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A COMPARATIVE LIMNOLOGICAL STUDY OF THE GUADALHORCE RESERVOIRS SYSTEM (MÁLAGA, S.E. SPAIN)

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RESUM

A partir de les dades obtingudes en les visites durant el període de barreja (març 1988) i estratificació (setembre 1988) en els tres embassaments del Sistema Guadalhorce, s'analitzen les respectives diferències físico-químiques i biològiques.

Tot i que els tres embassaments presenten un contingut en sals dissoltes relativament alt, Conde de Guadalhorce és d'aigües carbonatades, mentre que a Guadalhorce són importants els clorurs i Guadalteba té composició intermèdia. En aquests dos darrers embassaments la presència dels clorurs comporta la formació d'una haloclina molt marcada, que a Guadalhorce és permanent.

Pel que fa a les seves característiques tròfiques, Guadalteba i Guadalhorce són eutròfiques, la qual cosa es reflecteix en les altes concentracions de nutrients i de pigments fotosintètics, i en la seva elevada respiració i ETS. D'altra banda, Conde de Guadalhorce es pot considerar com a mesotròfic, a més de no esgotar-se l'oxígen de l'hipolimnion durant l'estiu.

RESUMEN

A partir de los muestreos efectuados durante el período de mezcla (marzo de 1988) y estratificación (setiembre de 1988) en los tres embalses del sistema Guadalhorce, se analizan sus diferencias fisicoquímicas y biológicas.

Aunque los tres embalses presentan un contenido de sales disueltas relativamente alto, Conde de Guadalhorce es de aguas carbonatadas, mientras que en Guadalhorce son importantes los cloruros y Guadalteba se encuentra en una posición intermedia. En estos dos últimos embalses la presencia de cloruros determina la existencia de una haloclina muy marcada, que en el caso de Guadalhorce es permanente.

Desde el punto de vista de sus características tróficas, Guadalteba y Guadalhorce son eutróficos, lo que se refleja en la alta concentración de nutrientes y pigmentos, así como por tener respiración y ETS elevados. Por el contrario, Conde de Guadalhorce puede considerarse como mesotrófico a partir de los mismos parámetros, además de permanecer con oxígeno en el hipolimnion durante todo el verano.

INTRODUCTION

Although there are more than 900 reservoirs in Spain, only a few of them have crenogenic meromixis in the sense of Walker & Likens (1975). Among them, two of the reservoirs in the Guadalhorce System, Guadalteba and Guadalhorce, have this type of stratification. In contrast, the third reservoir in this System, Conde de Guadalhorce, is warm monomictic in consonance with the climatic characteristics of the Mediterranean region.

As the reservoirs are together (Fig. 1) they are submitted to similar climatic conditions, and only the chemical composition of the water coming into each one can be considered as a factor of divergence in their ecology. The main chemical differences are due to the concentration of total dissolved salts and to the dominance of certain majoritary ions in the water composition.

This paper summarizes, from a comparative point of view, the temporal changes of each reservoir caused by the different total mineral content dissolved in the water and the vertical distribution of chloride. As these reservoirs were previously studied between 1972 and 1974 (Margalef et al., 1976), the changes in the main limnological characteristics of each reservoir are also considered.

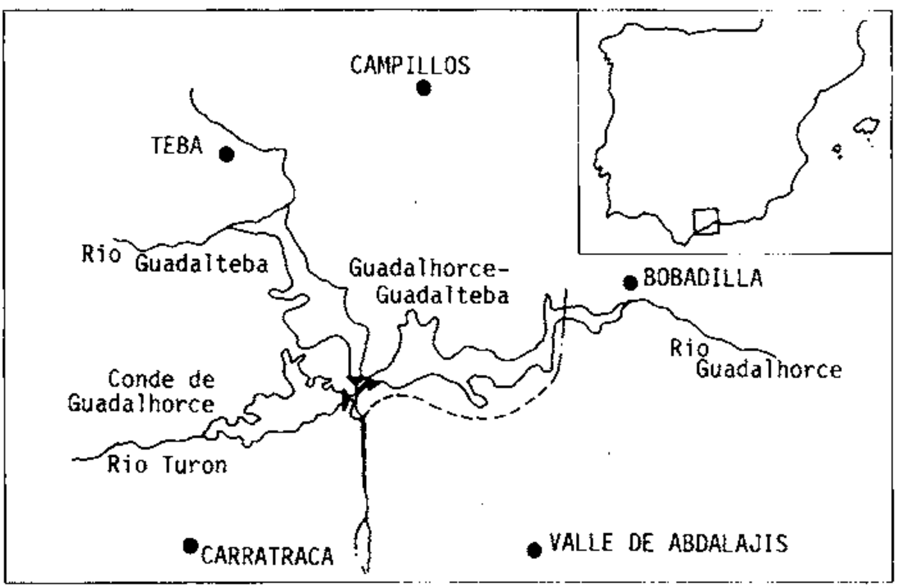

Figure 1. Location of the Guadalhorce Reservoirs System.

Table 1. Hydrographic and morphometric characteristics of the Guadalhorce Reservoirs System.

	Conde de Guadalhorce	Guadalteba	Guadalhorce
Altitude (a. s. l.) (m)	342	364	364
Volume (Hm^3)	83	164	148
Surface (ha)	510	796	759
Maximum depth (m)	37	58	58
Mean depth (m)	16,8	20,6	19,5
Catchment area (Km^2)	270,5	---------- 1431	--------
Average annual flow (Hm^3)	39,5	73,6	49,7
Residence time (days)	767	813	1087

STUDY AREA

Guadalhorce System is formed by three reservoirs placed in the confluence of the Guadalhorce river with its two larger tributaries (Turón and Guadalteba rivers); (Fig. 1, Table 1). They are situated in the NE foothills of the Serranía de Ronda (Málaga, SE Spain) and have the hydrological influence of two very different areas. Thus, Conde de Guadalhorce reservoir is located in the Turón river which drains the karstic area of Serranía de Ronda. Its water composition is dominated by salts coming from the dissolution of calcite and dolomite. In contrast, Guadalhorce reservoir, placed in the river of the same name, has its catchment area in the endorreic zone of Antequera. As a consequence, the dissolved mineral content of the water is higher and it is dominated by chloride and sulfate ions. In addition, a spring which is sometimes submerged (manantial de Meliones) delivers an average flow of 20 l s^{-1} of dense saline water (80-140 g l^{-1}) (Rodríguez Paradinas personal communication) to the deep part of the reservoir. As a result of both kinds of inputs, Guadalhorce becomes meromictic. Finally, Guadalteba reservoir is situated in an intermediate position. Its drainage basin also lies in the endorreic area of Antequera and it receives some deepwater coming from the Guadalhorce reservoir. Therefore, there is an accumulation of saline water in the bottom and it also becomes meromictic.

METHODS

The study of the Guadalhorce Reservoir System was carried out along 1988. Two samples were taken in each reservoir, corresponding to the mixing (9/3/88) and stratification (15/9/88) periods. Temperature and conductivity profiles were measured in situ wit th a WTW conductivimeter while pH and Eh were determined at each sampling depth with an Orion mod. 231 pH & Eh-meter supplied with Ross electrodes.

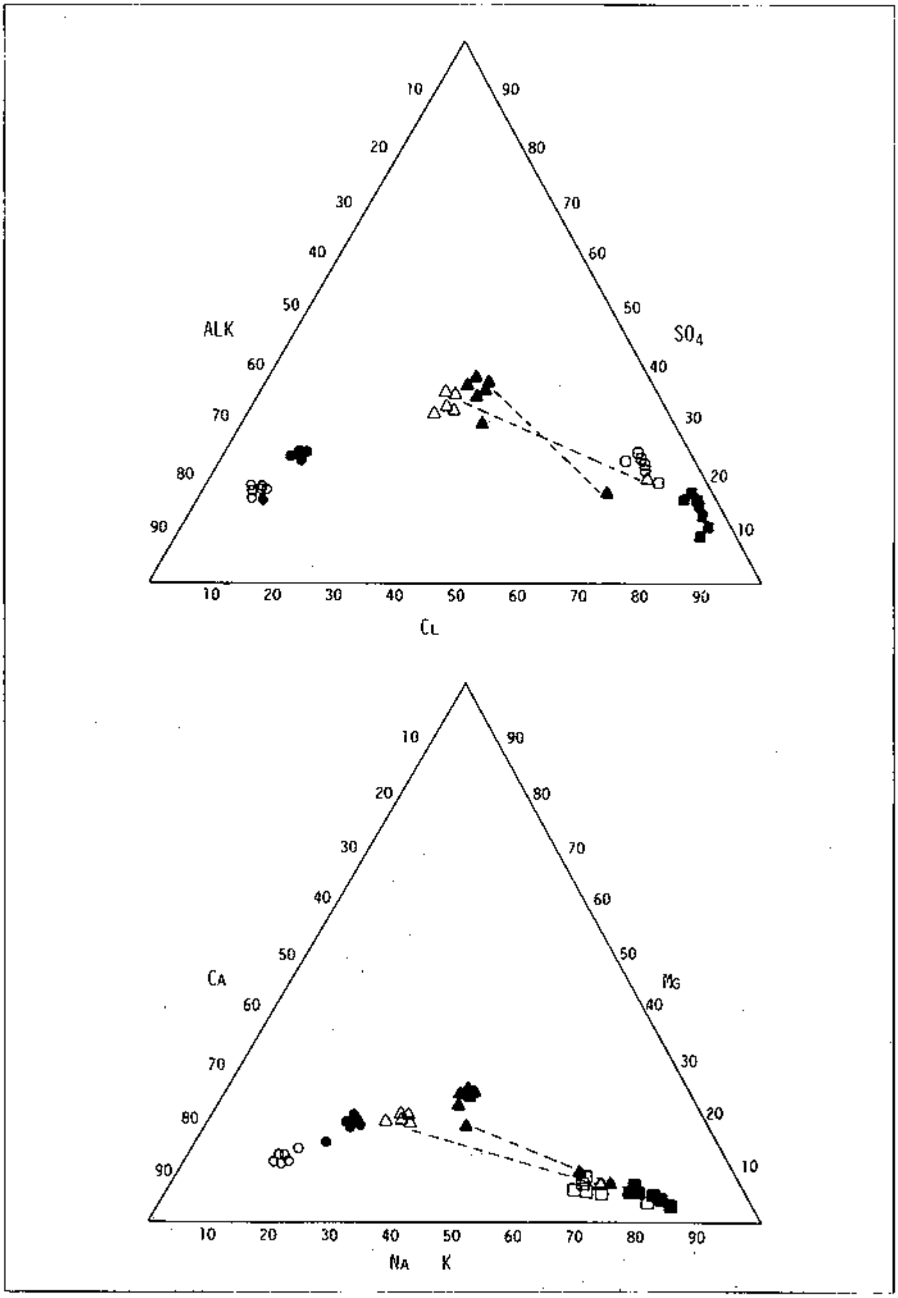

Figure 2. Relative anionic and cationic water composition along the vertical profiles of Conde de Guadalhorce (○), Guadalteba (△) and Guadalhorce (□) in winter (open symbol) and in summer (full symbol).

Some analysis, such as alkalinity and hydrogen sulfide by volumetric titration (Standard Methods, 1980) or the O_2 concentration and the dark bottle respiration by Winkler's method (Golterman, 1969), were immediately performed in order to prevent quick changes in the samples concentration.

Water samples were first frozen in liquid nitrogen and then conserved at -20 °C until they were taken to the laboratory. The following parameters were measured from water samples in the laboratory: SO_4^{2-} and Cl^- were determined by Ionic Chromatography; Na, K and Mg by Atomic Absortion Spectrometry; Ca, Fe, Mn, Cu, Al and total Si by Induced Coupled Plasma; Particulate organic carbon (POC) and nitrogen (PON) by means of a Carlo Erba CNH Analyzer and soluble reactive phosphate (SRP), nitrate, nitrite a and ammonia with a Technicon Autoanalyzer, according to the method of Grashoff et al. (1983), modified for freshwater analysis.

The chlorophylls were determined by a HPLC system according to Mantoura & Lewellin (1983), while phycobilins were extracted by the method of Stewart & Farmer (1984) and calculated after Siegelman & Kycia (1978). Phytoplankton countings were carried out u using Uterm÷hl's method. Finally, the respiratory electron transport (ETS) activity was measured following Packard et al. (1989).

RESULTS

Relative ionic composition

The Piper diagram (Fig. 2) shows the main differences in the major ionic components of water. Guadalhorce and Conde de Guadalhorce have respectively high saline and carbonate waters with minor differences in their relative composition along the vertical profile. On the contrary, Guadalteba has two types of water: while in the mixolimnion there is not a dominant ion, the monimolimnion has a saline type of water, very similar to that found in the Guadalteba reservoir production.

Thermal and chemical stratification

Conde de Guadalhorce is the least saline reservoir, because water is dominated by carbonate and calcium. The conductivities range between 378 and 441 $\mu S\ cm^{-1}$. In these conditions only thermal stratification is achieved (Fig.e 3). In summer there is an important outflow of deepwater, the thermocline falls close to the bottom and a 2 m thick hypolimnion can only be found.

In Guadalhorce reservoir, the water coming from the saline spring of Meliones accumulates in the bottom, displaces the less dense water, and forms a monimolimnion. In winter this deep zone remains well differentiated from the mixolimnion. During the summer heating the thermocline plunges while the halocline raises due to the accumulation of saline water. At the end of summer they are joined and only an hypolimnion can be seen (Fig. 3).

The Guadalteba reservoir has the most complex pattern of stratification (Fig. 3). The water coming from its catchment area reaches conductivities between 900 and 975 µS cm⁻¹ and it follows the same pattern of thermal stratification as Conde de Guadalhorce. At the same time, it receives deep saline water inputs from

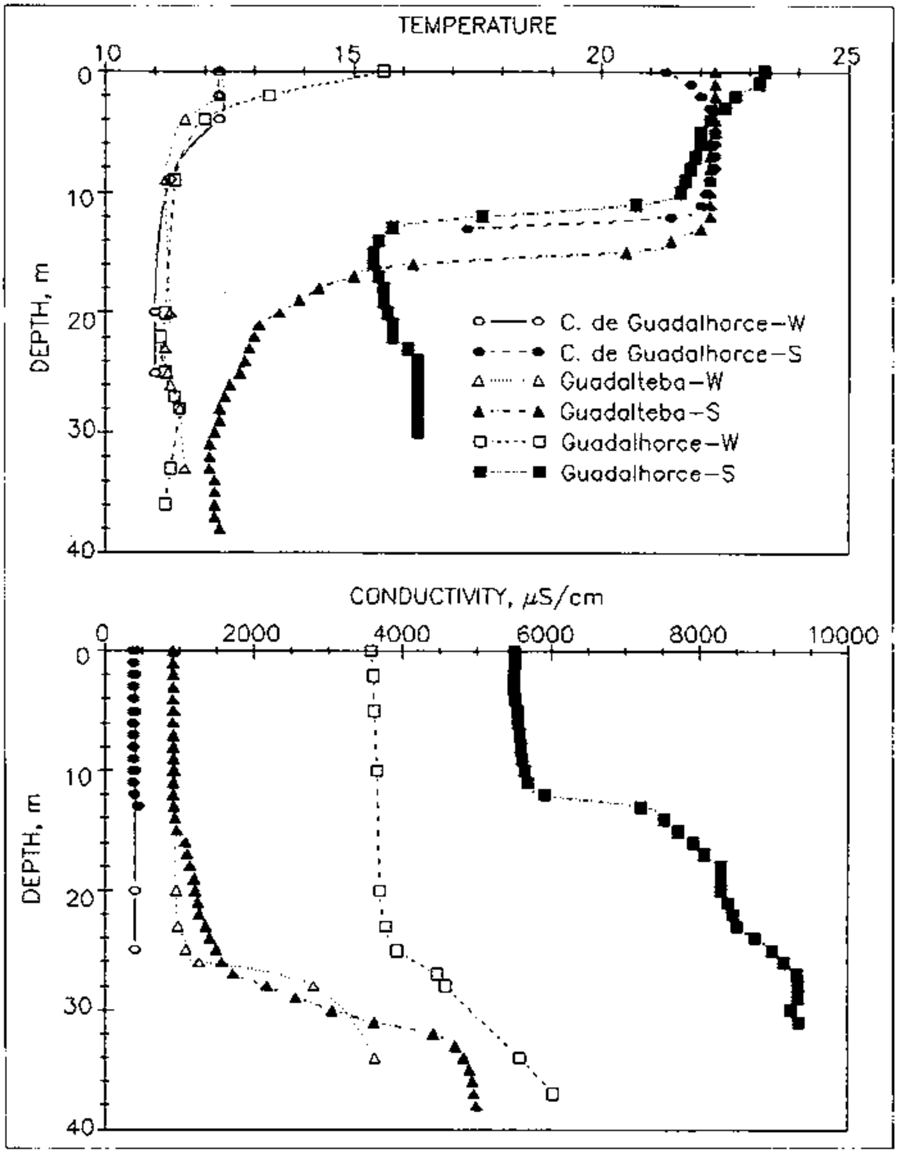

Figure 3. Vertical profiles of temperature and conductivity at 25 °C.

Table 2. Pearson's correlation coefficient between ETS and several environmental parameters in Conde de Guadalhorce and Guadalteba reservoirs. N.S. without significant correlation; $*p < 0,01$; $** p < 0,001$.

	Conde de Guadalhorce ETS	Guadalteba ETS
Respiration	0,88**	NS
POC	NS	0,98**
PON	NS	0,99**
Chl-a	0,73*	0,97**

Guadalhorce that are accumulated in a deep layer at the bottom. In these conditions the differentiation of a mixolimnion and a monimolimnion is very clear during all the year, but it is specially important in summer when an independent thermocline and halocline are developed.

Electron transport system and biological activity

The respiratory electron transport system (ETS) is the biochemical machinery responsible for oxygen consumption. From an ecological point of view, its measure gives an estimation of the maximum respiratory capacity of organisms. As we had so many problems with of accuracy with the respiratory values obtained by means of the dark bottle method, we have used the ETS data as the main estimate of the respiration. Unfortunately, samples from Guadalhorce reservoir were not well conserved, so we have no ETS data of the two samplings and of winter chlorophyll concentration.

In the other two reservoirs, ETS is highly correlated with chlorophyll-a concentration (Table 2), showing the prominence of primary producers. In general, ETS values were higher in winter than in summer (Fig. 4). Thus, in the surface waters of Guadalteba a, a very high maximum value of 230 $\mu l\ O_2\ l^{-1}\ h^{-1}$ was measured due to a bloom of *Anabaena variabilis* (291 mg Chl-a m^{-3}). In contrast, lower values were found in Conde de Guadalhorce where only 3,19 $\mu l\ O_2\ l^{-1}\ h^{-1}$ were attained at the surface with 2,7 mg Ch hl-a m^{-3}. At the end of summer, results of ETS show an important decrease of the potential respiratory activity, that is to say, of alive biomas. In Guadalteba the maximum value measured in summer was 5,21 $\mu l\ O_2\ l^{-1}\ h^{-1}$ while in Conde de Guadalhorce was o only 0.52 $\mu l\ O_2\ l^{-1}\ h^{-1}$, found near the bottom (Fig. 4).

When other biomass related parameters are compared with ETS results, the reservoirs show a divergent behaviour. In Guadalteba reservoir ETS and chlorophyll-a concentration are well correlated with particulate organic carbon (POC) and nitrogen (PON) (Table 2), showing the dominance of phytoplankton in the particulate organic matter. In contrast, ETS values in Conde de Guadalhorce are highly correlated with the dark bottle respiration. Although the correlation of ETS with chlorophyll-a is also significant t at the 0,05 level, it is lower than in Guadalteba, and there are no correlations with POC and PON (Table 2). These results suggest two processes with regard to the particulate organic matter: 1) In spite of the phytoplankton being the most important sou urce of respiratory activity,

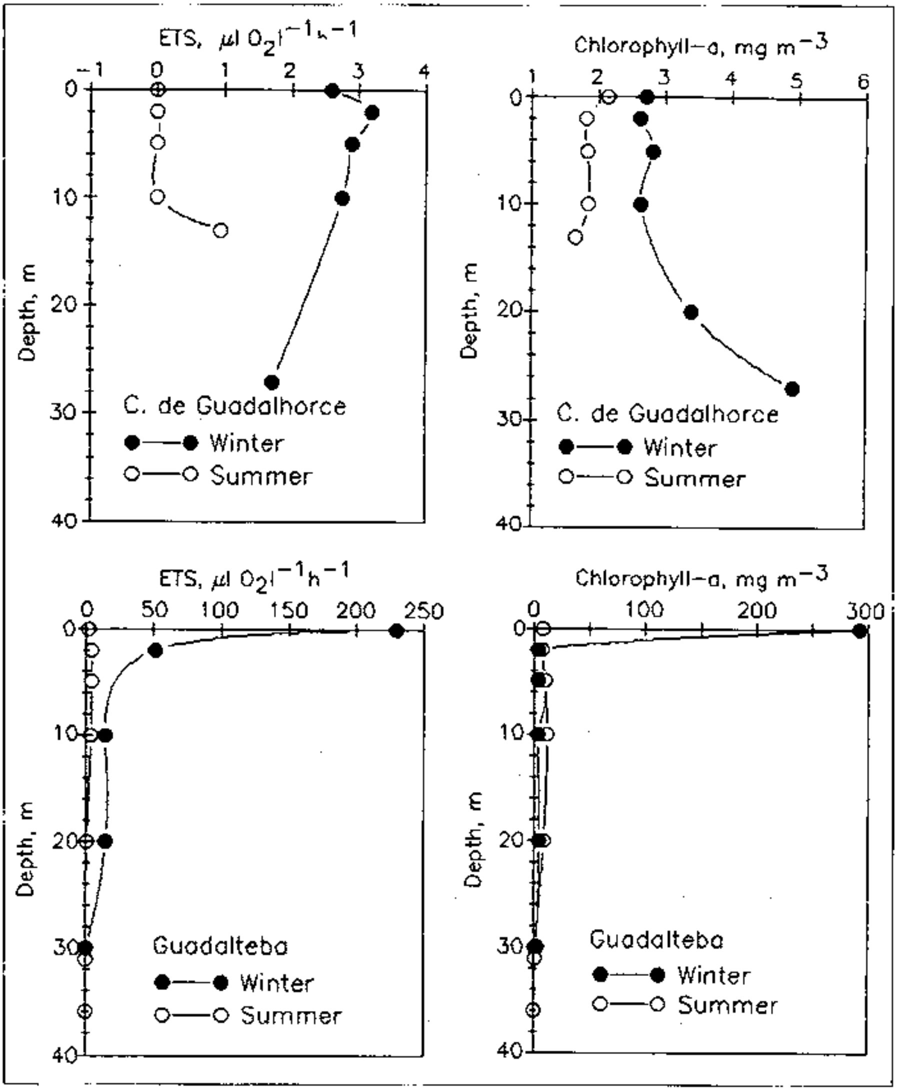

Figure 4. Vertical distribution of ETS activity and chlorophyll-a concentration.

zooplankton and decomposing bacteria have also its share 2) There are high quantities of organic matter not related with ETS, i.e. of detrital organic matter.

Environmental conditions associated to Eh profiles

As a consequence of the thermic and haline stratification beyond biological activity, the three reservoirs show important gradients of redox potential. While in winter the Eh profiles are not so strong as in summer, in the meromictic reservoirs some important differences between the mixolimnion and the

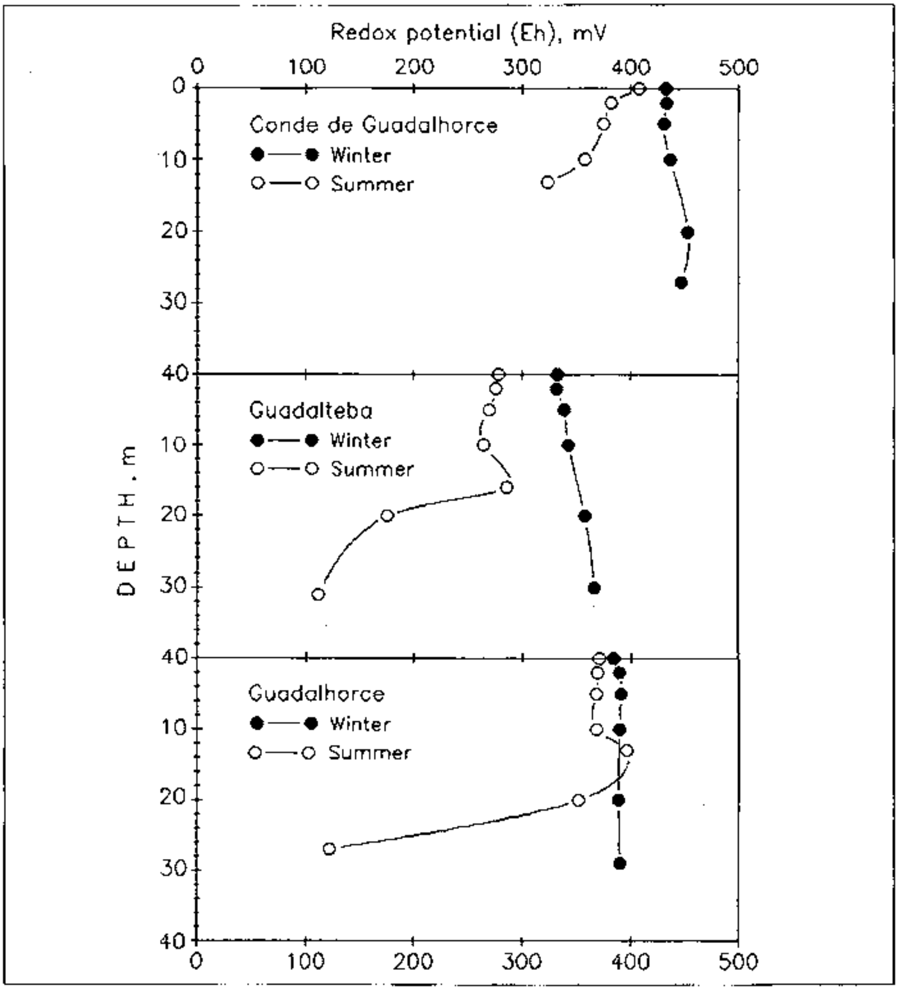

Figure 5. Distribution along the vertical profiles of redox potential.

monimolimnion can be found along the year. The summer Eh profiles are positively correlated at the 0,05 level with temperature (r=0,71), oxygen (r=0,57) and nitrate (r=0,52) concentrations and have high negative correlations with manganese (r=-0,66), hydrogen sulfide (r=-0,78), ammonia (r=-0,71) and SRP (r=-0,70) showing the presence of an abrupt oxycline, similar to those found at the end of summer in an eutrophic reservoir. In contrast, all Conde de Guadalhorce reservoir is holomictic and does not show any abrupt changes in the Eh profiles neither in winter or in summer. Only minor increases in the ammonia (29,44 µM) and manganese (10,4 µM) related with low oxygen concentrations (0,7 mg l^{-1}) were

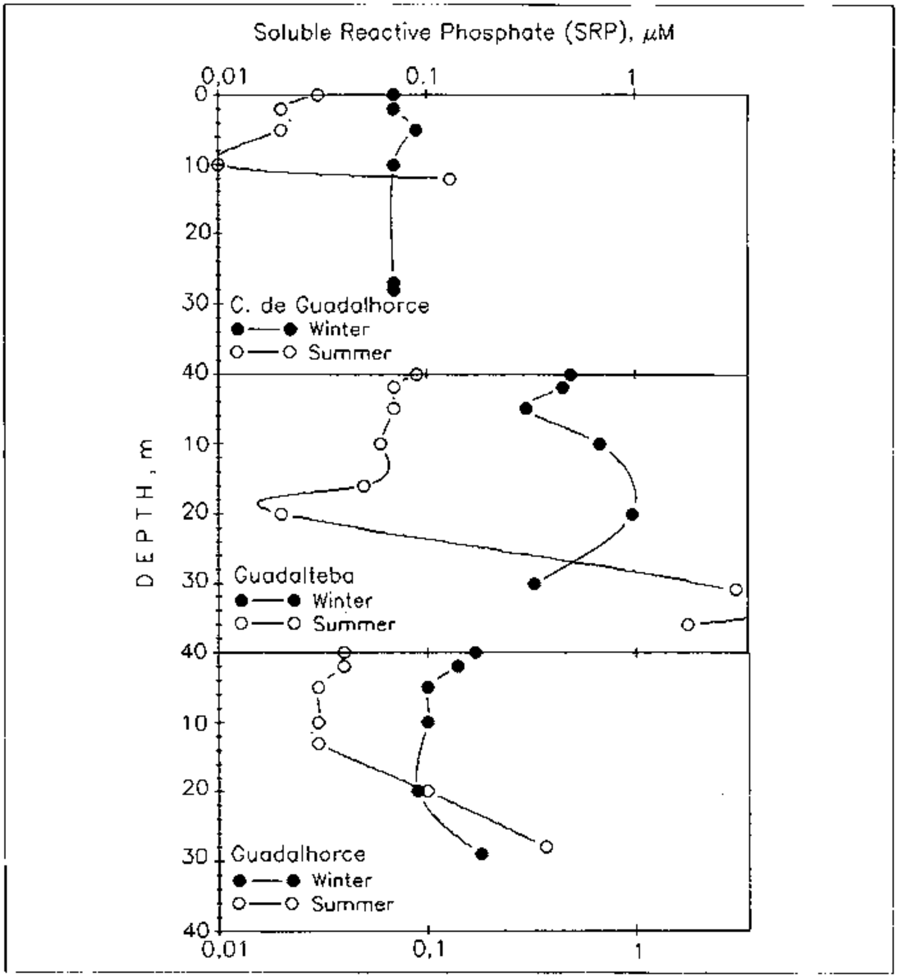

Figure 6. Vertical profiles of soluble reactive phosphate (SRP)

measured in the narrow 2 m hypolimnion. In the other two meromictic reservoirs, the monimolimnion were almost oxygen depleted in winter but without an equivalent increase in the H_2S and NH_4 concentrations. The saline water of the Meliones spring comes into Guadalhorce reservoir at the surface, or close to it, depending on the water level, and then falls to the bottom. This represents the injection of a certain amount of oxygen and nitrite associated with a reduction of SRP concentration by precipitation. This process can explain the low winter levels of hydrogen sulfide and ammonia, and the presence of some oxygen in the monimolimnion of the reservoirs. In Guadalteba reservoir the saline water of the bottom comes from Guadalhorce, and therefore the Eh and associated parameter profiles have the same, but stronger trends.

Nutrient and chlorophyll concentration and its relationship with the trophic status

Guadalteba and Guadalhorce should be classified as eutrophic because of the oxygen depletion and the high hydrogen sulfide and ammonia concentration in their hypolimnion. But if we consider that the meromixis of these reservoirs prevents the complete turnover of the nutrients, other variables must be used in order to establish their trophic status.

Although the three reservoirs have quite different nutrient concentration (for instance, the total soluble nitrogen, which is the sum of nitrate, nitrite and ammonia, range between 32 and 290 μM), they have in common a very low SRP. Thus, in summer the monimolimnetic concentrations of SRP are higher than 0,1 μM, while in winter, during the turnover period, they are lower than 0,2 μM (Fig. 6). In these conditions the N/P rate is nearly always over 1000, showing the limitant role of phosphorus in these reservoirs.

A more realistic estimate of the trophic characteristics of the reservoirs can be obtained by means of the chlorophyll concentration. According to Margalef (1983) only Conde de Guadalhorce can be considered as mesotrophic because it has less chlorophyll.

In Conde de Guadalhorce vertical chlorophyll distribution is very uniform both in winter and summer. In the photic zone, 2,5 times the Secchi disc depth, only between 30% and 40% of the total chlorophyll is accumulated. Because of the shallowness of the water and of the 2 m thick hypolimnion, almost all the profile is well mixed even in summer, and this prevents the loss of phytoplankton to the dark zone of the reservoir.

The Guadalhorce reservoir, from which only summer samples are available, has high chlorophyll concentration (> 10 mg Chl-*a* m^{-3}) over the thermocline.This accounts for more than 90% of the total vertical concentration.

Finally, the Guadalteba reservoir shows the more complex vertical distribution of photosynthetic pigments. In winter a very strong bloom of *Anabaena variabilis* which takes place in the surface represents more than 290 mg Chl-a m^{-3}. This concentration is only comparable to the neustonic blooms which appears in few eutrophic ponds (Catalan, 1984). Because *Anabaena variabilis* is a blue green algae, very important concentrations of phycocyanin (249 mg m^{-3}) and allophycocyanin (148 mg m^{-3}) are also present. In winter the chlorophyll maximun is situated in the limit of the photic zone. There around 10 mg chl-a m^{-3} has been measured over a nitrite maxima that may be the result of the algae excretion (Margalef, 1983).

In all the reservoirs the degradation pigments of the chlorophyll (phaeophytin, phaeophorbide and chlorophyllide) are less than 5% of the total pigments. These results show that there is a very slow phytoplankton degradation when it falls to the bottom.

Planktonic and benthic communities

The phytoplankton communities of the three reservoirs are dominated by colonial green and blue green algae. In contrast, centric diatoms and cryptomonads are only abundant in particular conditions, while chrysophytes and dinoflagellates have an occasional presence. The taxa are, in general, very common and widely distributed in the eutrophic Spanish reservoirs.

In summer the most abundant species in the phytoplankton of Guadalteba are *Cosmarium vexatum* and *Oocystis lacustris*, and *Microcystis aeruginosa* near the surface. In Conde de Guadalhorce the community is dominated by *Cyclotella comensis* and *Coelosphaerium kutzinqianum*. Finally, the Guadalorce reservoir has a more diversifield community. *Oocystis lacustris, Radiococcus nimbatus, Coelosphaerium kutzingianum, Merismopedia tenuissima* and *Microcystis flos-aquae* are de most important species. In this reservoir the presence of the centric diatom *Chaetoceros muelleri* is indicative of the high salt concentration there.

During winter the number of taxa is reduced, specially in Guadalteba where an important bloom of *Anabaena variabilis* (265.000 cels ml-1) takes place. In the other two reservoirs the green algae disappear. *Stephanodiscus hantzschii* is the only dominant species in Conde de Guadalhorce, while in Guadalhorce *Rhodomonas minuta var. nannoplanctonica* and *Cryptomonas ovata* are the most abundant planktonic species.

From a more general point of view, the rates between chlorophyll *a*, *b* and *c* also reflect the phytoplankton composition. When blue green algae are dominant (Guadalteba in winter and Guadalhorce in summer) Chl-*a*/Chl-*b* values are higher than 40 (w/w) and chlorophyll-*c* concentration is near 0. In contrast, when diatoms are the most abundant group (Conde de Guadalhorce in winter) the Chl-*a*/Chl-*c* index ranges between 5 and 10. Finally, the most diversified phytoplankton of Conde de Guadalhorce has intermediate Chl-*a*/Chl-*b* and Chl- *a*/Chl-*c* values (10-30 w/w) in summer.

Like the phytoplankton, the rotifera communities are dominated by common species typical of eutrophic reservoirs (Margalef et al., 1976). The temporal and spatial differences in the communities of the Guadalhorce System are mainly due to changes in the dominance of the most frequent species such as *Keratella* *cochlearis*, *Keratella quadrata*, *Sychaeta oblonga*, *Polyarthra vulgaris* and *Asplanchna priodonta*. Moreover in summer they are more diversified in addition to several warm stenotherm species as *Hexarthra fennica*, *Trichocerca similis* and *Filinia longiseta*. In this season some species with tropical distribution which usually appear in the Southernmost Spanish reservoirs were also present. This is the case of *Keratella tropica* and *Filinia opoliensis*.

The crustacean communities are, in general, simplified, dominated by cladocerans and with few changes in their composition along the year. The basic community is composed by two copepoda, *Lovenula alluaudi* and *Acanthocyclops robustus*, and a dominant species of cladocera. In winter, *Daphnia longispina* is the most important crustacea in Guadalteba and in Conde de Guadalhorce and is replaced by *Daphnia magna* in the most saline waters of Guadalhorce. During summer the number of species is even smaller reduced, and *Diaphanosoma mongoliatum* becomes the most abundant crustacea (between 50,93% and 96,3%). Other species of wide distribution in the Spanish reservoirs such as *Bosmina longirostris* and several *Ceriodaphnia (C. dubia, C. reticulata and C. quadrangula)* are also present, but without a clear temporal pattern and with low densities.

The benthic fauna of the three reservoirs is strongly influenced by the meromixis and the trophic conditions. During the oxygen depletion period, the benthos disappears (Guadalteba and Guadalhorce in summer) or is only represented by 1 or 2 species at low densities (Guadalhorce in winter). For this reason well developed benthic communities are found only in Conde de Guadalhorce and in the winter Guadalteba bottoms.

In Conde de Guadalhorce the most abundant chironomid species are *Procladius sp.* (with a maximum density of 2517 ind/m^2), *Tanypus punctipennis* and *Microchironomus sp.* which are characteristic of mesotrophic lakes and reservoirs. These species are predators of ostracoda and small oligochaeta which live in well oxygenated waters. The oligochaeta are mainly represented by *Limnodrilus hoffmeisteri* (between 17 and 25 ind/m^2) and a large number of immature *Limnodrilus sp.* (513 ind/m^2).

The Guadalteba reservoir has a completely differentiated benthic community dominated by oligochaeta. In winter, the only period with benthic fauna, the more important chironomids are *Stictochironomus sp.* and *Chironomus plumosus* which live in eutrophic lakes and reservoirs with low oxygen content. The oligochaeta fauna is more diversified than in Conde de Guadalhorce. Besides *Limnodrilus hoffmeisteri*, other low oxygen tolerant species such as *Limnodrilus claparedeianus* and *Branchiura sowerbyi* are present.

DISCUSSION

Guadalhorce and Guadalteba can be considered as eutrophic because of their high biomass, mainly due to phytoplankton and to the high overall metabolic rate measured by the ETS activity. This was also the result of the study carried out fourteen years ago by Margalef et al. (1976). In fact the limnological characteristics have not changed significatively. However, it is necessary to distinguish Conde de Guadalhorce from Guadalhorce and Guadalteba. These last two reservoirs were first filled in 1971 and 1973 respectively. This means that in the 1972-75 sampling they were at the beginning of their evolution. In this conditions their trophic status had, fourteen years ago, a different meaning it has in the present.

Conde de Guadalhorce was classified as mesotrophic according to the typology of Margalef et al. (1976) and its status has not changed. Although in the present there is a large quantity of organic matter, POC and PON are not correlated neither with chorophyll concentration nor with ETS activity.

The meromixis is one of the most important factors in the seasonal dynamics and can change from year to year because of human activity. Moreover its crenogenic origin the meromixis, can be modified by the selection of the level from which the water runs off.

From the communities' point of view, few changes have been taken place since 1972-75. In general, the three reservoirs have planktonic communities composed by widely distributed species in the Spanish reservoirs. The main changes in the zooplankton communities have been the disappearance of some heleoplanktonic species, such as *Tropocyclops prasinus* (Armengol, 1978) or the presence of species with tropical affinities like *Keratella tropica* (A. Guiset, personal communication).

The benthic fauna appears as the set of species more closely related with the trophic characteristics of the three reservoirs. While in the most eutrophic Guadalhorce reservoir there is not benthic fauna, Guadalteba remains eutrophic and Conde de Guadalhorce mesotrophic using the chironomids (Prat, 1978) and oligochaeta (Martínez-Ansenil & Prat, 1984) as indicators of the trophic status of the reservoirs.

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