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THE SEASONAL CHANGES OF THE TEMPERATURE, pH AND DISSOLVED OXYGEN IN THE CUEJDEL LAKE, ROMANIA

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Abstract: Cuejdel Lake, the largest natural barrage water body in Romania and the most recent natural dam lake in Europe, is situated in the Oriental Carpathians. The first small lake in this region formed in 1978 and a second one, which still exists, formed in 1991. Measurements were made in the period 2010 – 2012, with a Hach Lange multi-parameter instrument to identify the physico-chemical parameters of the water. Two basic ecological parameters were assessed, including temperature, pH and LDO (luminiscent disolved oxygen). Cuejdel Lake acts as a dimictic reservoir with direct thermal stratification during the summer, spring and autumn, and reverse stratification during the winter. In the winter, the water freezes with an ice cover of between 25 and 90 cm thick. At the lowest depths, the temperature is constant all year (5°C). The surface water is influenced by the air temperature. In the summer, the water is between 2 and 3°C cooler than the surrounding air. The water is slightly alkaline with values that oscillate around 8. The alkalinity of the water is caused by the elements that are transported in the water as the hydrographic basin drains. The water in the upper section of the lake is very rich in oxygen. However, below 10-11 m, dissolved oxygen is not present. The temperature, pH and dissolved oxygen are correlated during the spring, summer and autumn, but not during the winter (this phenomena is induced by the ice cover). In addition, the relationships between temperature, pH and dissolved oxygen are occasionally disrupted by local factors, such as high depths, high input values, and the existence of vortex currents. The linear tendencies of these three indicators are interrupted by the presence of two thresholds, one at 2 m and one between 4 and 5 m.

Keywords: bathymetry, ecological factors, natural dam lake, physico-chemical parameters.

1. INTRODUCTION

Cuejdel Lake is the largest Romanian reservoir and the most recent natural dam lake in Europe. This reservoir was formed by a landslide that blocked the course of the Cuejdel River. By using modern equipment and highly qualified personnel, several measurements regarding the bathymetry and physico-chemical parameters of Cuejdel Lake were made. The morpho-bathymetrical, hydrological, and climatic parameters and the water dynamics are ecological factors that impact the organisms living in or around the lakes.

Several specific studies have been conducted regarding the geomorphological parameters (genesis, morphology, bathymetry, lake shore dynamics, etc.) of the natural barrage lakes in Romania (Ciaglic, 2005; Gâştescu, 1971; Ichim, 1973; Nicu & Romanescu, 2010; Radoane, 2003; Romanescu, 2009a, 2009b, 2009c; Romanescu & Stoleriu, 2010). However, studies regarding the physico-chemical parameters of water from natural barrage lakes are sporadic and often provide little information regarding mostly temperature, pH and dissolved oxygen (Aplay et al., 2006; Belevantser et al., 2008; Coops et al., 2008; Davis et al., 1990; Duca & Porubin, 2009; Edinger, 1970; Genova et al., 2010; Hachey, 1952; Lampert & Sommer, 2007; Lis et al., 2010; Maberly, 1996; Malm & Zilitinkevich,1994; Maslanka, 2009; Mîndrescu et al., 2010; Moalla, 1996; Moundiotiya et al., 2004; Navodaru et al., 2008; Newcombe & Dweyr, 1949; Nolan & Brigham-Grettej, 2007; Skowron, 2008; Stauffer, 1992; Stefan & Fang, 1994; Sundaram & Rehm, 1972, 1973; Sweers, 1968; Tadesse et al., 2004; Tank et al., 2009; Thakur & Bais, 2006; Wand et al., 1997).

This study attempts to define (for the first time) the thermal stratification of the water in natural barrage lakes and to classify these lakes according to their physico-chemical properties. For this purpose, two reservoirs distinguish themselves in Romania, including the Lacul Cuejdel and the Lacul Rosu. Both of these reservoirs were studied in detail in the Geoarchaeology Laboratory at the Alexandru Ioan Cuza University of Iasi (Enea et al., 2011, 2012; Mihu-Pintilie & Romanescu, 2011, 2012; Romanescu et al., 2012, Romanescu & Stoleriu, 2013).

Cuejdel Lake is located in the Stanisoarei Mountains, which are part of the Central Group of the Oriental Carpathian Mountains. The lacustrine basin occupies the central part of the Cuejdel hydrographic basin in the course of the river where the landslide occurred. The lake input comes from the Cuejdel River and its tributaries, including the Glodu, Fagetu and Piciorul Crucii rivers. Mathematically, Cuejdel Lake is located between 47º01'54" lat. N and 47º02'21" lat. N, and 26º13'70" long. E and 26°13'02" long. E (Fig. 1).

The first landslide occurred in 1978 on the left slope of the Cuejdel River and approximately 1 km from the stream thalweg. In the first stage, the lake had a length of 300 m, a width of 30 m, and a maximum depth of 5 m. Due to the favourable local geomorphology, climate and anthropic influence, the landslide reactivated itself in 1991 when a much larger volume of earth was dislodged. After the landslide in 1991, the largest natural barrage lake in Romania was formed (13.95 ha) (Rădoane, 2003). The water level remains constant at an altitude of 665.5 m. The most well-known natural barrage lakes in Romania are located in the Oriental Carpathians, where few favourable conditions are present to trigger landslides. These lakes include the Rosu (on the Bicaz River), the Iezerul Sadovei and Bolatau (on the Sadova stream), and the Vulturilor (in the Siriu Mountains) (Romanescu et al., 2012). In addition, Cuejdel Lake is also called "Crucii Lake" (Cross Lake).

2. METHODS

To completely understand the limnoecological conditions, 7 sampling and measurement sites were chosen (Fig. 2). These sites cover the entire bathymetrical and morphological spectrum of the lake, including the main river outlet, the maximum depth of the lacustrine basin, and the area around the landslide body. The bathymetrical measurements were collected, with a Valeport Midas Ecosounder. To generate a bathymetrical model of the lake, over 45,000 scanning points were recorded at reading intervals of 0.25 m. This highly detailed scale was used to produce a correct database that would eliminate any suspicions regarding inaccuracies from older analytical methods. In addition, the evolution of the lacustrine basin was overseen in the context of the recent geomorphological changes.

A Hack Lange multiparameter instrument was used for rapid on-site analysis of the physico-chemical factors. Measurements were recorded at the surface and at every meter between the surface and the bottom of the lake. All of the measurements were repeated in the spring, summer, autumn and winter, for each year.

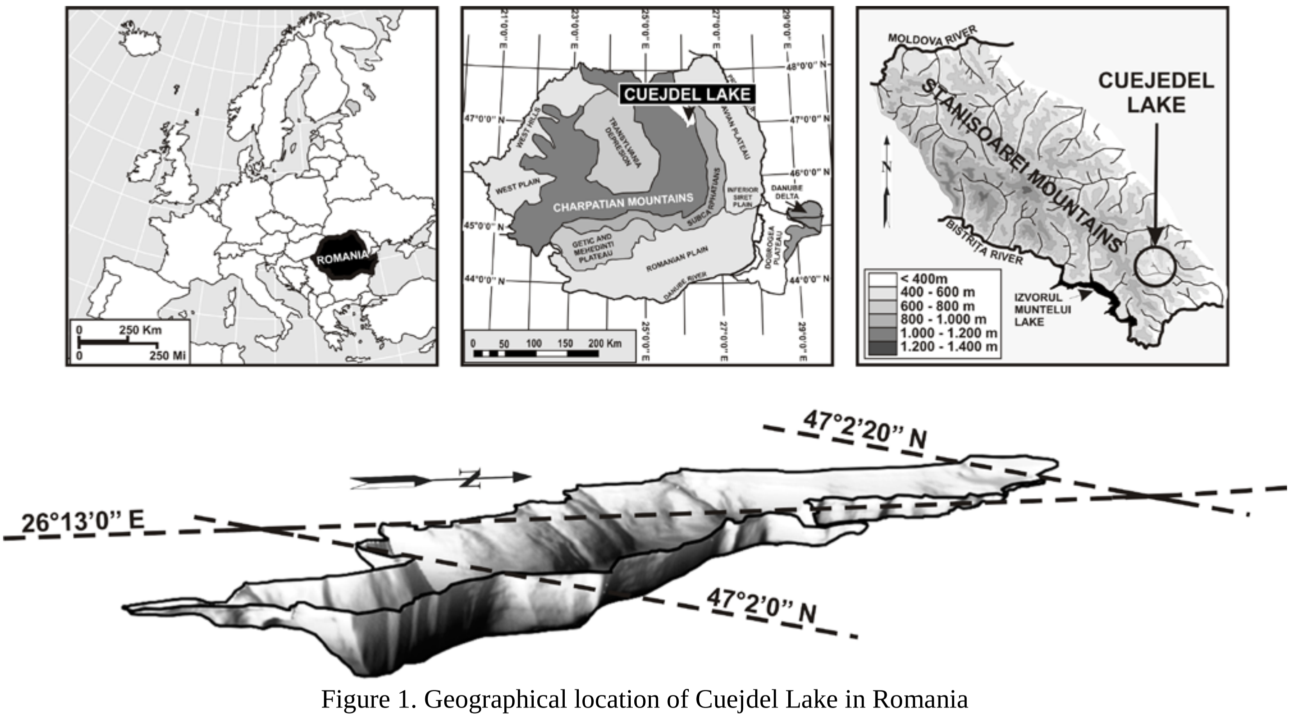

Figure 1. Geographical location of Cuejdel Lake in Romania

During the winter, the ice cover was more than 40 cm thick. With this method, sufficient data were gathered to correctly determine the variable life conditions throughout the volume of water.

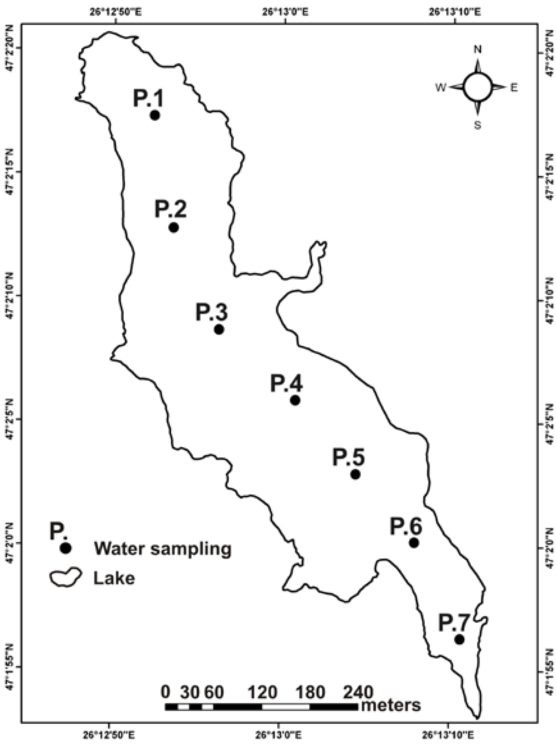

Figure 2. The distribution of water sampling and measurement points in Cuejdel Lake

In addition, the water sampling points were chosen to record the variations that resulted from the streams that supplied the lake. The positioning and synchronisation of the measurement points required the use of GPS. Although a very accurate instrument was used, the measurements could not be performed at exactly the same point every time, mainly due to surface and (especially) deep currents. Thus, the seasonal recordings do not reach the same bathymetrical values during each season. However, these differences can be expressed in centimetres. The data were collected during the day under clear skies between 09:00 and 17:00 h.

3. RESULTS

The thermal, pH and dissolved oxygen values were recorded over the entire depth of the lacustrine basin (from the surface down to a maximum depth of 16.45 m) (Fig. 3). The water level oscillations of the lake were insignificant because the streamflow into the lake was relatively regular and relatively low. The total water volume was calculated to be approximately 925347 m^3 (Table 1).

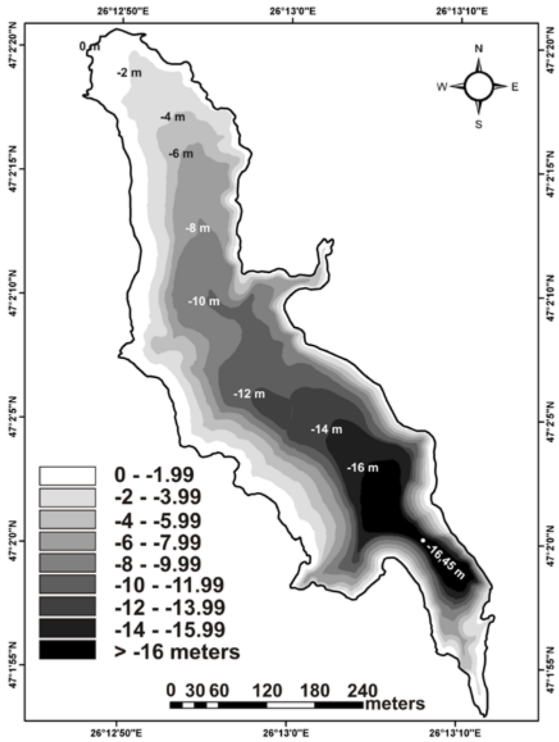

Figure 3. A bathymetrical map of Cuejdel Lake

Table 1. Surface, perimeter, width/length and low/high axis of the Cuejdel Lake

Morphometric elements		Index	Value	Units
Surface		S	13.95	ha
Bottom surface of the lake		S_r	14.3	ha
Length		L	1,004.8	m
Width	Minimum width	$l_{min.}$	19.25	m
	Average width	$l_{med.}$	138.83	m
	Maximum width	$l_{max.}$	282.6	m
Axis	High axis	-	973.76	m
	Low axis	-	299.53	m
Form factor (ratio of axes)		Cf	0.3	-
Perimeter		P	2,801.1	m
Coefficient of shoreline sinuosity		Cs	2.11	-
Depth	Maximum depth	$H_{max.}$	16.45	m
	Average depth	$H_{med.}$	10.1	m
Volume		V	925347	m^3
Volume development		D_v	1.84	-

Most of the shallow areas in the lake were located in the upstream sector near the outlet of the Cuejdel river. In this area, a fan-delta landform was formed. The great fan-delta alluvial type cone tends to occupy an extremely large area. However, illegal local deforestation has accelerated the soil erosion. Thus, the solid flow rate of the Cuejdel River is high, especially during floods when wood that was left by loggers is transported downstream. The maximum depth of the lake occurs near the lake outlet, where the Cuejdel River continues to flow downstream. This deep area corresponds with a circular current that forms during high waters as they meet the landslide body. In this way, the vortex current removes sediment from the bottom of the lake. The lake is deeper near the banks of the left side slope (from where the landslide body descends) than near the right side slope, which has gentler slopes. The right slope inherits the old river valley shape, which was formed by external factors over a long period of time.

The lacustrin basin's morphology causes the physico-chemical water parameters to vary widely. The permanent and the temporary water courses both induce vertical and horizontal differences due to the water that they transport. The slopes that are immediately next to the lacustrine basin are covered with coniferous and deciduous trees. Wetlands are only present in the shallow water regions (generally up to a depth of 50-70 cm).

At the surface, the maximum recorded temperature was nearly 23°C during the summer. Because the low flow of the tributaries generates very little turbulence, this value was the same across the entire lake surface. The minimum temperature in the winter results in the formation of an ice cover, which can reach a thickness of between 25 and 90 cm. Thermal inversions occur due to the general concave character of the landscape. These inversions dramatically decrease the air temperature. Thus, the ice on the lake persists for long periods of time. During the winters, the ice had reached a thickness ranging from 24 to 37 cm. In autumn, the minimum recorded temperature was 13°C. This warm temperature occurred because the large volume of water retained warmth for a long period of time.

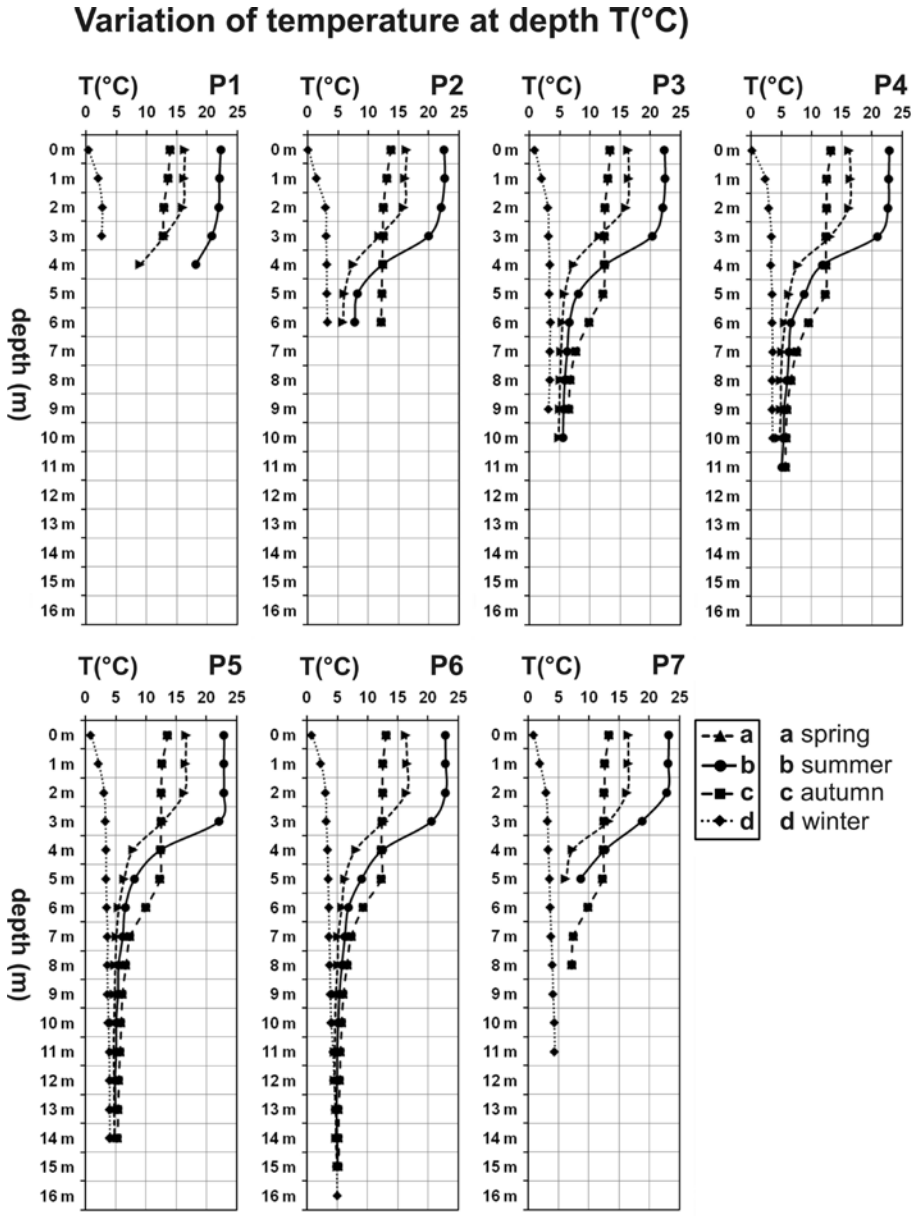

Figure 4. The seasonal and vertical temperature distribution in Cuejdel Lake

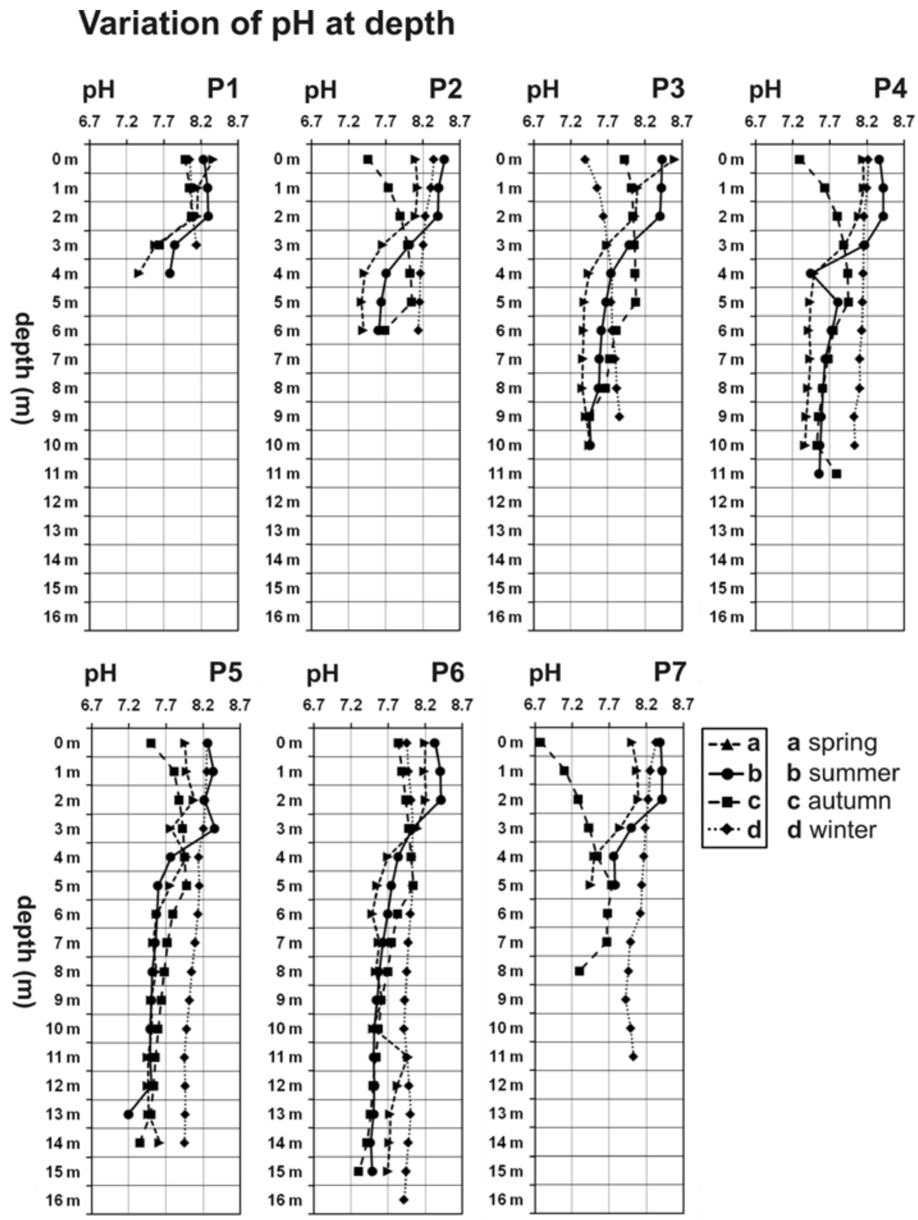

Figure 5. The seasonal and vertical pH distribution in Cuejdel Lake

At a maximum depth of 16.45 m, the temperature is consistently maintained at 5°C. At a depth of 3 m, a sudden drop in temperature occurs during the spring and summer. In the winter, the temperature oscillates between 3 and 4°C at a depth of 2 m. In the autumn, the temperatures are distributed relatively uniformly at all depths. A sudden but small drop in temperature occurred at a depth of 5 m.

In the outlet area of the Cuejdel River (the upstream sector) and around the landslide area, thermal turbulence and large temperature differences occurred between all of the seasons. In addition, turbulence occurs at deeper depths (P1, P2 and P7). From a thermal point of view, the Cuejdel Lake acts as a dimictic reservoir with direct thermal stratification during the summer, spring and autumn with opposite stratification during the winter (Fig. 4).

At the surface, the pH reaches a maximum of 8.6 during the spring and drops to a minimum of 6.7 during the autumn. Usually, the pH values at the surface oscillate between 8.0 and 8.3 (Fig. 5). The minimum surface pH that was observed was 6.7. At the deepest depths, the recorded pH values varied between 7.2 and 8.0 in the autumn and winter. The pH range was greater in the surface water than in the deep water. At a depth of between 2 and 3 m, the pH suddenly decreased from 8.5 to 7.5-7.7. The most obvious turbulence occurred around the landslide body, where the vortex was located. Among other factors, the quantity of dissolved oxygen in the Cuejdel Lake water depended on temperature, water dynamics and quality (Fig. 6). At the surface, a maximum dissolved oxygen concentration of 8.2 mg/L was recorded during the summer and spring.

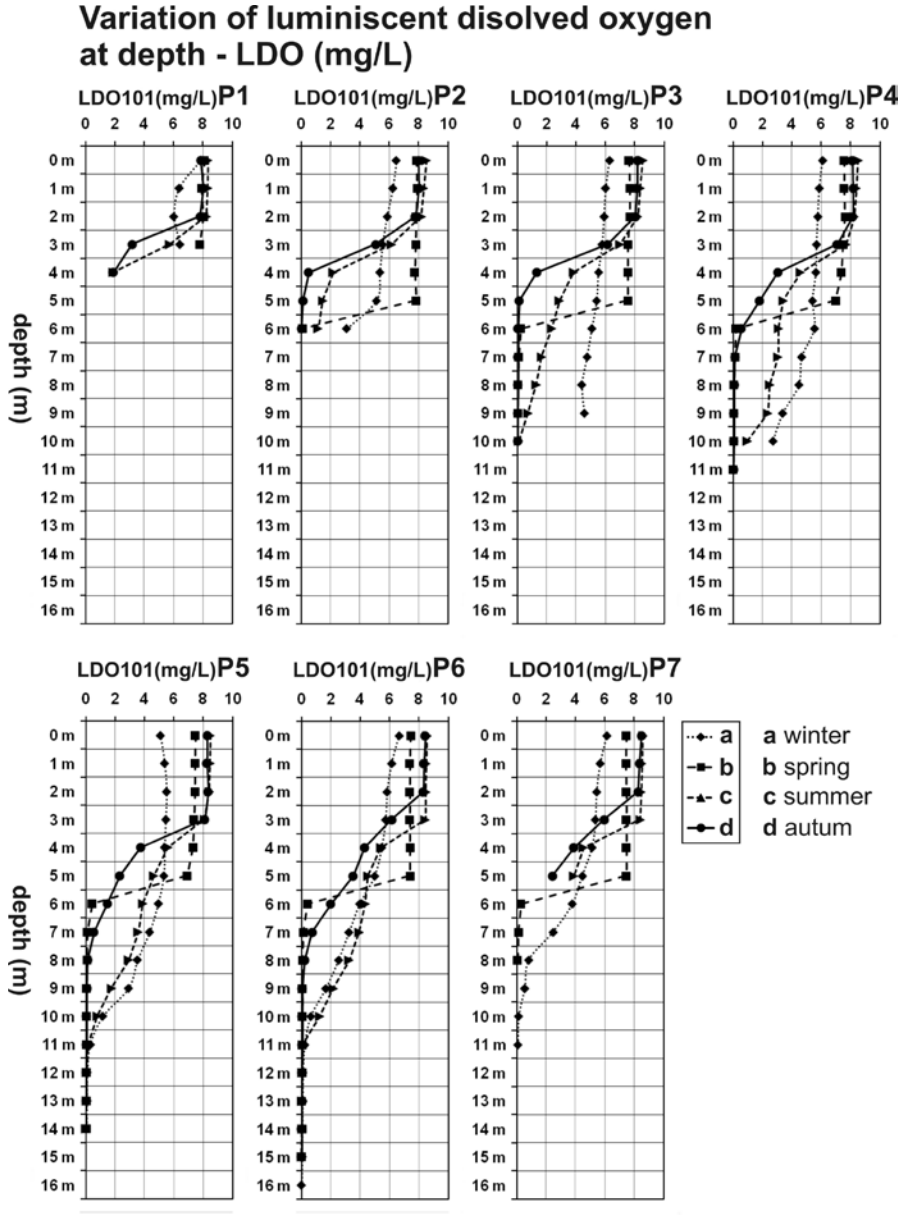

Figure 6. The seasonal and vertical distribution of dissolved oxygen in Cuejdel Lake

The minimum dissolved oxygen concentration was recorded during the winter and was 4.5mg/L. Intermediate dissolved oxygen concentrations of between 7 and 8mg/L were recorded in the autumn. The first sudden decrease in dissolved oxygen concentration was observed at 2 m. At a depth of 4 m, the dissolved oxygen concentrations reached between 2 and 4mg/L. A total deficiency in dissolved oxygen occurred at approximately 6m. On the bottom of the lake, dissolved oxygen was completely absent. During the winter, the vertical dissolved oxygen concentrations are more uniform when ice covers the water.

4. DISCUSSIONS

Because Cuejdel Lake is positioned inside a small concave drainage basin, thermal inversions frequently occur. Thus, the water temperature in the lake is not directly correlated with the air temperatures that are measured at the surrounding meteorological stations. Unfortunately, there are no meteorological stations within the drainage basin that can be used to determine correlations between the mean water and air temperatures.

The maximum surface temperatures occurred during the summer (22.77°C) and spring (16.45°C) (Fig. 7a, 7b). In addition, the low flow rates of the water resulted in a high flowing water temperature. Because of the low flow rate, the water temperatures were relatively uniform across the entire surface of the lacustrine basin. In addition, the spring and summer temperatures follow the same trendline and are very similar. The maximum water temperature is a few degrees (2-3°C) lower than the air temperature.

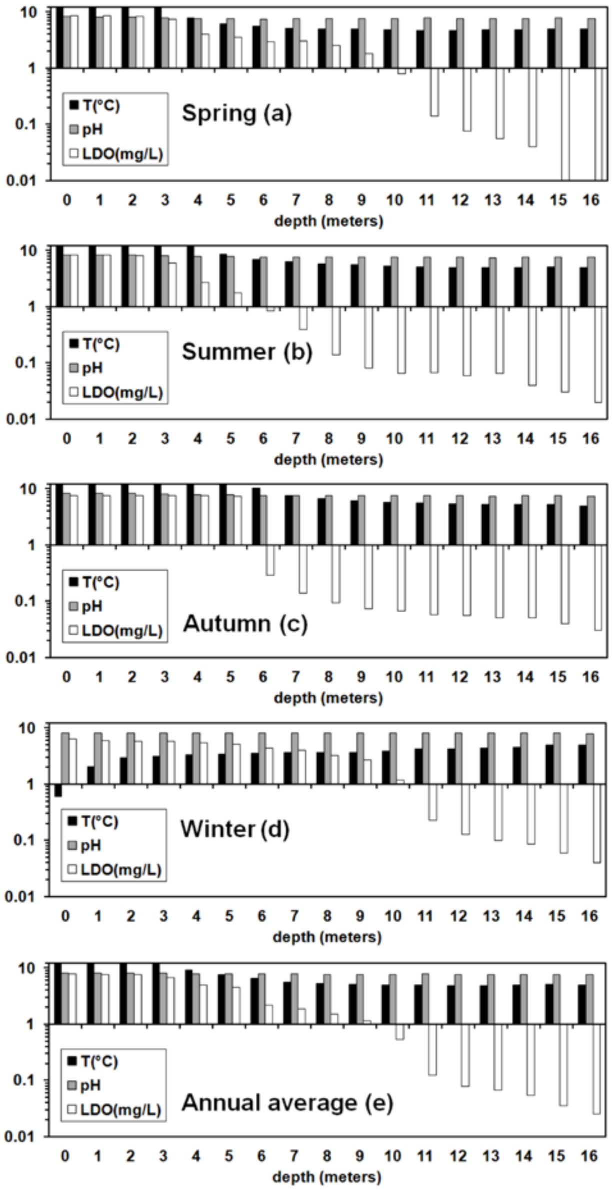

Figure 7. The vertical distribution of temperature, pH and dissolved oxygen during the (a) spring, (b) summer, (c) autumn, (d) winter and (e) annual average

In the autumn, the surface temperatures fluctuate between 13 and 14°C (Fig. 7c). During the winter, ice covers the entire surface of the lake (Fig. 7d). This ice can reach a thickness of up to 90 cm. Generally, the thickness of the ice is uniform across the lake surface. This uniform ice thickness occurs due to the presence of fossilised tree trunks, which are scattered across the entire surface of the lake, especially in the centre.

The gradual decrease in temperature with increasing depth is directly related to the exterior temperature. The existence of relatively uniform temperatures is determined by the thermal homogenisation of the water. The recorded temperature differences in the summer and autumn were low (3-4°C).

The vertical homogenisation of temperature during the autumn supports an interesting fact. During the autumn, temperatures of between 13 and 14°C occur on the surface and a temperature of 11°C occurs at a depth of 5 m. These homogenised temperatures could result from the higher stream flow rates that occur during the autumn, the existence of local winds that descend from the nearby slopes, and the disappearance of vegetation. All of these factors result in nearly perfect thermal homogenisation.

This thermal homogenisation is weaker during the winter with a temperature gap of 1-2°C for values of 4-5°C. Temperatures are maintained at 0-2°C at a depth of 1 m due to the ice cover in the winter. At a depth of 2 m, the temperatures quickly increase and reach between 2 and 2,5°C. At a depth of between 3.5 and 4 m and at the bottom of the lake, the temperature increase up to 4-5°C. In contrast, in the spring, summer and autumn, the temperature decreases with increasing depth (Fig. 7d). The formation of the ice cover does not allow the formation of a lacustrine winter microclimate. In the spring, summer and autumn, the temperature is approximately 5°C at a depth of more than 9-10 m.

At the surface, the pH oscillates approximately 8.0. During the spring, summer and winter, the pH of the water is relatively consistent with depth. However, in the autumn, the pH tends to increase with increasing depth. At the deepest depths, the pH is consistently between 7.2 and 8. However, at a depth of 16 m, the pH reaches 7.9.

The pH of the water depends on the nature of the water that is collected from the streams in the drainage basin. Thus, the geological composition and mineralogical nature of the rocks significantly impact the pH. In addition, the variable pH values depend on the properties of the water that is transported in the permanent and temporary drainage networks.

Clear differences in pH occurred in the autumn and winter (relative to the spring and summer). In the spring and summer, the pH is maintained at approximately 7.3-7.4. However, in the autumn and winter, the pH slightly decreases with depth but reaches values of between 7.8-8 (P3 and P4). During the spring and autumn, surface pH readings exceed 8. However, in the autumn and winter, the pH does not exceed 8. The pH of the water was slightly alkaline throughout the year (between 7.5 and 8.0) (Fig.7e). The pH value was occasionally circumneutral, but only during certain conditions.

The presence of dissolved oxygen is vital for life in a body of water. Despite this, Cuejdel Lake does not have a large amount of biological diversity because it was formed recently (from 1978).

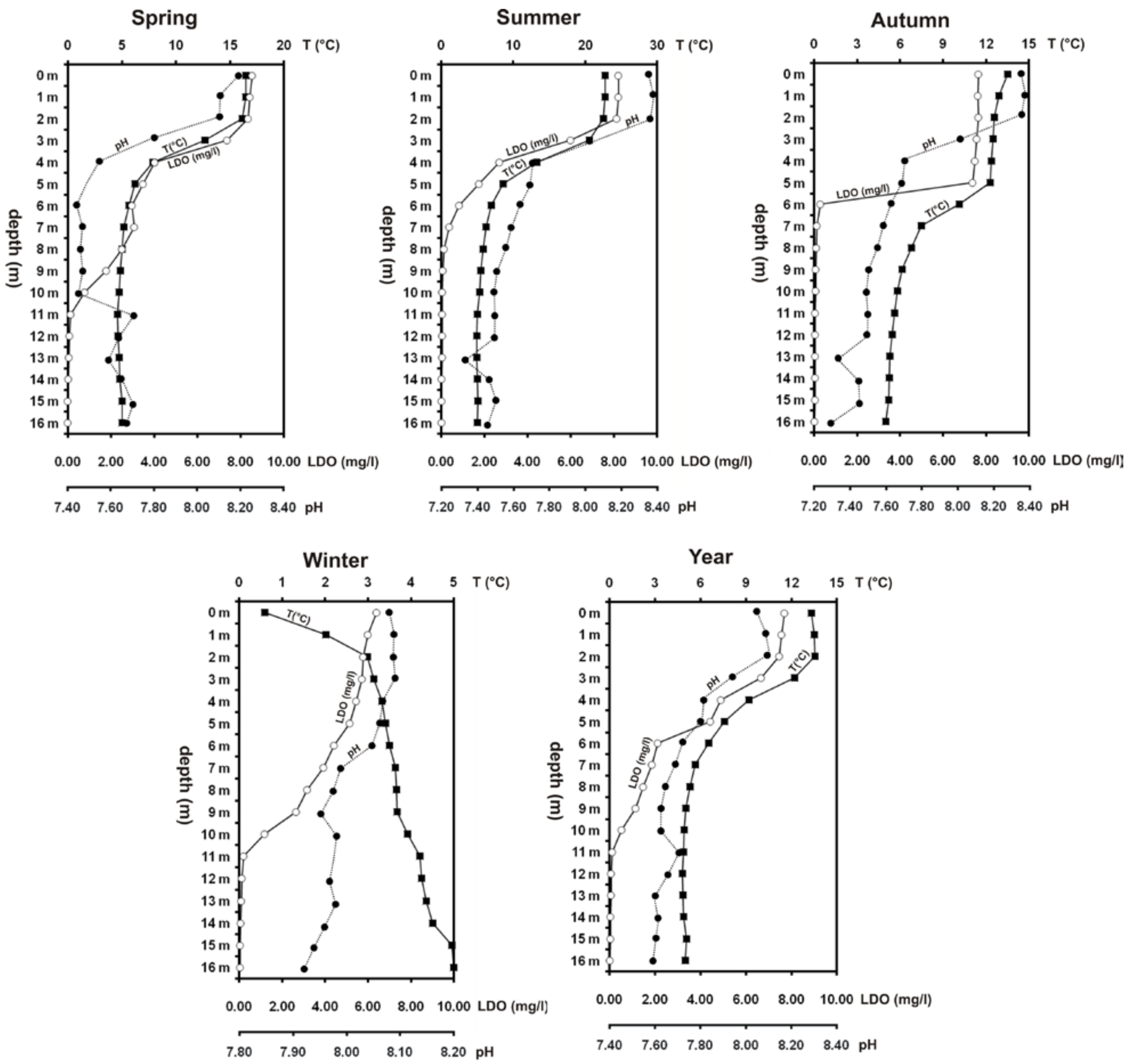

Figure 8. The annual and seasonal variation in the temperature, pH and dissolved oxygen in Cuejdel Lake.

In addition, the thermal stratification in Cuejdel Lake corresponds with decreasing dissolved oxygen concentrations with depth, which favours the appearance of different living environments.

Higher dissolved oxygen concentrations were recorded in the spring, summer and autumn. In contrast, the lowest dissolved oxygen concentrations were observed in the winter due to the ice cover that forms across the entire lake. The dissolved oxygen concentrations that were observed were consistent with the concentrations that are observed in mountain waters, mainly rivers. The high dissolved oxygen concentration was explained by the existence of the streams that supply the reservoir. These streams form a current in the upstream-downstream direction that refreshes the surface water. In addition, the circulation of the deep water is extremely low.

Between the summer and winter, an important difference occurs in which the dissolved oxygen concentrations are correlated with increasing depth. During the summer, the dissolved oxygen concentrations at a depth of 4 m fall below 4 mg/L. At a depth of 6 m, these concentrations oscillate approximately 2 mg/L. The lack of dissolved oxygen was obvious at a depth of 10 m. Thus, Cuejdel Lake is considered an euxinic-type lake with two different layers. The surface layers are life-sustaining, while the deeper layers support few living organisms.

In the deepest sectors, the most important threshold limit interruptions occur. In this case, the thresholds are greatly extended to values of up to 4-9 m. Between these limits, the differences between the values tend to be much larger. However, at depths of more than 9-10 m, these values remain the same regardless of the season. During one year, the temperature, pH and dissolved oxygen concentrations were well correlated with one another and decreased from the surface to the bottom of the lake in the spring, summer and autumn (Fig. 8). These correlations were disrupted in the winter, mainly due to the yearly ice cover that can persist between 15 and 60 days/year. The extremely long lifespan of the ice cover in the winter is caused by the thermal inversions, which help insulate the cold air mass on the bottom of the depression. An obvious inconsistency appears during the winter when the temperature curve is inverted.

The ice cover is relatively uniform in thickness across the entire lake and reaches depths of 20-90 cm. However, the thickness of the ice is frequently approximately 30 cm. The thickness of the ice depends on the air temperature and its duration. When the thermal inversions can lower the minimum temperature to nearly -30°C, the ice is much thicker. Two thresholds can be identified, one at 2 m and one between 4 and 5 m (Fig.8).

5. CONCLUSIONS

Cuejdel Lake is considered a mountain lake and has special characteristics that result from its genesis and geographical location. During its evolution, the two following stages occurred: the formation of the first small-sized lake in 1978 and the appearance of the current lake in 1991. Cuejdel Lake is located inside of a closed drainage basin with a local microclimate that influences its thermal parameters. From a thermal perspective, Cuejdel Lake is subjected to direct climatic influences that are specific to the mountain area in which it is located. Cuejdel Lake acts as a reservoir with direct thermal stratification during the summer, autumn and spring. However, this thermal stratification is reversed in the winter (dimictic character).

The main and temporary tributaries for the lake supply little water, which results in reduced circulation, especially in the bottom layer. This reduced circulation allows for the stratification of temperature, pH and dissolved oxygen. Furthermore, the lake water is slightly alkaline.

The dissolved oxygen concentrations that were present in the Cuejdel Lake water were similar to those that were previously observed in mountainous and running waters, but not in closed lakes. Thus, the dissolved oxygen concentrations in the Cuejdel Lake water can be explained by the fresh water supply that enters the lake through tributaries and exits through the outlet sector. Most of the surface tributaries that supply the lake with water have a permanent flow.

The variations in temperature, pH and dissolved oxygen were correlated in the spring, summer and autumn and either increased or decreased with depth. However, the temperature, pH, and dissolved oxygen did not follow the general trendline in the winter. This result occurred due to the ice cover, which persisted for a long time in the winter.

Due to its scientific importance and its natural environment, it was proposed that the Cuejdel Lake area should be conserved. Currently, the deterioration of the landscape is nearly non-existent because the access roads that lead to the lake are not accessible by regular cars. The only current issue that is a concern is the illegal tree harvesting, which must be stopped.

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