



Time Series Analysis of the Physicochemical Parameters and Meteorological Factors in a Mediterranean Lagoon

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Abstract

Global water resources are currently under increasing pressures that lead to their quantitative and qualitative degradation. Humanly imposed modifications of the environment lead to the deterioration of the quality and availability of the water resources, especially of vulnerable coastal, karstic systems. Towards the better understanding of the karst operational mechanisms, time series analysis is often employed, especially in lack of other resources. Under this scope, daily and hourly time-series of physicochemical characteristics (temperature, dissolved oxygen and electrical conductivity) for the period 2011–2015 at an especially vulnerable coastal wetland (Koumoundourou Lake, Athens, Greece) were statistically processed and analysed, so as to investigate the response of the lagoon to the underwater recharging karst system and the driving biological processes. Based on the results, the physicochemical variables are largely controlled by the groundwater inflows or sea water intrusion and macrophytes affect dissolved oxygen fluctuations. Precipitation affects the system after 72–79 days, while meteorological variables affect significantly the water temperature and electrical conductivity of the lagoon. Biological processes and freshwater inflows rather than climate factors seems to affect dissolved oxygen concentrations.

Keywords Automated monitoring survey · Biological processes · Karst · Koumoundourou Lake · Time series statistical analysis

1 Introduction

Global water resources are currently under increasing pressures that lead to their quantitative and qualitative degradation (Wetzel 1992). Humanly imposed modifications of the environment as consequence of industrial sprawl and intensive agricultural activities, together with

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urbanization and other unsuccessful water management strategies, lead to the deterioration of the quality and availability of the water resources and impact the integrity of water bodies. Especially in the case of sensitive ecosystems such as coastal estuaries, lagoons and salt marshes (Ruiz-Luna and Berlanga-Robles 2003) or geologically fragile environments such as karst, which are highly vulnerable to overuse and misuse (Ford and Williams 2007), specialist knowledge is required for proper management.

Towards the better understanding of a karst operational mechanisms, time series analysis is often employed, since it can provide information concerning the hydrologic processes and the physical properties of the system (Geyer et al. 2008). Although discharge and precipitation are the main variables usually used during these analyses, physicochemical parameters are also often employed (Raeisi and Karami 1997) and can provide an insight of the system characteristics, especially in lack of other resources.

Such is the case of Koumoundourou Lake near Athens, Greece, a small coastal lagoon with complex hydraulic conditions, which are controlled by the underwater karstic springs that primarily recharge the lagoon and the seawater intrusion (Dimitriou et al. 2008; Paraschoudis 2002). In order to investigate Koumoundourou Lake, a highly vulnerable coastal lagoon, advanced, automatic and low priced equipment was employed. The main scope of this effort was the better understanding of the system's complex operation and driving biological forces, in order to address social concerns (Fölster et al. 2014). Under this scope, the daily and hourly measurements of the main physicochemical characteristics (temperature, dissolved oxygen and electrical conductivity) from a monitoring station installed at the center of the lagoon were statistically elaborated, so as to investigate the response of the lagoon to the recharging karst system and the biological processes taking place. Additionally, the effect of the temporal meteorological variations to the physicochemical parameters of the lagoon was investigated.

2 Study Area

Koumoundourou Lake is located at the northeastern part of Thriassion plain, west of Athens, Greece, at the foothills of the Aegaleo Mountain (Fig. 1). It is a shallow, rather clear and blackish lagoon with a surface area of 146,500 m² and average depth of about 1.0 m (Mentzafou et al. 2016; Roussakis 2004). The lagoon is separated from Elefsina Bay by a coastal embankment, which is believed to be firstly constructed during 13th–twelfth century B.C. Nowadays the communication between Koumoundourou Lake and the sea is accomplished through an artificial weir, after an intervention proposed by the Agricultural University of Athens, so as to increase the water level of the lagoon and minimize the inflow of polluted groundwater (Dimitriou et al. 2012; Koutsomitros et al. 2001). The weir construction has inevitably affected the hydrological conditions of the lagoon, lead to the reduction of water salinity, and affected the distribution of the submerged macrophytes (*Chara corfuensis*, *Lamprothamnium papulosum*, *Potamogeton filiformis* and *Ruppia cirrhosa*) and reeds (*Phragmites australis*), and the ichthyofauna abundance (*Aphanius fasciatus*, *Gambusia holbrooki* and *Anguilla anguilla*; (Dimitriou et al. 2012; Mentzafou et al. 2016)).

The catchment area of the lagoon is 39.0 km² and has northeast-southwest direction. The climate of the study area can be classified as “Hot-summer Mediterranean” (Csa) with hot and dry summers and mild and wet winters (Dimitriou et al. 2012). The lowland of the basin is mainly structured by quaternary deposits (alluvial deposits, talus cones and scree, torrential fans, marls, sandstones and clays) that overly the moderately karstified dolomite and

limestones. The autochthonous impermeable schists, arcoses and graywackes has limited surface extent (Dimitriou et al. 2008). Koumoundourou Lake is mainly recharged by the underwater karstic springs located northeastern and southeastern which discharge, respectively, the karstic aquifers of Parnitha and Aegaleo mountains (Paraschoudis 2002). Nevertheless, recharge of the lagoon is also accomplished through numerous smaller underwater outlets of the complex karstic system throughout the entire lagoon bottom (Dimitriou et al. 2012), which forbids the direct measurements of the total groundwater that flows into the wetland. The catchment area is highly industrialized and the lagoon is under significant pressures due to the surrounding infrastructures (motorway, heavy traffic local roads, Elefsina port) and various pollution sources ((Mentzafou et al. 2016); Fig. 1).

3 Materials and Methods

3.1 Monitoring Program, Data Collection and Processing

The water quality monitoring program implemented at Koumoundourou Lake was designed following the common practice proposed by World Meteorological Organization (World Meteorological Organization 2013) and Bartram and Ballance (Bartram and Ballance 1996). More specifically, the following procedure was carried out:

- Definition of the objectives: In the specific effort the main objective was to investigate the karst system's complex operation and driving biological processes in the lagoon.
- Preliminary studies: Good knowledge of the study area was necessary for the efficient design of the monitoring program. Therefore, a review of the past surveys conducted in the area was implemented. Based on the literature, Koumoundourou Lake does not stratify, while salinity and temperature are rather uniformly distributed in the water column, with only exception the area of the underwater recharging springs at the northeast part (Papadopoulos et al. 2004). Additionally, the hydrological conditions of the lagoon

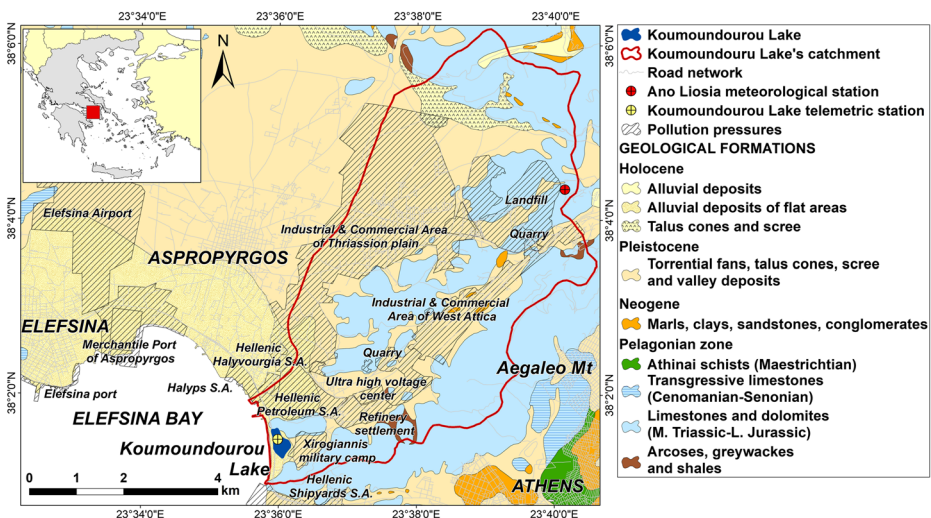


Fig. 1 Koumoundourou Lake catchment and geological structure of the wider area

- have changed after the weir construction that also affected the salinity and macrophytes abundance (Mentzafou et al. 2016).
- Design of monitoring program: Due to the small size of the lagoon, one monitoring station was considered adequate (Bartram and Ballance 1996). Nevertheless, in order to investigate the temporal variations of the water quality in detail, it was decided that small time step was necessary, and therefore, the installation of a telemetric station was appropriate. This technology allows the automatic and financially supported monitoring of the main physicochemical variables of the water with accuracy. In the specific effort, the main physicochemical parameters being monitored were water temperature, electrical conductivity and dissolved oxygen. These variables were chosen based on financial criteria, but also taking into consideration the fact that temperature and dissolved oxygen are two of the most important factors that affect ecosystems and the chemical and biological processes taken place (e.g., (Antonopoulos and Gianniou 2003)), while extreme values of dissolved oxygen (hypoxia and anoxia) indicate degradation (Wolanski and Elliott 2016).

Therefore, in the present effort, hourly and daily time-series covering the period 2011–2015 from the automatic telemetric station (AP-2000 Aquaprobe, Aquaread Ltd) installed by the Hellenic Centre for Marine Research (HCMR), Institute of Marine Biological Resources and Inland Waters (IMBRIW) at the center of Koumoundourou Lake (lon 23.599801°, lat 38.024729 °) were elaborated.

- Data storage, retrieval and distribution: The time series of the telemetric station are automatically stored at an FTP, while the graphical visualization of the dataset is available in real time online (<http://imbriw.hcmr.gr/en/koumoundourou-lake-data/>).
- Quality-assurance procedures: The quality assurance and control of the database involves field operations and data processing operations. Field operations include station installation, maintenance and calibration based on the manufacturer's specifications. Probe was also rinsed after each calibration, because due to the intense biological processes taken place in the lagoon, organic material was frequently attached to the electrodes. Data screening and processing operations were performed by checking the data against specified screening criteria such as the allowable ranges, historical maxima or minima, allowable rates of change, comparison with measurements conducted by different instruments, etc.

Climatic data were available from Ano Liosia automatic telemetric meteorological station, located northeast of the lagoon, which is part of the Hydrological Observatory of Athens network (National Technical University of Athens-Centre for Hydrology and Informatics; <http://hoa.ntua.gr/stations/d/17/>; lon 23.670833°, lat 38.075278°; (Papathanasiou et al. 2013); Fig. 1). Data included air temperature, precipitation, relative humidity, wind speed and sunshine duration at 10 min intervals. The station has the most accurate and detailed meteorological variable dataset in the broader area of the lagoon.

3.2 Time Series Statistical Analysis

The statistical tools employed so as to examine the time variations of Koumoundourou Lake's water physicochemical parameters (water temperature, dissolved oxygen and electrical conductivity) were descriptive statistics, box-plots, correlation matrixes, frequency histograms and

autocorrelogram. Additionally, correlation analysis (autocorrelation, cross-correlation functions) and principal component analysis (PCA) was performed so as to study the relationships between quantitative variables. Finally, bivariate spectral analysis (cross-amplitude, coherency and gain functions) were used so as to investigate the effect of precipitation on water quality and electrical conductivity in particular, assuming that the main factor impacting the latter is the discharge of the karstic, underwater springs that recharge the lagoon.

Statistical analysis was performed with IBM SPSS Statistics v.24.

3.2.1 Correlation Analysis

Autocorrelation is a measure of the linear correlation between successive data series values (Lambrakis et al. 2000). The Autocorrelation Function (ACF) measures the memory effect of the examined variables (Mangin 1984), which is computed on the basis of decorrelation lag time, defined as the time at which the autocorrelation function attains a predetermined value (0.1 to 0.2 based on (Benavente and Pulido-Bosch 1985); 0.2 based on (Mangin 1984)). For the needs of this effort, 0.2 was adopted. Autocorrelation function is represented with an autocorrelogram. The slope of the autocorrelogram is determined by the response of the system to an event. If the event has only a short-term influence on the response of the variables, the slope of the autocorrelogram will have a steep and rapid decrease. However, if the system is influenced by a long-term event, the slope of the autocorrelogram will be gentle (Mayaud et al. 2014). Autocorrelograms were also used to investigate the seasonal variations of the physicochemical parameters. Autocorrelation function (ACF) $r(k)$ is defined as (Eq. 1):

$$r(k) = \frac{C(k)}{C(0)}, C(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(x_{t+k} - \bar{x}) \quad (1)$$

where k is the time lag ($k = 0$ to m), n is the length of the time series, x is a single event, \bar{x} is the mean of the events, and m is the cutting point. The cutting point determines the interval in which the analysis is carried out and is usually chosen to circumscribe a given behaviour like annual or long-term effects (Larocque et al. 1998; Mangin 1984).

In a second approach, cross-correlation function was used, so as to examine the response of electrical conductivity to precipitation. Given that the input stress is an uncorrelated process, such as the daily rainfall, the cross-correlogram between precipitation and electrical conductivity can give information about the response of the system (Larocque et al. 1998; Padilla and Pulido-Bosch 1995). The time lag between lag 0 and the lag of the maximum value of the cross-correlation coefficient (CCF) gives an estimation of the pressure pulse transfer times through the aquifer (Panagopoulos and Lambrakis 2006). If the input signal is a random process, then the cross-correlation function has the form of the impulse response of the system (Mayaud et al. 2014). Cross-correlation function $r_{xy}(k)$ can be defined as (Eq. 2):

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y}, C_{xy}(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(y_{t+k} - \bar{y}) \quad (2)$$

where $C_{xy}(k)$ is the cross-correlogram, and σ_x and σ_y are the standard deviations of the time series (Larocque et al. 1998).

Finally, in order to examine the relationship between electrical conductivity and precipitation, the correlation (Pearson correlation coefficient R) between electrical conductivity and 1 to 90 days cumulative precipitation and 0 to 10 days time lags were examined. Based on the

results, the response of the karst system that recharges the lagoon was examined, assuming again that the main factor impacting the latter is the inflow of the karstic, underwater springs that recharge the lagoon.

3.2.2 Principal Component Analysis (PCA)

A common and simple multivariate analysis that is widely used in environmental sciences is principal component analysis (PCA) (Johnson et al. 2007). The objective of PCA is to determine the minimum number of variables that contain the maximum amount of information and to determine which variables are strongly interrelated, so as to provide a simple interpretation of processes causing variation in variables (Brown 1998). Prior to the analysis, the Kaiser-Meyer-Olkin (KMO) and Bartlett’s test of sphericity were conducted.

In a PCA analysis, a dataset containing p variables, interrelated or correlated to various degrees, is transformed to a new dataset containing p new orthogonal, uncorrelated variables called principal components (PCs) (Eq. 3). The variances of the PCs are the eigenvalues and the coefficients or weights, a_{ij} , are the eigenvectors extracted from the covariance or correlation matrix (Olsen et al. 2012).

$$PC_1 = a_{11}x_1 + a_{12}x_2 + \dots + a_{1p}x_p = \sum_{j=1}^p a_{1j}x_j \tag{3}$$

and so on for all p PCs.

3.2.3 Spectral Analysis

The study of the input and output signals of a system can be investigated with spectral analysis. The cross-spectral density function $S_{xy}(f)$ corresponds to the Fourier transform of the cross-correlation function and can be expressed as a function of the cospectrum $h_{xy}(f)$ and the quadrature spectrum $\lambda_{xy}(f)$ (Eqs. 4, 5, 6):

$$S_{xy}(f) = h_{xy}(f) - i\lambda_{xy}(f) \tag{4}$$

where i is the imaginary unit

$$h_{xy}(f) = 2 \left[r_{xy}(0) + \sum_1^m (r_{xy}(k) + r_{yx}(k))D(k)\cos(2\pi fk) \right] \tag{5}$$

$$\lambda_{xy}(f) = 2 \left[r_{xy}(0) + \sum_1^m (r_{xy}(k) + r_{yx}(k))D(k)\sin(2\pi fk) \right] \tag{6}$$

The cross-spectrum can be expressed as a function of cross-amplitude (CAF) $|S_{xy}(f)|$ and phase $\Phi_{xy}(f)$ (Eqs. 7, 8):

$$|S_{xy}(f)| = \sqrt{h_{xy}^2(f) + \lambda_{xy}^2(f)} \tag{7}$$

$$\Phi_{xy}(f) = \arctan\left(\frac{\lambda_{xy}(f)}{h_{xy}(f)}\right) \tag{8}$$

Finally, the coherence (CF) $CO_{xy}(f)$ and gain (GF) $G_{xy}(f)$ functions are expressed as (Eqs. 9, 10, 11, 12):

$$CO_{xy}(f) = S_{xy}(f) / \sqrt{S_x(f)S_y(f)} \quad (9)$$

$$G_{xy}(f) = S_{xy}(f) / S_x(f) \quad (10)$$

where

$$S(f) = 2 \left[1 + 2 \sum_{k=1}^m D(k)r(k)\cos(2\pi fk) \right] \quad (11)$$

$$D(k) = \left[\left(1 + \cos\left(\pi \frac{k}{m} \right) \right) \right] / 2 \quad (12)$$

The cross-amplitude function indicates the filtering characteristics of the periodic components of the precipitation by the system (Padilla and Pulido-Bosch 1995). A poorly developed karst aquifer with high storage capacity can be considered as an “inertial” filter, while a well developed and connected karst network behaves mostly as a “non-inertial” filter (Panagopoulos and Lambrakis 2006). In the frequency domain, the cross-amplitude function is characterized by a large spectral band which is necessary to attain frequencies higher than 0.2 to get a good filtering effect (Benavente and Pulido-Bosch 1985).

The coherence function shows whether variations in the output time-series respond to the same type of variations in the input series, and thereby expresses the linearity between these time-series (Larocque et al. 1998). The linearity is a characteristic of well developed karst aquifers, where heavy precipitation events lead to almost direct high water discharges through karst springs (Panagopoulos and Lambrakis 2006).

The gain function expresses the amplification (>1) or attenuation (<1) of the input data, attributable to the intervening system (Larocque et al. 1998; Padilla and Pulido-Bosch 1995). In karstic systems, an amplification means release of water from repository, whereas an attenuation means increase of water repository (Amraoui et al. 2003). In gain function, value of 1 represents the duration of “baseflow” in the aquifer, values smaller than 0.4 corresponds to the duration of the “quickflow”, while values between 0.4 and 1 can be attributed to “intermediate flow” of the system (Padilla and Pulido-Bosch 1995).

4 Results

4.1 Descriptive Statistics

The number of valid data per examined parameter were above 1200 except for electrical conductivity (EC, 878 values). The lagoon’s quality relevant parameters (DO and EC) fluctuations indicate a lagoon environment that receives significant volumes of freshwater and probably some organic pollution pressures (25% of the DO measurements were below 2.26 mg/L and 75% of the EC values were higher than 13,505 $\mu\text{S}/\text{cm}$). The total

rainfall for the entire period of study was 2924.3 mm, meaning that the average annual precipitation for the period 2011–2015 was 584.9 mm. Based on the correlation matrix, the relation among the physicochemical and meteorological parameters was significant ($p < 0.01$ or $p < 0.05$) in all cases. Pearson correlation coefficient R between water and air temperature at Koumoundourou Lake can be characterized as very strong (0.941, significant at $p < 0.01$). Also, water temperature was moderately correlated to sunshine duration (0.617, significant at $p < 0.01$) and humidity (-0.615 , significant at $p < 0.01$). Concerning DO, the highest correlation was achieved with electrical conductivity (-0.202 , significant at $p < 0.01$). Finally, electrical conductivity was weakly correlated to humidity (-0.350 , significant at $p < 0.01$), air temperature (0.394, significant at $p < 0.01$) and sunshine duration (0.219, significant at $p < 0.01$) (Table 1).

4.2 Time Variations

Based on Fig. 2a, b, water temperature and DO fluctuate during the day significantly. Both variables gradually increase during the day, reaching the peak at 17:00 or 18:00, and then decrease. The minimum value has been recorded at 08:00 at both cases. The correlation between the two variables was negative, which is evident of the antagonistic effect of high temperature to dissolved oxygen solubility (Table 1). Nevertheless, this diurnal DO concentration fluctuation is typical and not connected to the typical diurnal fluctuation of temperature, and it can be attributed to chemical and biological processes taking place by the biota and photosynthesis during the day, which can lead even to DO oversaturation of water, and respiration during the night (George 1961; Whitney 1942). Such diurnal variation was not observed in the case of electrical conductivity (Fig. 2c).

The seasonal variation of water temperature is evident, with the lowest values being reported in winter (December, January and February) and the highest values in summer (June, July and August). Concerning monthly variation of water temperature, it was noted that it is small, except in the case of the months February and October. Finally, during summer (May to September) most of the values are greater than the mean and median (Fig. 3a, d).

The seasonal variation of DO is small. The maximum value of DO was recorded in July, when the temperature values was also the highest, although the correlation between these parameters was negative (Table 1). This can be attributed to the smaller impact that temperature has on DO, in relation to the photosynthetic processes. During spring and summer the fluctuation is larger, while the highest median value is observed at the beginning of spring (Fig. 3b, e).

Concerning electrical conductivity, the highest values and the largest monthly variations were reported between June and September and the smallest in December (Fig. 3c, f).

Autocorrelograms of water temperature and electrical conductivity showed an evident seasonal pattern with a period of 365 days (Fig. 3g, i). Concerning water temperature, the autocorrelogram showed a negative maximum at time lag 180 (in summer) and a positive maximum at lag 365 (in winter), while concerning electrical conductivity, the autocorrelogram showed a negative maximum at time lag 170 (in summer) and 365 (in winter), and a positive maximum at time lag 270 (in autumn). DO autocorrelogram showed decrease and decay to zero, indicating a non-stationary behaviour of the time-series. The “curvy” shape can be attributed to seasonality (Hyndman and Athanasopoulos 2018); Fig. 3h).

Table 1 Descriptive statistics and correlation matrix of main water physicochemical and meteorological parameters - daily values

	Valid	Water temperature [°C]	DO [mg/L]	E. Conductivity [µS/cm]	Rainfall [mm]	Air temperature [°C]	Humidity [%]	Wind speed [m/s]	Sun duration [min]
Descriptive statistics									
N	1361		1227	878	1828	1828	1828	1828	1828
Mean	467		601	950	0	0	0	0	0
Std. Deviation	21.31		6.90	15.39992	1.60	17.81	44.44	2.10	499.69
Variance	6.42		5.08	2631.39	6.52	7.83	16.37	.90	248.09
Skewness	41.16		25.79	6.924,202.91	42.52	61.23	267.95	.80	61,549.27
Minimum	-434		39	842	7.82	-34	505	.81	-59
Maximum	5.38		.02	11,122.62	.00	-54.84	-13.66	.34	0
Percentiles	32.06		19.52	21,762.88	95.80	35.05	98.28	6.99	832
	16.32		2.26	13,505.47	.00	31.17	31.17	1.44	326.00
	22.52		6.28	14,827.64	.00	16.96	42.86	1.94	542.50
	26.70		11.33	16,790.10	.10	24.76	54.40	2.65	712.00
Correlations									
Water temperature [°C]	1								
DO [mg/L]		1							
E. Conductivity [µS/cm]			1						
Rainfall [mm]				1					
Air temperature [°C]					1				
Humidity [%]						1			
Wind speed [m/s]							1		
Sunshine duration [min]								1	

** . Correlation is significant at the 0.01 level (2-tailed)

* . Correlation is significant at the 0.05 level (2-tailed)

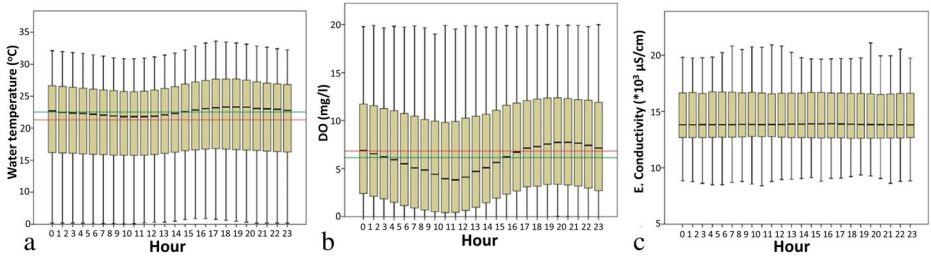


Fig. 2 Hourly box-plots of a water temperature, b DO, and c electrical conductivity of Koumoundourou Lake (red line: mean, green line: median)

4.3 Impact of Meteorological Variations on Lake’s Physicochemical Parameters

Based on the autocorrelograms, the memory effect of electrical conductivity in the system was rather low; ACF overcomes the value 0.2 after 79 days and value 0.0 after 100 days. The autocorrelation function shape of the precipitation decreases rapidly, and the maximum ACF was 0.13 and reached the value zero in 5 days, indicating a random occurrence of the precipitation events (Fig. 4a).

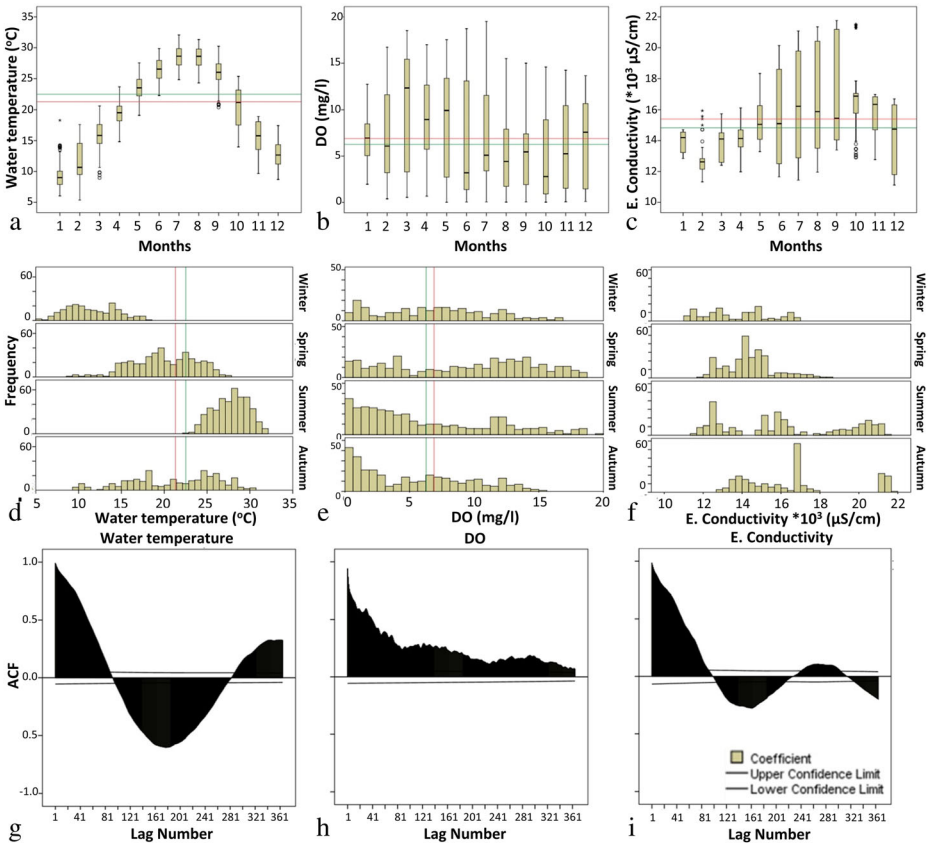


Fig. 3 Monthly box-plots, seasonal frequency histograms and autocorrelogram of water temperature (a, d, g), DO (b, e, h) and electrical conductivity (c, f, i) of Koumoundourou Lake (red line: mean, green line: median)

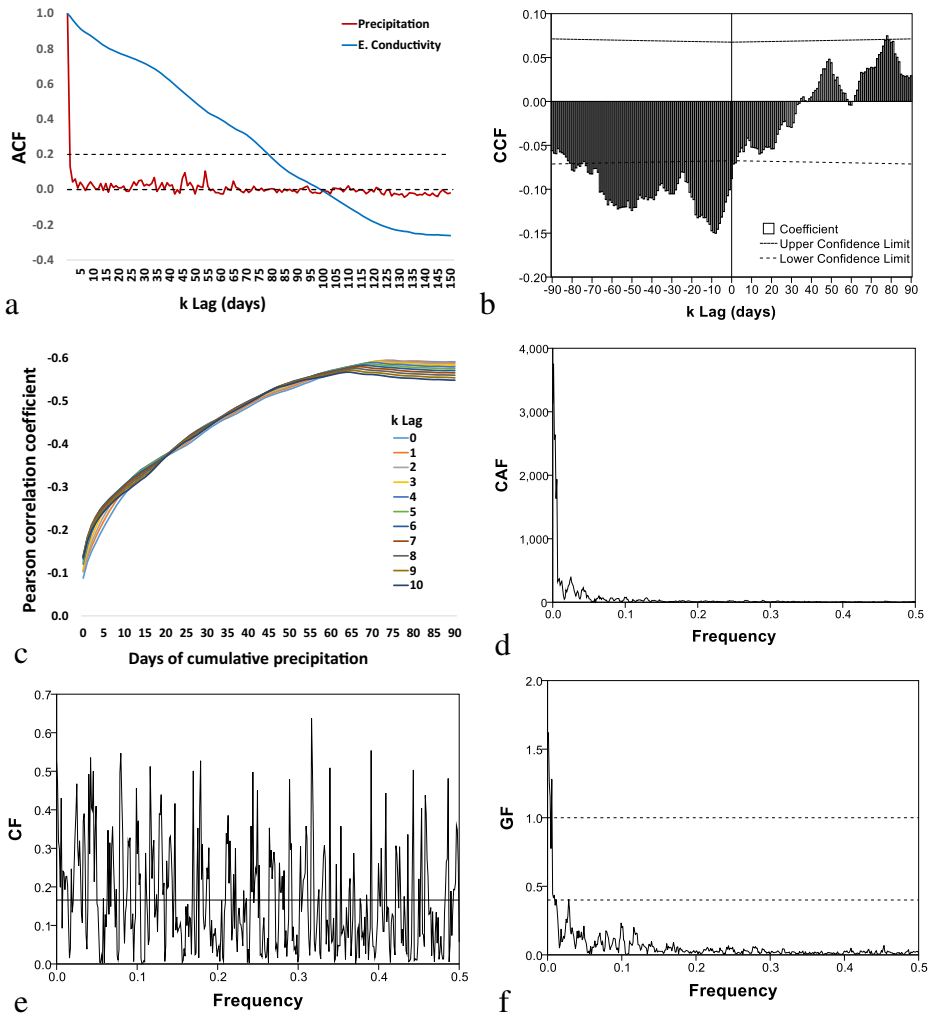


Fig. 4 (a) Autocorrelogram (ACF), (b) cross- correlogram (CCF), (c) Pearson correlation coefficient, (d) Cross-amplitude function (CAF), (e) Coherence function (CF), and (f) Gain function (GF) of electrical conductivity and precipitation

The CCF showed a clear dissymmetry towards the positive values which means that the precipitation affects the electrical conductivity in the lagoon. The highest CCF was achieved after 78 days (Fig. 4b). Additionally, the maximum CCF was relatively low and thus the precipitation input signal was substantially reduced after passing through the system (Larocque et al. 1998).

The best correlation value ($R: -0.596$; p value < 0.00001 , significant at $p < 0.01$) was achieved after 74 days of cumulative precipitation and zero days lag (Fig. 4b).

The cross-amplitude (Fig. 4d) and gain (Fig. 4f) functions confirmed an attenuation of the input signal by the karstic system for frequencies higher than $f = 0.014 \text{ day}^{-1}$ (< 72 days) and an amplification for very low frequencies. The average value of the coherence function (Fig. 4e) was very low (0.17), which indicates that the specific karstic system is not linear.

The PCA analysis explained 60% of the variation in the first two principal components. The first PCA axis (PC1) explained most of the variation of the parameters examined (44%) and was represented mainly by positive influence of air temperature, water temperature, sunshine duration and electrical conductivity and negative influence of humidity. The second component (PC2) showed strong negative association with dissolve oxygen and positive with rainfall and electrical conductivity (Fig. 5). The PCA indicates a strong grouping between air and water temperature, as expected while conductivity is slightly related to wind speed and to a lesser degree to water temperature. DO, rainfall and air humidity cannot be grouped with any other parameter and do not seem to be influenced by the rest of the measured variables.

5 Discussion and Conclusions

During the last decades, vulnerable water bodies such as coastal estuaries, lagoons and salt marshes are imposed to multiple pressures due to anthropogenic modification of the natural environment. Lake Koumoundourou, a small peri-urban coastal lagoon in close proximity to Athens, is an extremely vulnerable water body due to the complex hydraulic conditions, but also due to the geological structure of the wider area, which is characterized mainly by karstified dolomite and limestones. The recharge of the lake is mainly controlled by multiple underwater karst spring, which are not possible to monitor. Under this scope, advanced,

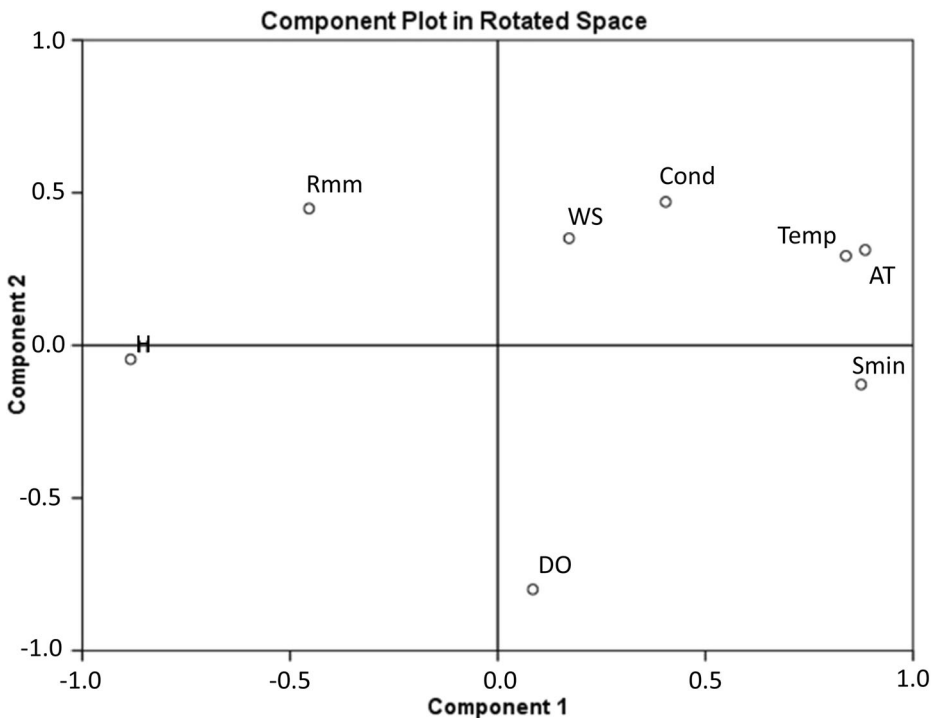


Fig. 5 Principal component plot of the main physicochemical and meteorological time-series at the study area (Temp: water temperature [°C], Cond: electrical conductivity [$\mu\text{S}/\text{cm}$], DO: dissolved oxygen [mg/L], AT: air temperature [°C], Rmm: rainfall [mm], H: air humidity [%], WS: wind speed [m/s], and Smin: sunshine duration [min])

automatic and low-priced equipment was employed, aiming at the investigation of the response of the lagoon to the recharging karst system and the effect of the temporal meteorological variations to the physicochemical parameters of the lagoon. For this purpose, daily and hourly datasets of the main physicochemical characteristics (temperature, dissolved oxygen and electrical conductivity) of the lagoon were employed.

Based on the results, water temperature and DO fluctuate during the day significantly. This diurnal DO concentration fluctuation is typical and not connected to the typical diurnal fluctuation of temperature, and it can be attributed to chemical and biological processes, such as photosynthesis occurring during day and respiration during night by organisms (George 1961; Whitney 1942). Especially at habitat such as Koumoundourou Lake, where the distribution of submerged aquatic vegetation is dense (Dimitriou et al. 2012; Mentzafou et al. 2016), diurnal fluctuation of DO at the near-surface water is mainly affected by biological processes (Frodge et al. 1990) and may lead even to supersaturation of the water in the afternoon (Boyd 2015). The effect of biological processes on the diurnal DO fluctuation has been reported to similar environments in many cases. Cyronak et al. (Cyronak et al. 2014) mentioned that DO trends were consistent with biological drivers, while Wallace et al. (Wallace et al. 2016) reported that DO values in wastewater lagoons were higher during high photosynthetic activity.

The seasonal variation of water temperature and electrical conductivity is evident, with the lowest values being reported in winter and the highest values in summer. This is in agreement with a corresponding seasonal variation of freshwater inflow to the lagoon through the underwater karstic springs, that during high discharge season leads to a decrease of water temperature and electrical conductivity, while during low discharge season seawater intrusion was the main factor affecting the value of these parameters. This effect of water recharge to electrical conductivity or salinity is quite common to similar systems. For example, Psilovikos et al. (Psilovikos et al. 2006) concluded that high water flow rates to the deltaic area of Nestos coincide with low values of electrical conductivity. Menció et al. (Menció et al. 2017) investigated the influence of groundwater to coastal lagoons and salt marshes, and concluded that water salinity was controlled by sea water intrusion and groundwater fluxes, with salinity values decreasing with increasing groundwater recharge. Likewise, Liefer et al. (Liefer et al. 2014) reported that submarine groundwater discharge in a coastal lagoon in the USA was the main source of freshwater affecting water salinity values.

The seasonal variation of DO was small. The fact that during summer DO and electrical conductivity were relatively high is contradicting, since the saturation of DO in water decreases with increasing salinity (Fox 1909) and consequently electrical conductivity. This can be attributed to the smaller impact that temperature has on DO, in relation to the photosynthetic processes of the aquatic vegetation, but also to the smaller groundwater inflow through the underwater karstic springs and the higher recharge with sea water, that has higher concentration of DO in relation to groundwater. During spring and summer the abundance of submerged macrophytes leads to increased DO concentrations due to high photosynthetic processes. During winter, DO concentrations are lower, affected by the higher inflow of groundwater and the absence of aquatic vegetation in the lagoon. Similar phenomenon concerning the fluctuation of DO and salinity (or electrical conductivity) in relation to freshwater inflow and water circulation has also been reported to other lagoons (e.g., (Margoni and Psilovikos 2010)).

Concerning the impact of meteorological variables on the physicochemical parameters of Koumoundourou Lake, based on correlation analysis, precipitation affects the system after 72–

79 days. This can be attributed to the considerable extent of the aquifer which is developed in the intensively karstic carbonate formations that recharge the lagoon with 2.5 months lag time (Mentzafou et al. 2017). The average value of the coherence function indicates that the specific karstic system is quite complex and not linear. Additionally, regarding meteorological variables there is a strong relation between air and water temperature, as expected while conductivity is slightly related to wind speed and to a lesser degree to water temperature. Dissolved oxygen concentrations seems to be affected mainly by biological and photosynthetic processes rather than climate factors. It has been reported that concerning urban lakes, the trophic state is critical on the response of water quality to climatic variation, and that lakes with trophic state better than highly eutrophic, are not vulnerable to variations of meteorological variables (Wu et al. 2014). This is the case of Koumoundourou Lake, the trophic status of which can be classified as oligotrophic based on phosphorus concentrations and as mesotrophic - eutrophic based on Chl-a concentrations (Markogianni et al. 2014), while during the last decade qualitative improvement of water has been recorded (Mentzafou et al. 2016).

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