Rev. Biol. Trop., 35(2): 277-285, 1987.

Morphometric and basic limnological properties of the Laguna de Río Cuarto, Costa Rica*

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(Received December 3, 1986)

Abstract: The Laguna de Río Cuarto, situated 360 m above sea level on the Caribbean side of the Cordillera Volcánica Central in Costa Rica, is a meromictic Maar. The water surface has an area of 33.24 hectars, the maximum depth reaches 66 m and the mean depth 45.5 m. The lake volume is 15.12 x 10^6 m^3. Seasonal variations of surface temperature have been observed between 26.4 and 29.9 ^oC, whereas the temperature of the hypolimnion (at 60 m) fluctuates only between 24.2 and 24.4 ^oC. The depth of the boundary layer between the oxic and the anoxic, H_2S containing water body oscillates between 25 m (January/February) and 20 m (May/June). About 55 % of the water body (mean value) is permanently anoxic. The vertical distribution of the nutrients, low concentrations in surface waters and high ones in deep waters, is related to the permament stratification of the lake.

In 1928 A. Thienemann published an article about the typology of lakes, which had a very stimulating effect on the then still young science of limnology. Thienemann's ideas arose during comparative investigations of several interesting lakes belonging to the type "maar" in the most western part of Germany (Thienemann 1913, 1915). Maars are related to volcanic activity. They are formed by an explosion, when ascending magma degasses or comes into contact with ground water. Due to their mode of formation maars are generally very small, usually circular or nearly circular lakes with diameters less than 2 km (Wetzel 1975). Relative to their small size, they are generally very deep and possess steep rims.

Maars occur in many regions with actual or former volcanic activity. An example of such a lake in Costa Rica is the Laguna de Río Cuarto (Fig. 1). In 1954 M. Kohkemper already performed some limnological studies of this lake, which in those times was called Laguna del Misterio (Lake of the Mystery), probably due to its form and seclusion. The mode of origin of the lake was unknown. Even speculations about meteoritic formation were published in newspapers. Bergoeing (1978) and Bergoeing and Brenes (1978), however, clearly proved the Laguna de Río Cuarto to be a maar, situated in a fracture zone stretching from the active Poas volcano along the old Congo volcano and the Laguna Hule caldera to the maar "Laguna de Río Cuarto".

As already mentioned Kohkemper (1954) performed several basic limnological measurements in spite of the then extremely adverse conditions. In 1978/79 a study of the primary productivity of the Laguna de Río Cuarto was performed by Gocke *et al.* (in prep.). Information about the seasonal distribution of the phytoplankton is given by Camacho (1985) and the seasonal distribution of the zooplankton was studied by Ramírez (1985). The present paper gives some information on morphometric features and stratification properties of the lake which are supplemented by some physico-chemical data. Thus, this publication is intended to serve as a basis for more detailed future investigations.

MATERIAL AND METHODS

Morphometric Survey The depth recordings were performed using a portable echo-sounder

* Contribución No. 122 del CIMAR

Fig. 1. Location of the Laguna de Río Cuarto.

along a number of transects parallel and perpendicular to the long axis of the lake. Additional soundings were performed on near shore transects which were located like the chords of a circle connecting prominent points of the shore. For control several depth measurements were done by hand using a weighted disk connected to a marked cable. The water volume of the lake was calculated according to Hutchinson (1957).

Physico-chemical Survey Measurements were always performed in the morning between 9:00 and 10:00.

A reversible thermometer was used to determine water temperature at various depths.

Oxygen determinations were performed by the Winkler method.

To obtain the oxygen deficiency, a method proposed by Andersen and Foyn *et al.* (1969) was used. This method has the advantage that it requires the same reagents as the oxygen determinations. According to the authors it measures the amount of reduced compounds such as H_2S, Fe^{2+}, Mn^{2+} etc. Their concentrations are given as negative oxygen units (mg $O_2 l^{-1}$) Andersen and Foyn (1969) state that this method provides a measure of the true oxygen deficiencies in the water. It is therefore of special interest related to biological studies. The method is given in detail by Grasshoff *et al.* (1983).

Hydrogen sulphide was determined by the methylene blue method (Grasshoff *et al.* 1983). For the determination of nutrients (NH_4^+, NO_2^-, NO_3^-, orthophosphate and reactive silicate) standard methods were employed using, however, small water samples (5 ml). For reference of the standard methods see Grasshoff *et al.* (1983).

Conductivity, pH and alkalinity were determined according to APHA (1971).

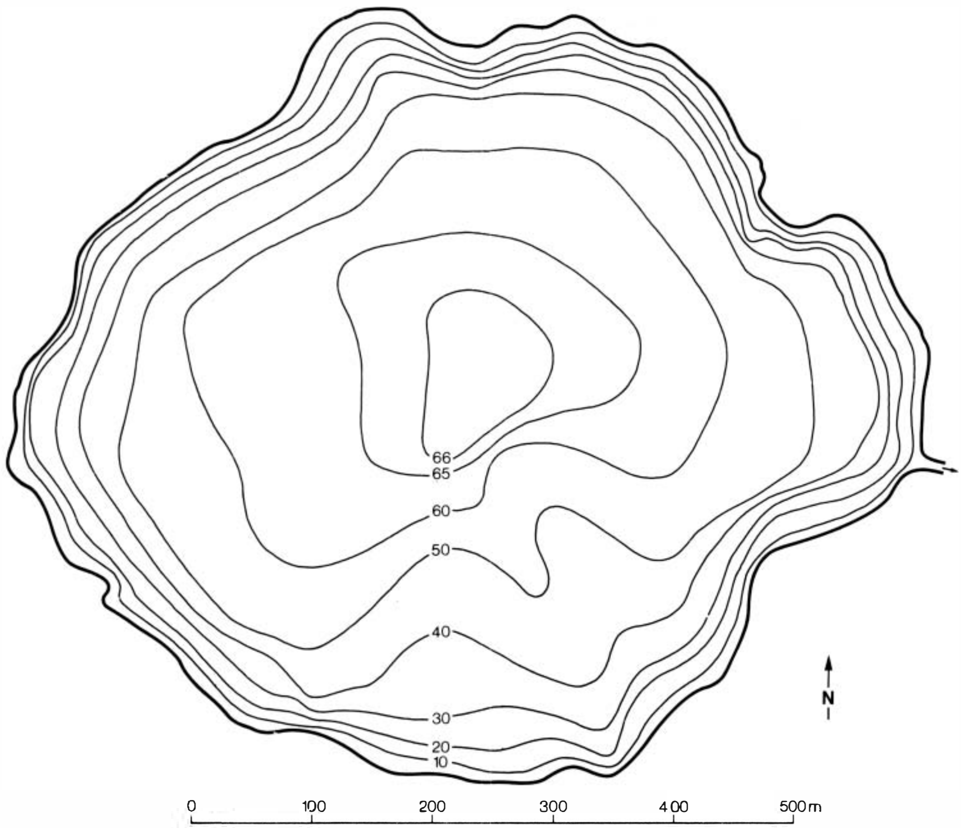

Fig. 2. Bathymetric map of the Laguna de Río Cuarto. Depth contours in meters.

RESULTS AND DISCUSSION

Morphometric Properties The Laguna de Río Cuarto is located at 360 m above sea level on the Caribbean slope of the Cordillera Volcánica Central in Costa Rica. The region, as far as the vegetation zone is concerned, belongs to the premontane belt transition of the tropical wet forest (Holdridge 1978). The lake has an area of 33.24 ha, a mean depth of 45.5 m and a water volume of 15.12 x 10^6 m^3. The drainage area extends to only 17.4 ha. Thus, it has only about half the area of the lake itself.

As shown by the Figs. 2 to 4 and Table 1 the Laguna de Río Cuarto fits very well into the morphological scheme of the maars. The lake is nearly circular, its long axis runs in an east-westerly direction. The length is 760 m and the width is 610 m. The greatest depth, located in the center of the lake, reaches 66 m.

As usually observed with most maars the lake resembles a deep basin with steep side walls. The mean inclination angle between the surface and the 10 m isobath is 45°, between the 10 and 20 m isobaths 43° and between the 20 and 30 m isobaths 35°. Thus, the slope of the side walls below the lake's surface is approximately as steep as that of the rim above the surface. The height of the rim of the depression in which the Laguna de Río Cuarto is situated, reaches from the water surface to the surrounding rather flat area about 30 m.

The small drainage area is reduced to the densely forested rims of the depression, in which the lake is situated. Several small brooks have its sources in the rims. A small river originates from the lake which runs into the Río Cuarto. Since much more water leaves the lake by the river than enters by the brooklets, it is assumed that the difference is balanced by rainfall and subterranean entrance of water. The annual rainfall (mean of the observation period 1972-1977) measured in the nearby located village of San Miguel de Sarapiquí amounts to 4170 mm (Servicio Meteorológico Nacional, San José, Costa Rica).

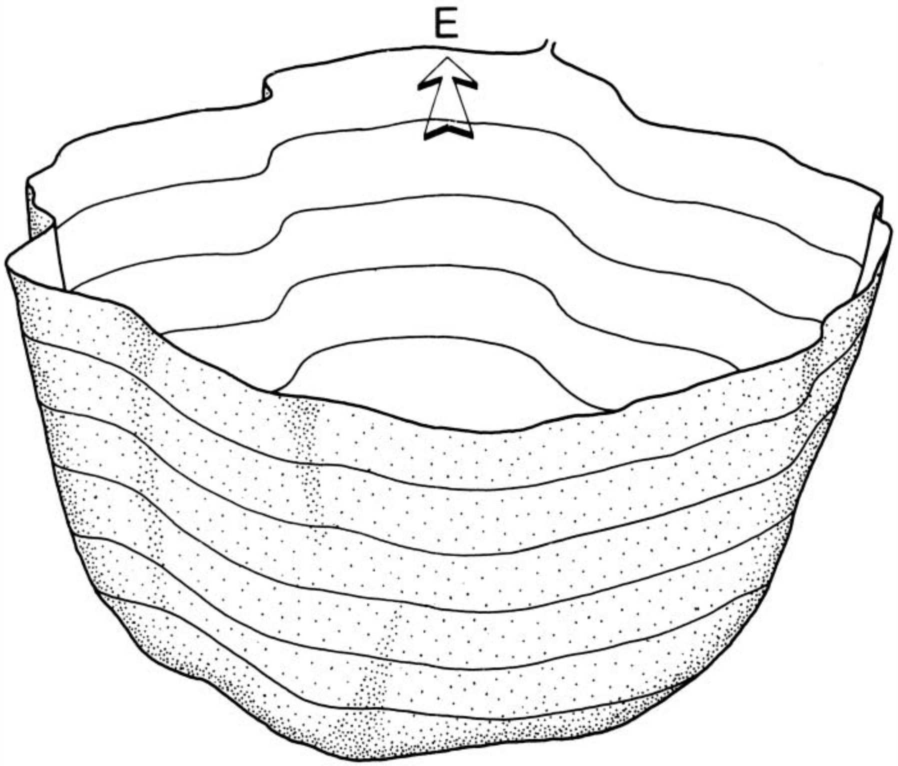

Fig. 3 Three-dimensional view of the Laguna de Río Cuarto from the west to the east. Proyection angle 20°. Vertical exageration 5 times.

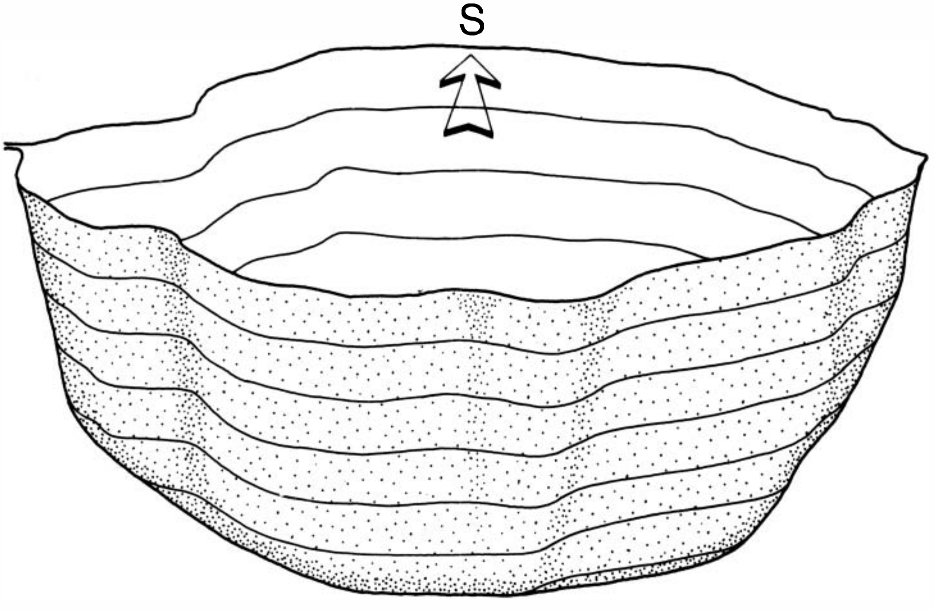

Fig. 4 Three-dimensional view of the Laguna de Río Cuarto from the north to the south. Proyection angle 20°. Vertical exageration 5 times.

TABLE 1

Morphometric properties of the Laguna de Río Cuarto

Location	84° 13' W, 10°21' N
Drainage area	17.40 ha
Lake area	33.24 ha
Shore line	2260 m
Maximum length	760 m
Maximum width	610 m
Maximum depth	66 m
Mean depth	45.5 m
Depth of the aerobic surface layer (annual mean)	22 m
Volume (total)	15.12×10^6 m^3 = 100%
Volume of the aerobic surface layer (annual mean)	6.81×10^6 m^3 = 45%
Volume of the anoxic deep layer (annual mean)	8.31×10^6 m^3 = 55%

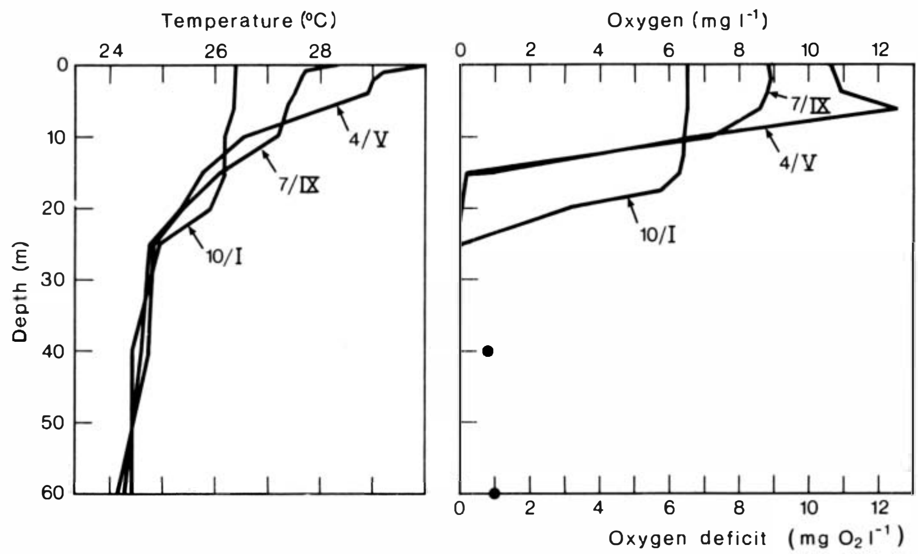

Fig. 5 Temperature profiles from January, May, and September (left side).
Oxygen profiles from January, May and September. The black dots at 40 and 60m represent the oxygen deficit as the mean of the three months (right side).

At present no exact data can be given on the age of the Laguna de Río Cuarto. According to Bergoeing (pers. communication) it might have come into existence not before the Upper Pleistocene. An indication of a rather young geological age is that in spite of the very heavy precipitation, the rims are still very steep and the brooks have not yet formed small erosion valleys.

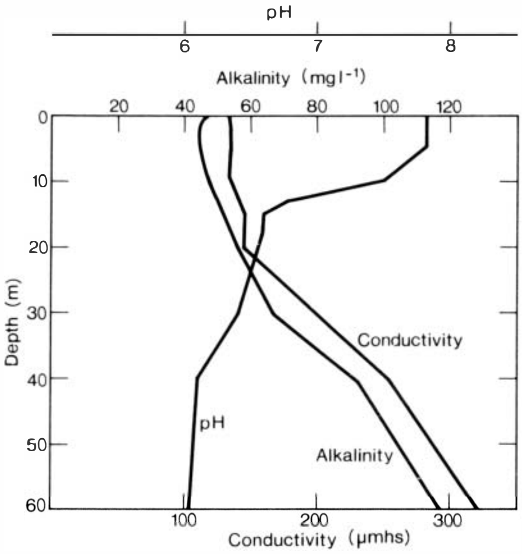

Fig. 6. Vertical distribution of pH, conductivity and alkalinity (the latter is given as mg $CaCO_3$ per liter), 7th September 1978.

Limnological Properties In Fig. 5, the vertical distribution of the water temperature is shown. The figure includes the month with the lowest surface temperature observed (January), the highest (May) and an intermediate value (September). Typically for tropical lowland lakes, the vertical and seasonal variations of temperature are quite small. In January the temperature of the nearly homothermic epilimnion was 26.4 ^{o}C. Thus, it was only about 2 ^{o}C above the lowest values found in the hypolimnion (24.2 ^{o}C). In May the surface temperature increased to 29.9 ^{o}C, but decreased rapidly with depth.

The vertical differences of the surface and deep water temperatures, which occasionally may fall below 2 ^{o}C (Fig. 7), are sufficient to create density differences, which prevent a complete mixing of the total water body. It should be stated that the density of the hypolimnion is somewhat increased due to the accumulation of salts in the deep layer (Fig. 6). Thus, the Laguna de Río Cuarto, as far as the stratification behaviour is concerned, belongs to the type of a meromictic lake, which means that no complete mixing between epi- and hypolimnion occurs. This stable stratification, however, is not a unique feature but is typical for tropical lowland lakes.

Seasonal variations are found insofar as the depth of the thermocline oscillated between 20 m (May, June) and 25 m (January, February). Apparently the deep layers below 25-26 m are normally never mixed with the surface waters. This has far-reaching consequences for the oxygen budget. Fig. 5 shows the vertical distribution of oxygen, which is present only in the mixed epilimnion. The depth(annual mean value) of the lower limit of the O_2-containing surface waters lies at 22 m, which means that about 55% (mean value) of the total water volume is permanently anoxic. During the mixing processes in January caused by the decreasing water temperature of the epilimnion, the boundary layer descends to 25 m water depth. Particularly steep is the depth variation of the 0,2 mg O_2 l^{-1}-isopleth, which in December is observed at 17.5 m and in January descends to about 24 m. As a consequence the epilimnetic waters are mixed with the upper layers of the hypolimnion. This process causes the O_2-saturation of the epilimnion near the surface to decrease to values between 75 and 80%.

Fig. 7 shows that the hydrogen sulphide concentrations in the hypolimnion increased to 6 μmol l^{-1}. In spite of the lack of further seasonal measurements of this compound, it is safe to assume that the H_2S concentration constitutes only a rather small part of the O_2 deficiency in the hypolimnion. The greatest part of the oxygen deficiency, which was about 1 mg O_2 l^{-1} (Fig. 5) as an annual mean, is most probably caused by the relatively high concentration of ferrous compounds. Although the amount of Fe^{2+} was not measured separately, an indication of their presence is given by the fact, that some hours after aerotion of the normally clear hypolimnetic water samples a yellow-brownish precipitation can be seen, which consists obviously of $Fe(OH)_3$.

The vertical profiles of the most important nutrients are shown in Fig. 7. Concerning the inorganic nitrogen compounds the usual distribution in lakes with anoxic hypolimnion was observed. Nitrate is present only in the epilimnion. This is also the case for nitrite, which was found in very low concentrations. Ammonia is present in huge concentrations up to 300 μmol l^{-1} in the hypolimnion.It makes up also the greatest part of the N-compounds in the surface waters (ca. 5 μmol l^{-1}). The vertical distribution of orthophosphate resembles that of NH_4^+. Concentrations up to 30 μmol l^{-1} in the hypolimnion and between 0.1 - 0.2 μmol

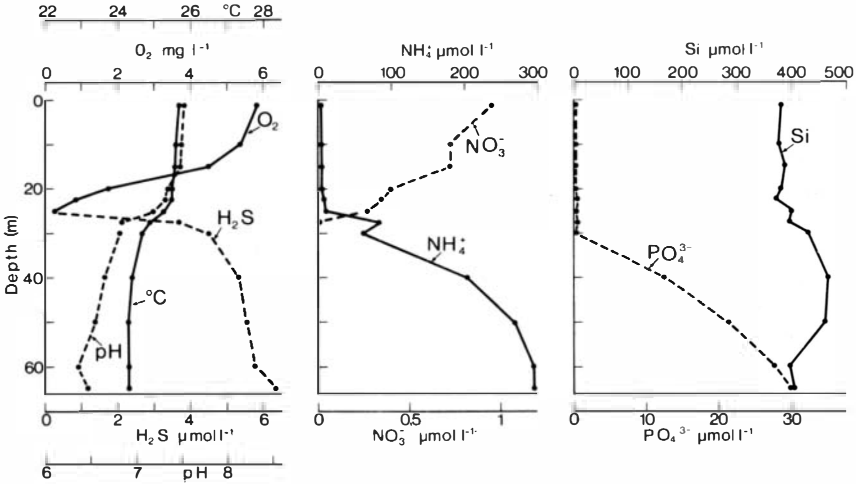

Fig. 7 Vertical distribution of temperature, pH, O_2, H_2S and some nutrients, 27 January 1986.

l^{-1} in the eplimnion were found. Reactive silicate shows a rather uniform distribution with depth.

The vertical distribution of the nutrients was measured only in January 1986. It is assumed that seasonal variations of concentrations in the hypolimnion are nearly absent or quite small. Thus, the hypolimnion acts as a sink, in which the nutrients are trapped after their liberation from settling organic material. Greater variations of nutrient concentrations will occur seasonally only in the upper parts of the water column. Here the highest amounts of these compounds are probably present in January/February. This is deduced from the observation that during these months the thermocline lies quite deep and, as already mentioned, the upper part of the hypolimnion is mixed into the epilimnion. As a further support for this assumption the time course of the primary productivity may be taken, which reaches its highest values in March/April. It is obviously stimulated by the relative high nutrient concentrations occurring a short while before.

The annual gross primary productivity of the Laguna de Río Cuarto amounts to 470 g C m^{-2} (Gocke *et al.*, in prep.). According to Camacho (1985) green algae are the dominant species of the phytoplankton. The phytobenthos developes only a small belt due to the steep side walls of the lake. It consists mainly of *Chara* sp., which occurs in relatively dense populations at some points of the shore. The input of allochthonous organic material from the densely forested rims of the lake plays an important role in the carbon cycle of the Laguna de Río Cuarto. This consists mainly of leaves and litter, the residues of which in all stages of decay make up a great part of the lake sediments.

To conclude it may be worthwhile discussing some ideas about the stability of the stratification of the Laguna de Río Cuarto. During the investigation period between March 1978 and March 1979 the lowest surface temperature observed was 26.4 °C. Camacho (1985) reports a lowest value of 25.8 °C for the period 1984/85. In our own measurements performed in January 1986 the surface temperature was 25.6 °C. Since the temperature of the hypolimnion oscillates only between 24.2 and 24.4 °C, this means that the temperature difference between the two water layers may fall to 1.2-1.4 °C. The density differences due to external thermal forcing between the epi- and hypolimnion are therefore quite small, even considering that at this relatively high water temperature each degree of temperature difference causes a relatively large density change. Due to the higher concentration of salts in the deep water the density of this layer is marginally greater. The wind cannot play an important role in the mixing processes, since the lake is very well protected by its surroundings. It is obvious that under the existing climatic conditions a breakdown of the meromixis is most unlikely. Application of a simple two-layer model in which the necessary temperature to reduce the density of the upper to that of the lower layers shows that only a cooling of the surface temperature down to 23 °C for many months would result in a complete mixing of the lake.

During the investigation period, the depth of the mixed surface layer oscillated seasonally between 20 and 25 m. As already mentioned, the oxygen saturation in January decreased to <80 % due to the incorporation of anoxic deep water into the epilimnion. A longer period of anomalously cold weather in December/January combined with extremely strong winds, which at least to some extent assist the mixing process, would cause a sinking of the thermocline substantially below 25 m. This would result in a further decrease of the O_2 saturation, since a larger part of the H_2S and Fe^{2+} containing deep water would be entrained.

That such mixing occasionally occurs may be deduced from accounts by the local people. According to them the lake had in earlier years very occasionally adopted a yellow-reddish discolouration accompanied by a massive fish mortality. A possible explanation could be that hypolimnetic Fe^{2+} was mixed into the epilimnion, which was then oxydized to insoluble yellowish $Fe(OH)_3$. The fish mortality may be caused by very low oxygen concentrations.

ACKNOWLEDGEMENT

We thank Hans-Jürgen Krambeck for providing computer drawings of the isobaths which served for drawing the threedimensional views, and the students of a summer course who helped in the determination of the physico-chemical properties of the Laguna de Río Cuarto. This study was supported by grants from the Universidad de Costa Rica, from the Consejo Nacional de Investigaciones Científicas y Tecnológicas of Costa Rica and from the Ministry for Economic Cooperation of the Federal Republic of Germany.

RESUMEN

La Laguna de Río Cuarto está situada a una altitud de 360 m sobre el nivel del mar en la vertiente Caribeña de la Cordillera Volcánica Central en Costa Rica. Se trata de un "Maar" meromíctico cuyo origen está relacionado con la actividad volcánica.

Las características morfométricas de la laguna son las siguientes:

Area de la cuenca	17.40 hectáreas
Area de la laguna	33.24 hectáreas
Perímetro	2260 m
Longitud máxima	760 m
Ancho máximo	610 m
Profundidad máxima	66 m
Profundidad media	45.5 m
Profundidad de la capa aeróbica (promedio anual)	22 m
Volumen (total)	15.12×10^6 m³ = 100%
Volumen de la capa aeróbica (promedio anual)	6.81×10^6 m³ = 45%
Volumen de la capa anaeróbica (promedio anual)	8.31×10^6 m³ = 55%

Se han observado variaciones estacionales de la temperatura superficial entre 26.4 y 29.9 °C, mientras que la temperatura del hipolimnion (a 60 m) fluctúa solamente entre 24.2 y 24.4°C. El límite entre aguas oxigenadas y aguas anóxicas con H_2S se encontró a 25 m en enero/febrero y a 20 m en mayo/junio.

Aproximadamente el 55% (valor promedio) del volumen total de la laguna permanece constantemente anóxico. La distribución vertical de los nutrientes, bajas concentraciones en las aguas superficiales y altas en aguas profundas, está relacionada con la estratificación permanente del lago.

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