LIMNOLOGY OF A MEROMICTIC COASTAL LAGOON. *L'ESTANY* DEL *CIBOLLAR* (MAJORCA, BALEARIC ISLANDS)

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Palabras clave: Coastal lagoons, meromixis, chemocline, water chemistry, phototrophic bacteria.

ABSTRACT

Some features of the physical, chemical and biological limnology of the Cibollar coastal lagoon in the Albufera of Majorca were monitored. These parameters were light, temperature, pH, alkalinity, conductivity, chloride, oxygen, sulphate, sulphide, nitrate, nitrite, phosphate, chlorophyll-u, bacterio-chlorophylls and carotenoids.

The lagoon is defined as ectogenically meromictic. Biological activity helps sustain meromixis, however the major factor leading to this is the morphology of the lagoon basin due to human activity. Because of its meromictic state the lagoon provides a favourable environment for the development of anaerobic bacteria1 populations.

INTRODUCTION

Meromictic lakes are charactenzed by the presence of a deep water layer, generally anoxic and salty, called monimolimnion (FINDENEGG, 1935), that remains temporarily or permanently isolated from the upper layers and unaffected by the mixing processes taking place throughout the year. It is caused by a high gradient zone or chemical cline (chemocline) that determines the upper limit of the monimolimnion and its extension (HUTCHINSON, 1937).

Stratification phenomena, especially persistent in meromictic lakes, enable the study of limnological and biochemical processes of great ecollogical interest (WEIHER & LEE, 1973; PARKIN *et* al., 1980; LÓPEZ et al., 1984).

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HUTCHINSON (1937, 1957) considers three reasons for meromixis: Ectogenic, crenogenic and biogenic, which give rise to three types of meromictic lakes, described with widespread examples. Meromictic lakes are reported as an uncommon phenomenon (WALKER, 1974). However this is probably due more to lack of study. Only in the Iberian Peninsula, where meomixis was an unknown phenomenon, a considerable number of examples have been found recently (MIRACLE & VICENTE, 1983; GUERRERO et al., 1987).

The study of the limnology of the Albufera of Majorca by MARTÍNEZ TABERNER et al. (1987a) indicated the possible presence of a meromictic condition in the Cibollar lagoon, and this was subsequently confirmed by MARTÍNEZ TABERNER et al. (1987b).

The present work carries out a more detailed study of its limnological characteristics during one annual cycle.

STUDY AREA

The Cibollar is a small lagoon on the northeast of the Albufera of Majorca (fig. 1), 750 m from the sea. The lagoon has a dual connection with the sea, either through another lagoon *–Estany dels* Ponfs– or directly through a canal. It is linked with the inner zone of the Albufera by means of another canal.

The lagoon has been recently enlarged and dredged for recreational purposes. These alterations are noticed in the contour, which appears sinuous in the less disturbed areas but straight in the constructed zones, and in the bathymetry, due to uneven dredging.

The lagoon is small, with a surface area of almost 4 Ha, its volume is over 130 Dm^3, the average depth is 3.3 m and the maximum depth is 8.24 m.

The disturbed shores are densely covered by *Phragmites australis*, *Chaetomorpha linum*, *Ficopomatus aenigmaticus* and, to a lesser extent, by *Ruppia* cirrhosa.

MATERIALS AND METHODS

The lagoon was visited about once every three weeks and the samples were taken from the same sites as in previous studies mentioned above. Prior to sampling, temperature and light profiles were determined. Between seven and ten samples were taken throughout the profile, depending on the steepness of the cline.

Transmittance, temperature and pH were measured *in* sifu. A 07024.00 Phywe luxometer was used for trasmittance, measuring the visible spectrum between 0 and 300 Klux, and for temperature and pH two Crison measuring devices were used: A T-637 thermometer and a 503 pH-meter.

At the laboratory and within a maximum delay of three hours so as to minimize error, a second pH measurement was done with a Crison 501 pH-meter, precalibrated to ambient temperature, and conductivity was recorded with a Radiometer CDM2f conductimeter, correcting all data for 20°C

Alkalinity, chlonde, oxygen, sulphide and soluble reactive phosphate were determineded following methods descnbed in GOLTERMAN ef al. (1978), STRICKLAND & PARSONS (1972) and APHA-AWWA-WPCF (1981) and sulphate after FRITZ & YAMAMURA (1955).

Pigments were extracted with 90% acetone and measured by spectrophotometry. The amount of Chl-a was calculated following STRICKLAND & PARSONS (1972), bacteriochorophyll-d following TAKAHASHI & ICHIMURA (1968), bacteriochlorophyll-e with the formula Bchl-e = 10.2 x D_{640} x v/V (ABELLÀ, pers. comm.) and carotenoids after GUERRERO et al. (1980).

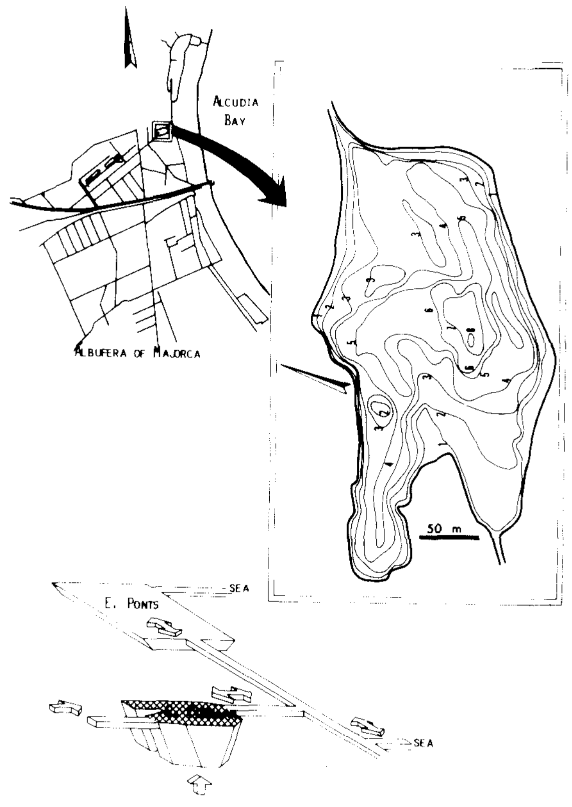

Figure 1.- Bathymetric map of the Cibollar lagoon. Its location in the Albufera of Majorca and connections with other water bodies are indicated.
Mapa batimétrico del estany del Cibollar. *Se* indica su localización en la Albufera de Mallorca y las conexiones con otras masas de agua.

RESULTS

Ligth transmittance expressed as the percentage of surface light that penetrates the water column showed important differences over the period studied. Maximum values were detected in November and also between March and July. Minimum transmittances corresponded to October, August and September.

Variation in the transmittance values reflects changes in the vertical extinction coefficient of light. The mean value of the different depths give a maximum of 1.06 Klux (M.04) at the end of March and a maximum of 2.66 Klux (±0.25) in October. These values correspond approximately to 35% and 7% transmittance, respectively.

Minimum values for transrnittance coincide with vertical extinction coefficient maxima in the first metre of water. This coefficient decreases with depth. When transmittance is highest the vertical extinction coefficient is minimal for the top metre and remains constant or shows a small tendency to rise with increasing depth (fig. 2).

Surface temperature in the lagoon followed atmospheric temperature variations and fluctuated between 8.4°C and 28.4°C, recorded in December 1986 and August 1987 respectively. The extreme values for the lagoon (8.1°C and 28.6°C) were recorded at 2 and 1.5 m depth respectively, coinciding in time with the extreme values on the surface.

The annual thermal cycle was characterized by three different periods (fig. 3). The first occurred through the autumn and most of the winter. There were thermal differences between the upper and lower layers, with temperatures highger at the lower ones than on the surface. This contrast gradually reached a maximum of 9.6°C in January 1987.

The second period comprised the end of the winter and most of the spring. The surface layers gradually increased their temperature until April, when the water column was at a uniform 19°C.

The third period lasted from the end of spnng to the beggining of autumn. At this time differential heating between surface and bottom layers lead to an increase in temperature of the upper layers. Thus the differential was of 4.1°C in May,

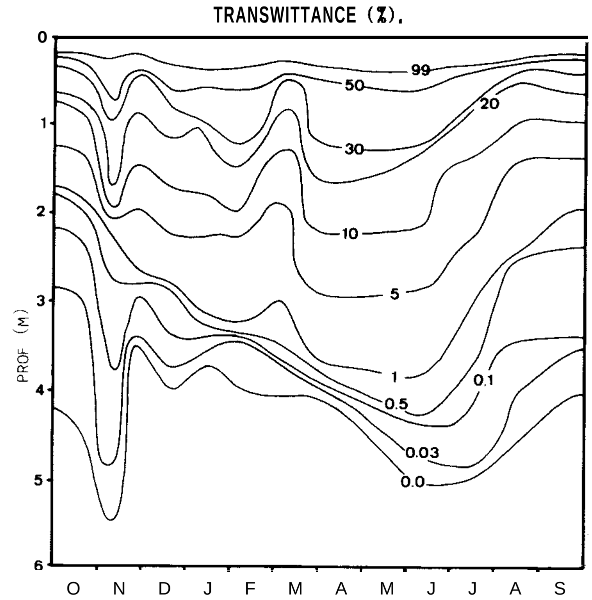

Figure 2.- Distribution of transmitted light as a function of time and depth.
Distribución del tanto por ciento de la luz transmitida en función del tiempo y la profundidad.

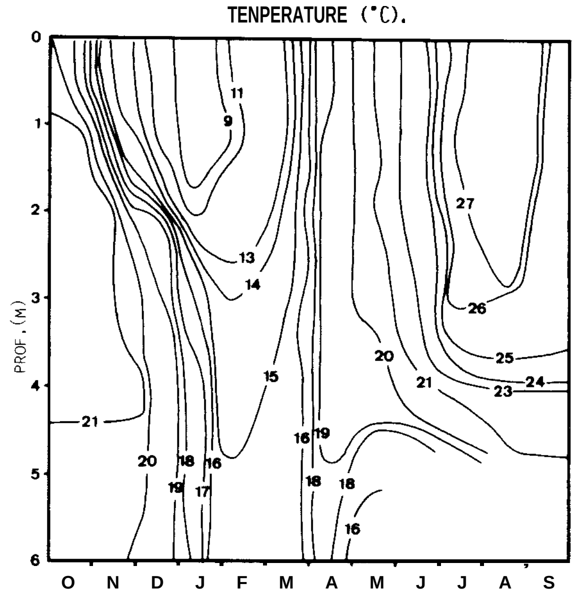

Figure 3.- Distribution of temperature (°C) as a function of time and depth.
Distribución de la temperatura (°C) en función del tiempo y la profundidad.

reaching a maximum of 7°C in August. Henceforth and until autumn the tendency was towards a decrease in this differential.

Conductivity showed high fluctuationsalong the annual cycle (fig4). At the surface the lowest values occurred in the winter and reached a minimum of 4.24 mS cm-' at the beginning of March. Highest values were recorded in the summer, remaining below 20 mS cm-' (MARTÍNEZ TABERNER ef al., 1987). At the deepest point conductivity remained between 30 and 35 mS cm', reaching values of 50 mS cm-' only on rare occasions.

The conductivity gradient was strong throughout the water colum and, with the exception of the summer of 1984, (MARTÍNEZ TABERNER et al., 1987) the maximum values over one metre ranged from 10.62 to 37.07 mS cm-'(fig. 4).

Chlorides were the main anions contributing to salinity, their concentration pattern paralleling thatof conductivity.Surfacevaluesranged usually from 1.5 to 4 g $Cl \cdot l^{-1}$, reaching more than 10 g $Cl^-.l^{-1}$ dunng the summer in 1984 and 1985. At the bottom values oscillated between 15 and 20 g $Cl^-.l^{-1}$.

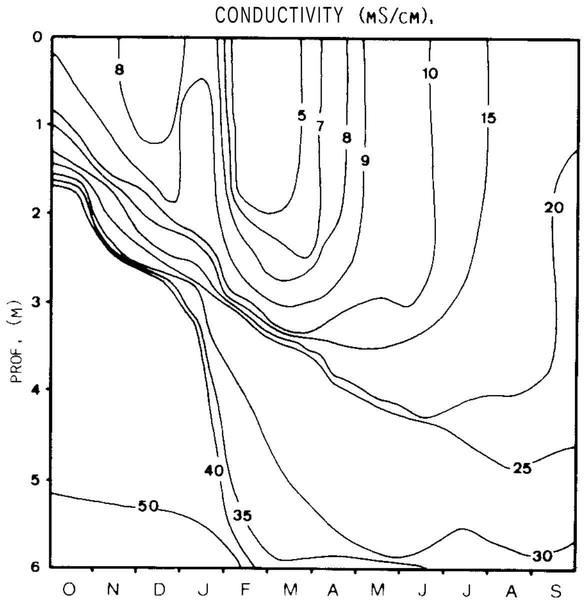

Figure 4.- Distribution of conductivity ($mS.cm^{-1}$) as a function of time and depth.
Distribución de la conductividad ($mS.cm^{-1}$) en función del tiempo y la profundidad.

The nextanions in importance weresulphates. Surface values varied behveen 0.12 and 2.66 g $S\text{-}SO_4^{-2}$ l-' and those from the bottom, between 0.63 to 2.95 g.$S\text{-}SO_4^{-2}.l^{-1}$. However maximum values appeared in the high gradient zone; i.e., the lowest maximum read 1.70 g $S\text{-}SO_4^{-2}.l^{-1}$ at 3.20 m depth in March and the highest 4.06 g $S\text{-}SO_4^{-2}.l^{-1}$ in June at 4.40 m depth.

Bicarbonates varied significally with the seasons. The water column maintained similar values, although some increases were noticed towards the bottom layers. Alkalinity values on the surface were behveen 4 and 9 $meq.l^{-1}$. After minimum values in the autumn, they rose gradually, reaching their maxima at the end of the winter and beginning of spnng. A slight decrease then followed, which was more enhanced in early autumn.

At the surface dissolved oxygen varied from 7.26 $ml.l^{-1}$ (10.37 $mg.l^{-1}$) to 3.39 $ml.l^{-1}$ (4.84 $mg.l^{-1}$), measured at the beginning of March and June respectively.

Oxygen concentration usually decreased progressively from the surface, although some peaks were found exceptionally at 0.8 and 1.6 m depth. Anoxia was always present at the lower layers.

The depth where dissolved oxygen was minimal vaned from 1.2 m in October to 4.3 m in May and June. Between both situations a first period took place when the anoxic water volume remained constant (from November to January). This volume decreased until May and started rising again from July onwards (fig.5).

Sulphide levels followed completely opposite dynamics. Their concentration started to be significant from the anoxic layer downwards. This ranged from 1.39 mg $S\text{-}S^{-2}$ l^{-1} to 171.43 mg $S\text{-}S^{-2}$ l^{-1}. Usually the concentration increased progressively with depth (fig.5).

Phosphates showed great changes over the study period. Values below the sensitivity of the method used (0.03 mg-at $P\text{-}PO_4^{-3}.l^{-1}$) occurred at the surface in January and March, and at 2.4 and 3.2 m depth in March and July.

In general, phosphate levels showed a strong gradient down the water column, values rising from less than 1 to more than 20 mg-at $P\text{-}PO_4^{-3}.l^{-1}$ over less than half a metre drop in depth. Only in

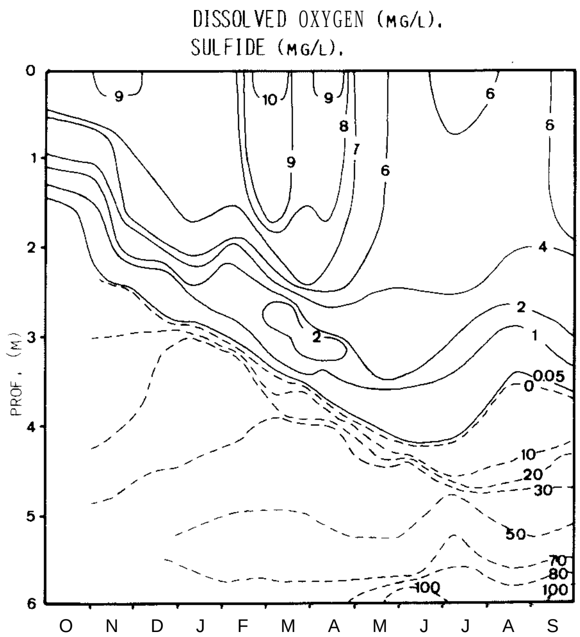

Figure 5.- Distribution of dissolved oxygen (full line) and sulfides (broken line) as a function of time and depth Both in mg.l-1.
Distribución del oxígeno disuelto (línea continua) y del sulfhídrico (línea discontínua) en función del tiempo y la profundidad. Ambos en mg.l-1.

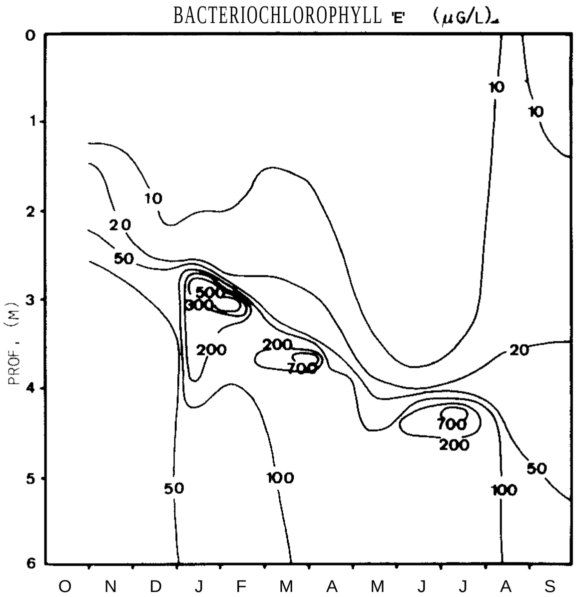

Figure 7.- Distribution of bacteriochlorophyll-e (μg.l-1) as a function of time and depth.
Distribución de la bacterioclorofila-e (μg.l-1) en función del tiempo y la profundidad.

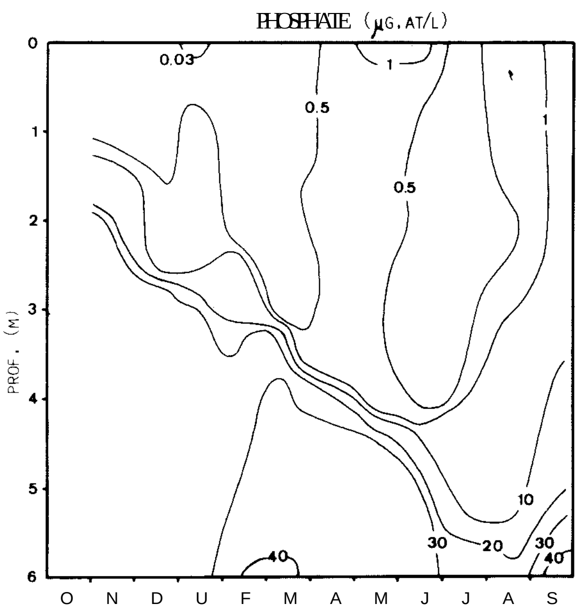

Figure 6.- Distribution of total reactive phosphorus (μg.l-1) as a function of time and depth.
Distribución del fósforo reactivo total (μg-át.l-1) en función del tiempo y la profundidad.

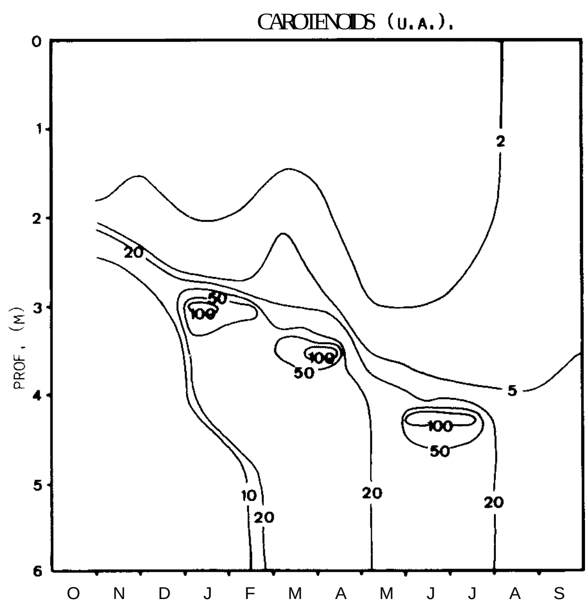

Figure 8.- Distribution of carotenoids (U.A.l-1) as a function of time and depth.
Distribución de los carotenoides (UA.l-1) en función del tiempo y la profundidad.

September was the gradient less pronounced, the concentrations ranging between 2.5 and 6.9 ug-at $P\text{-}PO_4^{-3}.l^{-1}$ at the surface and at 3.5 m depth respectively.

At the surface chlorophyll-a concentration oscillated between 23.20 $mg.m^{-3}$ in August and 2.71 $mg.m^{-3}$ in February.

During the whole study period surface chlorophyll-a values were over 10 $mg.m^{-3}$, except in February, March, June and July, values remaining bassically constant throughout the two first metres of water.

Bacteriochlorophyll-e values were characterized by the existence of mixolimnion with never more than 20 $mg.m^{-3}$ and a monimolimnion with values over 50 $mg.m^{-3}$. Maximum reading were detected at the chemocline **(fig. 7).**

Bacteria1 carotenoids followed a pattem similar to that of bacteriochlorophyll. The value for the upper layer was 5 AU, while deeper layers yielded always over 10 AU. The boundary between both layers, where values were highest, matched that of the bacteriochlorophyll (fig. 8).

DISCUSSION

The results above reveal the existence in the lagoon of an important picnocline which remains constant throughout the year, albeit with some minor vertical fluctuations.

The density gradient is due to the presence in the lagoon of two water bodies of a different nature. One iscomposed of waterof continentalorigin and low density. This water mass, which has mostly circulated over a broad area of the Albufera, enters the lagoon along a canal of the SW. Continental inputs depend essentially on the rainfall pattern with distinct maxima in the autumn and spring. Consequentlly the picnocline drops progressively from the autumn to the end of spring, and even part of the summer in rainy years such as shown in the results above. The other water body is of marine origin. Because of this the type of water circulationin the Cibollar fits the model of the dynamics of a positive estuary. However, the morphometric features of the lagoon allow as to postulate the filtration of seawater through its bottom (fig. 1).

The volume of seawater in the lagoon depends on the input of water of continental origin, i.e.: the minimal volumes coincide with the end of the rainy season in the spring, and subsequentlly increase in the latter half of the summer and early autumn, as the inflow of continental water drops and evaporation increases. The picnocline can rise gradually, or often quickly, and may be even reach the surface in dry an extremely hot years, as happened in the summer of 1984.

The picnocline, which is basically a chemocline sometimes reinforced by the superposition of a thermocline, evolves in a way basically identical to that of similar lagoons (LÓPEZ et al., 1984). The thermal perfomance of the lagoon resembles that of dimictic lagoons. However mixing is only effective at the surface layer, of lower density. Nevertheless the temperature pattem is totally different from what is commonly found in littoral lagoons.

The constancy of the picnocline is therefore the main factor affecting the differential heating of the lower layers. This feature could initially recall a heliothermal type of lake. However, although we have not calculated the thermal balance, it is believed that the quantity of heat accumulated in the lower layers must be low and the overall thermal balance of the lagoon very close to that of lakes found in similar latitudes and altitudes because of weak lake penetration. The Cibollar is thus comparable to La *Massona* (ARMENGOL et al., 1983) and Cullera (Miracle y Vicente, 1985).

The scarce water transparency in the lagoon is the result of its markedly eutrophic nature. Phosphate levels dissolved in the water must be interpreted as very high, especially if we consider the significant losses due to assimilation by photosynthetic organisms as well as to processes of coprecipitation with carbonates in a highly alkaline medium.

Primary production in the lagoon can be attributed mainly to phytoplankton as shown by pigment analysis. Phytoplankton biomass within the upper oxygenated layers causes the highest extinction coefficientof light in the top metre of the water column.

In the lower strata of the lagoon primary production is due to anaerobic photosynthetic bacteria. This environment releases essential nutrients (sulphide and phosphate) as a byproduct of the activities of other anaerobic microorganisms or of processes of redissolution of precipitates accumulated in the sediment. There is a total extinction of light below this layer and we thus conclude that the pigment levels present in lower layers correspond to inactive forms.

The organic matter resulting from production processes constitutes a source of reducing power as it is decomposed in the deeper layers. This organic matter decomposition is the cause of the persistent anoxia in the monimolimnion and enables the accumulation of various substances which contnbute to the maintenance of densitiy differences and thus reinforce the existing picnocline, at least in some stages.

The dynamics of the *Cibollar* established in the course of our studies define without doubt its meromictic character, as already stated by MARTÍNEZ TABERNER et *al.* (1987b). This feature is clearly distinct from conditions prevailing in other lagoons within the same *Albufera* salt marsh, and can only be explained as the result of dredging. The *Cibollar* is thus a case of ectogenic merornixis.

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RESUMEN

LIMNOLOGÍA DE UNA LAGUNA MEROMÍCTICA COSTERA. L'ESTANY DEL CIBOLLAR (MALLORCA, ISLAS BALEARES)

Algunas de las características físicas, químicas y biológicas del *Estany del Cibollar*, una laguna costera en la Albufera de Mallorca, fueron analizadas. Estos parámetros incluyen: Luz, temperatura, pH, alcalinidad, conductividad, cloruros, oxígeno, sulfuros, sulfatos, nitratos, nitritos, fosfatos, clorofila-*a*, bacterioclorofilas y carotenoides.

La laguna muestra unas características de meromixis ectogénica. La actividad biológica ayuda a mantener la meromixis en la laguna; sin embargo, el factor más determinante de la meromixis es la morfología de la cubeta que ocupa, originada por la actividad humana. Debido a este estado meromíctico la laguna permite la proliferación de bacterias anaeróbicas.

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