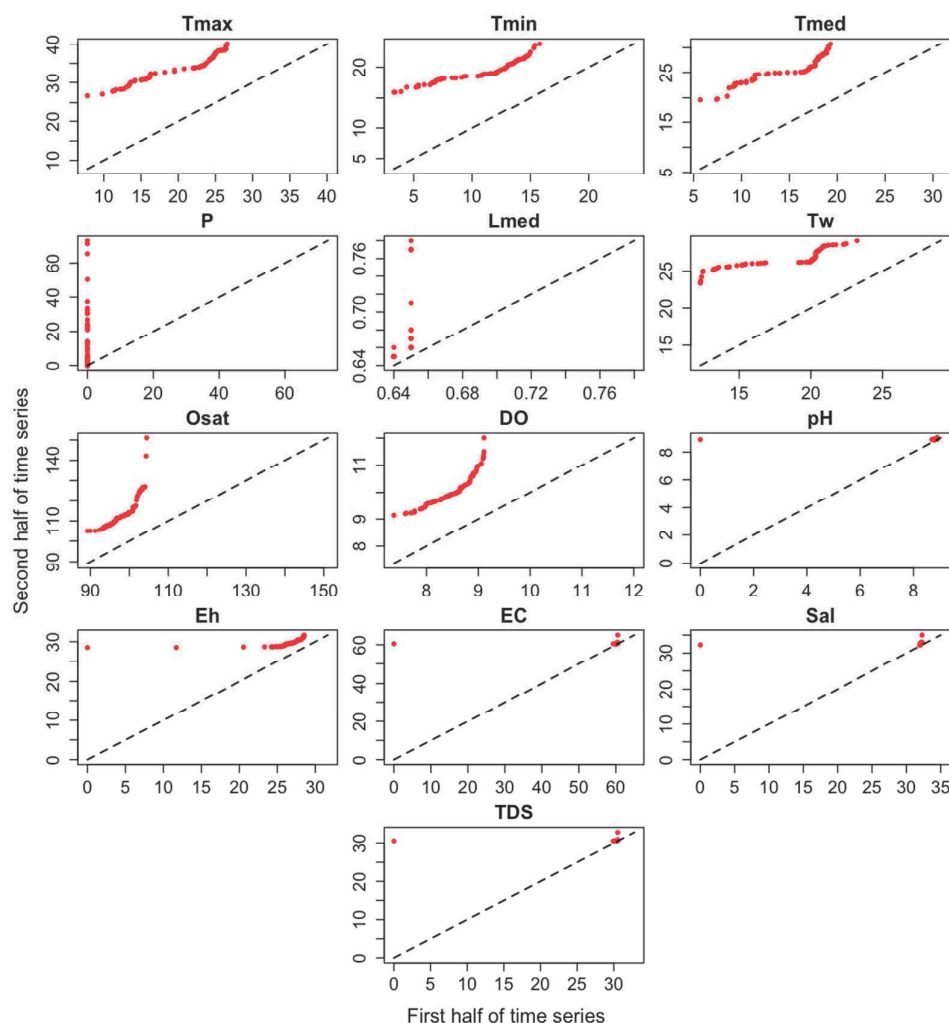


Figure 12. Results of the ITA for the variables under study.

From 2021 to 2023, sediment characteristics were analysed at the Gran Carro archaeological site. The sediments hosting the settlement are predominantly sandy to loamy-sand in texture and exhibited significantly higher organic carbon content in areas in direct contact with WAW (referred to as Wsed), compared to sediments outside this zone (Sed) [18]. Among the key chemical parameters influencing the biological degradation of wood, pH and redox potential (Eh) are particularly relevant. At Gran Carro, sediment pH was classified as neutral to slightly alkaline (according to USDA standards) (Figure 13), while redox conditions were generally suboxic (scarce DO) to anoxic (absent DO) (Figure 13).

Natural fluctuations in these parameters were observed over the three-year monitoring period, likely reflecting seasonal dynamics, varying climatic conditions, and human pressures. Nonetheless, these redox and pH conditions did not inhibit microbial activity. Evidence of consistent nitrification suggests that oxidative microbial processes were ongoing [37]. Notably, a slight but significant acidification and increase in Eh were recorded in Winter 2022 and Summer 2023 in Wsed, possibly reflecting enhanced microbial decomposition near the WAW interface.

Total phosphorus (TP) content in sediments serves as a useful indicator of lake eutrophication. At Gran Carro, sediment TP concentrations ranged from 422 to 545 mg kg⁻¹ [37], corresponding to nominal to moderate pollution levels based on the United States Environmental Protection Agency [60] classification (nominal pollution < 450 ppm; moderate

pollution > 450 ppm). Water column phosphorus levels were consistent with values reported by Mosello et al. [23], who observed an increase from 9 to 16 ppb between 2004 and 2017. These authors concluded that Lake Bolsena had transitioned from oligotrophic to mesotrophic status due to increased external nutrient input.

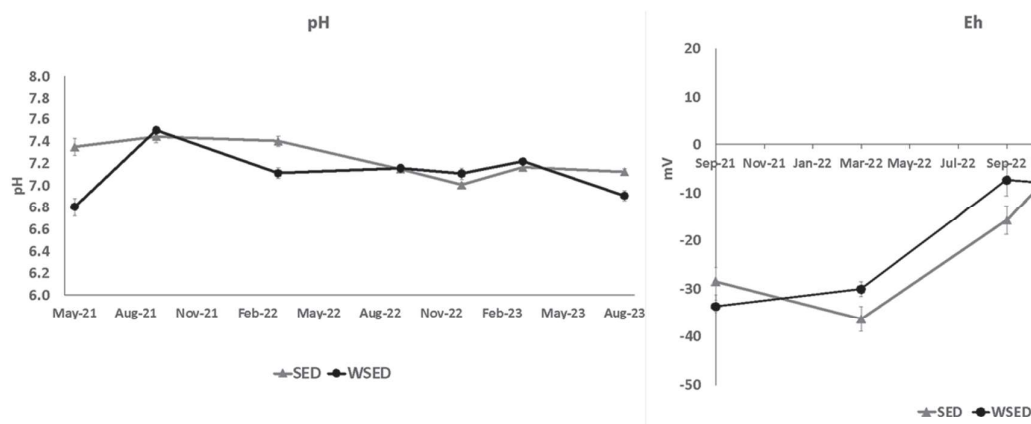


Figure 13. Redox potential (Eh) and pH of sediments measured at the Gran Carro archaeological site from 2021 to 2023. Wsed refers to sediments in direct contact with waterlogged archaeological wood (WAW), while Sed refers to sediments not in contact with WAW.

Furthermore, phosphorus loading in the water may be amplified by reduced redox potential associated with thermal stratification driven by rising temperatures. The reductive dissolution of iron and manganese compounds under low Eh conditions can lead to the release of phosphorus previously bound to these minerals, thus increasing its availability in the water column.

3.7. Possible Scenario for Wood Degradation in Waterlogged Lake Conditions

Waterlogged wood is subject to degradation by wood-decaying fungi and bacteria, primarily classified as erosion and tunnelling bacteria [48]. Soft rot fungi, while tolerant of low oxygen concentrations, still require oxygen to be metabolically active. These fungi can survive across a wide pH range (3–9), with optimal activity between pH 6 and 8; fungal growth is significantly restricted only under highly alkaline conditions (pH 9) [61]. This implies that in the presence of oxygen, fungal degradation of wood remains possible even when pH conditions are suboptimal.

Among bacterial agents, tunnelling bacteria are typically found in wood samples not buried at significant depths, whereas erosion bacteria are more tolerant to oxygen-deprived (anaerobic) environments. Erosion bacteria are particularly effective at degrading wood in the presence of toxic heartwood extractives, which often inhibit fungal colonization. Microbial activity under anoxic conditions promotes the accumulation of sulphur compounds and contributes to environmental acidification [18,62]. Similar considerations apply to ammonium accumulation. Thus, understanding bacterial activity in relation to redox potential, conductivity, and pH is essential for evaluating the preservation potential of archaeological wood [48].

Redox potential values between +100 and +400 mV are generally considered conducive to wood preservation [20]. However, no direct correlation has yet been established between redox potential and actual rates of wood degradation. Therefore, the interpretation of redox, conductivity, and dissolved oxygen values in the context of active decay remains uncertain. Under low redox (reducing) conditions, organic matter decomposition by anaerobic microorganisms can lead to oxygen depletion, which could influence the balance between preservation and degradation.

Each lake habitat possesses intrinsic environmental characteristics that shape distinct bacterial communities [63], leading to specific microbial biogeographies within lake systems [64]. Under projected climate warming scenarios, elevated temperatures are expected to influence bacterial communities, potentially selecting for species that pose a greater threat to wood preservation. Nevertheless, the impact of temperature depends on depth and the nature of the surrounding sedimentary environment.

Experimental attempts to assess the influence of environmental parameters on wood-degrading bacterial activity have yielded inconsistent results. While higher temperatures are known to accelerate the activity of erosion bacteria in laboratory conditions—where they are often used to stimulate decay [65]—there is no conclusive evidence that long-term high temperatures promote decay in natural setting [48]. This is likely due to the interplay of multiple environmental factors, including soil composition, redox potential, and oxygen demand. Previous microcosm studies have shown that increased nitrogen concentrations do not necessarily enhance erosion bacterial activity [59]. Similarly, ammonium concentrations alone may not be predictive of bacterial degradation potential without consideration of Eh, EC, and pH [48].

In the case of Lake Bolsena, sediment analysis revealed heightened biological activity near wooden archaeological remains, consistent with bacterial (particularly erosion bacterial) activity under anoxic conditions. If a general lowering of lake level is assumed—as may result from enhanced evaporation—greater oxygen penetration could occur, accelerating wood degradation. Under such conditions, soft rot fungi, which degrade wood more rapidly than bacteria, may become dominant agents of deterioration.

4. Conclusions

Identifying reliable climatic proxies to characterize the dynamics of lacustrine ecosystems remains a significant challenge, particularly in large and heterogeneous basins such as Lake Bolsena. There is a direct correlation between extreme weather temperatures and the lake's water temperature, with an inertia effect lasting for at least three days. With the increasing frequency of extreme events, a prolongation of this inertia effect should also be expected to month like September and even October. That means we could consider weather data as proxy of water environment. Notably the temperature led to a decrease in redox potential and, although to a lesser extent, in dissolved oxygen.

The aquatic impact on sediments and submerged archaeological wood which are climate-driven changes in lacustrine systems are difficult to track, and our investigation is to pose some milestones which can be considered in more addressed investigations.

Among the physical parameters that exert the greatest influence on water chemistry and biotic activity, DO concentrations between October and May during the period 2014–2019 consistently remained above 9 mg/L, indicating generally favorable oxygenation throughout the water column during the mixing season. Conversely, summer stratification leads to oxygen depletion in deeper layers. A clear inverse relationship between DO and temperature was observed; whereby rising temperatures correspond to decreased oxygen availability in the water. Although variability in precipitation does not appear to directly impact oxygen levels, temperature plays a pivotal role by driving increased water abstraction for agricultural irrigation and intensifying anthropogenic pressures in the catchment. These environmental changes may promote the proliferation of anaerobic wood-degrading microorganisms, such as erosion bacteria, as suggested by sediment characteristics surrounding submerged archaeological wooden poles. Furthermore, enhanced evaporation and consequent reductions in water levels could expose submerged organic remains to aerobic conditions, potentially accelerating their deterioration. However, this process is complicated by the presence of arsenic in Lake Bolsena, which precipitates under reducing

conditions and is known to contribute to wood preservation, thereby adding complexity to the mechanisms governing organic matter degradation in this environment.

This study has a limited temporal resolution of climatic and limnological records, incomplete metadata for some historical datasets nevertheless for the methodological point of view it represents a viable pathway to consider in lake health conditions monitoring. The collection in situ data through submerged probes presents significant challenges, as frequent malfunctions and the high maintenance requirements hinder continuous operation. Leveraging environmental and climatic data from weather stations as proxies—provided that the robustness of the resulting datasets and relationships is further enhanced—offers a more practical and efficient approach for rapid monitoring. Such a strategy can yield valuable insights into changes in the conditions of lake waters, sediments, and preserved organic remains.

Moreover, microbial degradation is a central theme, and the complex results and interlink analysed in our contribute, suggest that it would be helpful in the future to make insights on the microbiological evidence (e.g., microbial DNA analyses or culture-based assessments) in the water lake.

The spatial variability of environmental conditions—driven by climate, anthropogenic pressures, and water abstraction—further complicates extrapolations across the catchment. This is another big issue to be considered especially when great lakes as Bolsena are object of study, therefore the variability are acknowledged as a potential limitation. Applying advanced time series methods, such as RAPS and ITA, to more complete datasets could further improve early detection of abrupt changes.

The submerged poles in archaeological settlements as in Gran Carro site represent an irreplaceable cultural and historical legacy. Preserving this underwater heritage is both a scientific and conservation challenge, and a responsibility toward safeguarding the archaeological identity of the region for future generations in the face of ongoing climate change.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/hydrology12090235/s1>: Table S1: Additional analysed climatic indices of the Expert Team on Climate Change Detection and Indices (ETCDDI) reported in the supplementary materials. Table S2: Monthly mean of water temperature (Tw), dissolved oxygen (DO), pH and electrical conductivity (EC) in the years 2014–2018, data from regional agency of environmental protection of Lazio (ARPA). All parameters are referred to the epilimnion zone. Figure S1: Walter-Lieth diagram of temperature and precipitation in Bolsena in the period 1990–2022. Figure S2: Monthly percentage of rainy days (R0, R1, R10, R20, and R50) for the period 1990–2022 (data from ARSIAL and PC). The highest concentration of rainy days occurs in November, with most events falling into the R1 or R10 categories. Figure S3: Percentage of consecutive dry days per month (May–October), showing a slight increase from 2014 to 2022.

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