Temperature and dissolved oxygen in lakes of the Lower Orinoco River floodplain (Venezuela)

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ABSTRACT

For two years, temperature and dissolved oxygen (DO) measurements were taken from five floodplain lakes of the Lower Orinoco River on a monthly basis. For several of these lakes, diel cycles of temperature and DO were also measured. Thermal gradients were usually small (ca. 1 °C from top to bottom); gradients of 3 °C were observed at high water in two lakes. Considering the generally weak and unstable thermal stratification, these bodies of water could be classified as continuous warm polymictic lakes. In all lakes, the DO showed a highly significant negative relationship with water depth. The lakes were generally below DO saturation. Although anoxic conditions were rarely observed, hypoxic conditions did develop in all the lakes during the high water phase, and persisted through the falling water phase. At low water, no DO stratification was recorded, suggesting a continuous mixing of the water column. The absence of marked thermal stratification during this phase could be explained by the general shallowness of the lakes, which would allow wind and nocturnal convection to erode thermal stratification. At high water, when lake depths increase, the entrance of river water into the lakes reduces the likelihood of development of a strong and stable thermal stratification. During this phase, however, the weak thermal gradient was sufficient to prevent the mixing of the water column for several weeks. DO and thermal properties of the Orinoco lakes seem to be strongly affected by the morphometric characteristics of these water bodies independently of the river floodwave.

KEY WORDS : Temperature, Oxygen — Seasonality — Floodplain lakes — Orinoco River — South America.

RÉSUMÉ

TEMPÉRATURE ET OXYGÈNE DISSOUS DANS LES LACS DE LA PLAINE D'INONDATION DU BAS ORÉNOQUE (VENEZUELA)

Des mesures mensuelles ont été faites sur cinq lacs pendant deux ans. Des cycles nycthéméraux ont également été observés. Le gradient thermique vertical était généralement faible (de l'ordre de 1 °C de la surface au fond) mais des différences jusqu'à 3 °C ont pu être observées durant les hautes eaux dans deux des lacs. D'une façon générale, ces lacs peuvent être classés comme polymictiques chauds. Dans tous les lacs, l'oxygène dissous était corrélé négativement avec le niveau de l'eau, les lacs étant en général en dessous de la saturation. Une hypoxie s'est développée durant les hautes eaux dans les cinq lacs, persistant durant la décrue. En basses eaux, il n'y a pas de stratification d'oxygène, ce qui indique une circulation verticale de la masse d'eau. Celle-ci résulte de la faible profondeur du milieu qui favorise l'influence du vent et du refroidissement nocturne. En période de hautes eaux, lorsque le niveau monte, l'arrivée de l'eau dans les lacs réduit la probabilité de développement d'une stratification stable et durable. Cependant le faible

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gradient thermique peut s'opposer à une circulation pendant plusieurs semaines. La morphométrie des différents lacs de l'Orénoque apparaît comme facteur déterminant dans la distribution de la température et de l'oxygène dissous.

MOTS CLÉS : Température — Oxygène — Plaines d'inondation — Orénoque — Amérique du Sud.

RESUMEN

TEMPERATURA Y OXÍGENO DISUELTO EN LAS LAGUNAS DE INUNDACIÓN DEL BAJO ORINOCO, VENEZUELA

Se efectuaron mediciones mensuales de temperatura y de oxígeno disuelto (OD) durante 24 meses en cinco lagunas de inundación ubicadas en el Bajo Orinoco. Adicionalmente, se efectuaron mediciones semanales y ciclos diarios de temperatura y de OD (aguas altas y aguas bajas) en algunas de estas lagunas. Los gradientes térmicos fueron generalmente débiles (ca. 1 °C entre la superficie y el fondo). En aguas altas, se observaron gradientes superiores a 3 °C en dos lagunas. Estas lagunas pueden ser clasificadas como cálidas polimícticas continuas dadas las estratificaciones térmicas débiles e inestables que generalmente presentan. En todos estos cuerpos de agua el OD presentó una relación negativa altamente significativa con la profundidad del agua. Todas las lagunas se presentaron generalmente subsaturadas de OD. A pesar de que raramente se observaron condiciones de anoxia, en aguas altas se observaron condiciones de hipoxia que persistieron hasta la época de aguas en descenso. En aguas bajas no se observó estratificación de OD lo cual sugiere una mezcla continua de la columna de agua. La ausencia de una estratificación térmica fuerte durante esta fase podría explicarse por la someridad general de las lagunas lo cual permitiría la erosión de toda estratificación por la acción del viento y por la convección nocturna. En la fase de aguas altas, cuando las profundidades de las lagunas aumentan, la entrada de aguas del río reduce la posibilidad de desarrollo de una estratificación térmica marcada y persistente. Durante esta fase, sin embargo, el escaso gradiente térmico observado fue suficiente como para evitar la mezcla de la columna de agua por varias semanas. Tanto el OD como la temperatura de las lagunas del Orinoco aparentan encontrarse bajo la influencia marcada de las características morfométricas de estos cuerpos de agua independientemente de las crecidas estacionales.

PALABRAS CLAVES : Temperatura — Oxígeno — Estacionalidad — Lagunas de inundación — Río Orinoco — Sur América.

INTRODUCTION

The Orinoco has three distinct floodplain types : 1) the fringing floodplain (7 000 km^2), 2) the internal deltaic floodplain (70 000 km^2) in the vicinity of the Apure and Arauca rivers, and 3) the coastal deltaic floodplain (20 000 km^2). As a whole, these areas rank the Orinoco basin as one of the most important wetland sites in the neotropics (HAMILTON and LEWIS, 1990a). The floodplain is under the dynamic influence of erosive and sedimentary processes that cause continual change in complex formations composed of islands, bars, levees, floodplain lakes, and swamps. The floodplain has some 2 300 lakes that retain water during the dry season ; these cover 5-12 % of the Orinoco fringing floodplain. At high water, these lakes may lose definition as they merge into a continuous sheet of water covering the entire region (VÁSQUEZ, 1989 ; HAMILTON and LEWIS, 1990a).

On the Orinoco floodplain, relatively small changes of water level cause large changes in the area of inundation (VÁSQUEZ, 1989). Seasonal cycles in physical, chemical, and biological variables are mainly explained by the seasonality of river discharge (JUNK *et al.*, 1989). HAMILTON and LEWIS (1990b) for example, observed that, at low water, the Orinoco lakes showed a chemical divergence caused by differing rates of sedimentation of inorganic particles, nitrate depletion, and phytoplankton growth. In addition, SÁNCHEZ and VÁSQUEZ (1986) found a divergence in species composition and plant cover of aquatic macrophytes at low water among different lakes.

The seasonal pattern of dissolved oxygen (DO) is a highly valuable descriptor of the functioning of floodplains because it reflects the balance between production and decomposition (NEIFF, 1990). Temperature is an important companion variable because it indicates the vertical gas exchange between the bottom and surface of the water column. The present study gives the results of seasonal and diel studies of temperature and dissolved oxygen in five Orinoco floodplain lakes.

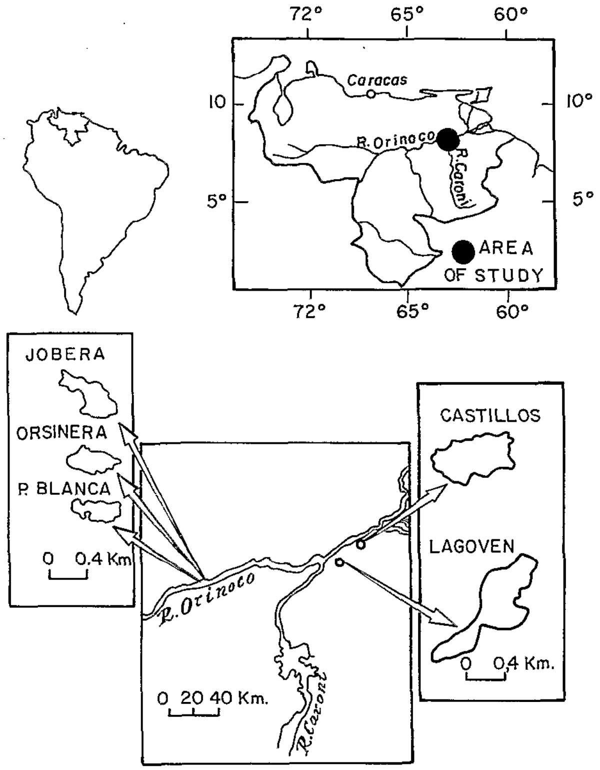

FIG. 1. — Location of lakes Playa Blanca, Orsinera, Jobera, Lagoven, and Castillos on the Orinoco floodplain.
Situation des lacs étudiés dans la plaine d'inondations de l'Orénoque.

RESEARCH SITES AND METHODS

The five permanent floodplain lakes considered in this work are : Playa Blanca, Orsinera, Jobera, Lagoven, and Castillos (Fig. 1). They are located in the lower section of the Orinoco River fringing floodplain. A detailed morphological description of these lakes is given by VÁSQUEZ (1989), who classified them as lateral levee lakes, a common type in the Orinoco floodplain. They are formed in areas of sedimentation and generally display relatively slow water movement and a long hydraulic residence time (HAMILTON and LEWIS, 1990b). With the exception of L. Castillos, which during inundation receives the waters of a small intermittent river (the Supamo River), all lakes are inundated only by the main channel of the Orinoco. Morphometric features of the lakes are listed in Table I. These features correspond to the low water period and to the maximum level of water retention in the lakes before complete inundation of the floodplain. The lakes are small and shallow. The ratio of maximum to minimum depth ranged from 14 in L. Playa Blanca to 4.8 in L. Orsinera in relationship with the yearly rise and fall of the Orinoco River (Fig. 2).

In the area of study, the Orinoco River hydrograph usually shows an amplitude ranging from 10 m to 12 m. Four hydrological phases were distinguished among the floodplain water bodies, which are influenced by the river : 1) a low water phase (December-June) ; 2) rising water phase (July-

TABLE I

Morphometric data of the studied lakes
Morphométrie des lacs étudiés

	l (m)		b (m)		L (m)		A (ha)		Dl		l:b		Zmax. (m)	
	Hw	Lw	Hw	Lw	Hw	Lw	Hw	Lw	Hw	Lw	Hw	Lw	Hw	Lw
P. Blanca	690	450	210	200	1900	1500	9.6	5.1	1.73	1.87	3.29	2.25	4.2	0.3
Orsinera	640	590	300	280	1500	1400	12.1	11.5	1.22	1.17	2.13	2.11	5.8	1.2
Jobera	670	560	470	360	2300	1600	14.7	10.1	1.69	1.42	1.43	1.56	4.8	0.6
Lagoven	1120	820	660	580	4400	2400	40.9	29.3	1.94	1.25	1.70	1.41	4.5	0.9
Castillos	860	860	540	540	2000	2300	31.0	27.2	1.01	1.24	1.59	1.59	3.6	0.7

(Hw : high water, Lw : low water). (l : length ; b : breadth ; L : shore line ; A : area ; Dl : development of shore line ; Zmax : maximum depth).

(Hw : en période de hautes eaux ; Lw : en étiage ; l = longueur, b = largeur, L = longueur des rives, A = surface, DI = développement du rivage, Zmax = profondeur maximale.

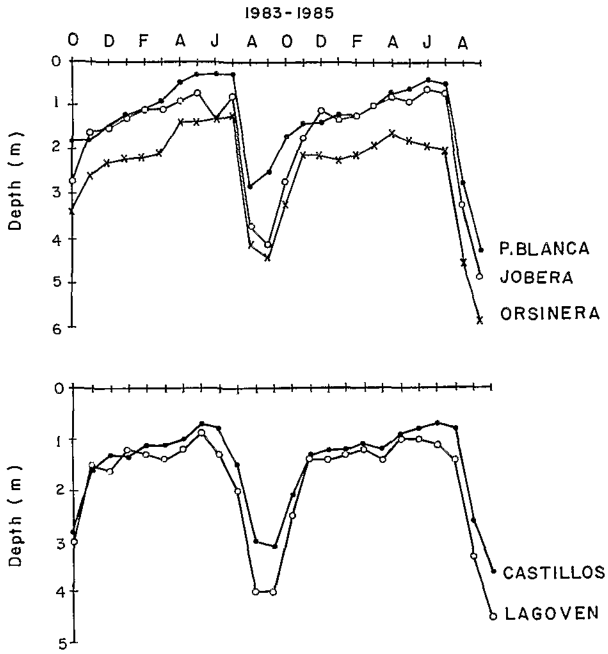

FIG. 2. — Water depth variations in the Orinoco lakes.
Évolution de la profondeur des cinq lacs étudiés dans la plaine d'inondation.

August); 3) a high water phase (August-September); and 4) falling water phase (October-November) (VÁSQUEZ, 1989). The five lakes are surrounded by seasonal várzea forests that are inundated at high water. Seventeen species of floating and emergent aquatic macrophytes have been recorded in the lakes. These aquatic plants are most abundant at high water; highest plant cover was reported for L. Castillos (15.7 %) followed by L. Orsinera (14.7 %), L. Playa Blanca (13.6 %) and L. Lagoven (9.0 %) (SÁNCHEZ and VÁSQUEZ, 1986).

In all lakes, temperature and oxygen profiles were measured monthly during morning hours (8:00-12:00) over a two-year period (1983-1985). The profiles were recorded at 10-cm intervals in an open-water area where water was deepest. From September to November of 1984 (high water and falling water phases), weekly profiles were measured at lakes Lagoven and Castillos. Three diel cycles (every 6 hours) of temperature and DO were recorded in L. Lagoven on August 29-30, 1984 (high water); April 16-17, 1985 (low water); and August 27-28, 1986 (high water). On August 27-28, 1986, diel measurements were also conducted below a mat of floating aquatic vegetation and vertical profiles were measured in the Orinoco River main channel down to 4 m depth and in the channel that interconnects the river to the lake. One additional diel cycle was also recorded in L. Castillos on April 15-16, 1985 (low water). Temperature and oxygen were measured with a YSI meter (model 51B) incorporating a combined thermistor and temperature corrected polarographic probe. When measurements were being taken, the electrode was always gently hand-stirred. Before each profile, the instrument was air calibrated.

The research area is under the influence of the trade winds. Data recorded at Ciudad Bolívar by the Venezuelan Air Force represent a general pattern for the area (Fig. 3). The predominant winds come from the east. Mean monthly wind velocities are highest during the first months of the year; the highest frequency of calm weather (July-September) coincides with the high-water phase of the Orinoco River when the floodplain is inundated and the lakes are deeper. The lowest frequency of calm weather coincides with the low-water phase of the river hydrograph when the lakes are shallowest.

RESULTS

The lowest mean temperature was 27.5 °C; mean DO ranged from 5.0 mg/l to 5.7 mg/l (Table II). The temporal variations of temperature did not show any relationship to lake depths (Fig. 4); a weak thermal stratification was common in the lakes. The differences between the highest and lowest temperatures values were most frequently about 1 °C. The highest gradients of temperature between surface and bottom usually occurred at the high water phase (3 °C, lakes P. Blanca and Lagoven). The generally weak gradients suggest that these lakes mix frequently.

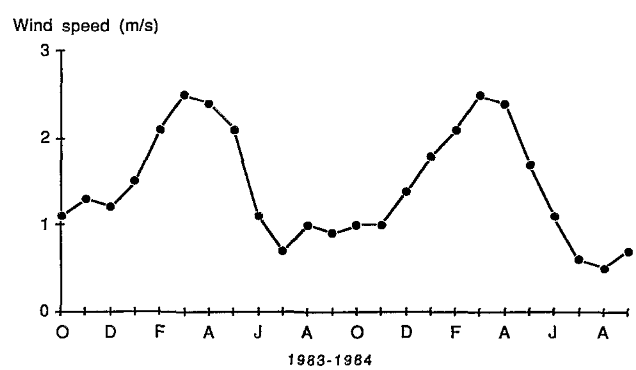

FIG. 3. — Wind speed at Ciudad Bolivar.
Vitesse du vent (moyennes mensuelles) à Ciudad Bolivar.

TABLE II

Temperature and dissolved oxygen values recorded in the studied lakes (minimum, maximum, mean, and standard deviation)
Température et oxygène dissous dans les lacs étudiés (valeurs extrêmes, moyenne et écart-type)

	Temperature				Dissolved oxygen			
	min	max	mean	SD*	min	max	mean	SD*
P. Blanca	27.0	32.5	29.5	1.78	0.2	7.3	5.0	1.98
Orsinera	26.0	31.5	28.4	1.38	0.4	7.6	5.2	1.67
Jobera	26.5	31.0	28.7	1.14	0.4	7.8	5.0	1.71
Logoven	25.2	31.5	28.5	1.11	0.2	7.8	5.5	1.52
Castillos	24.0	29.5	27.5	1.20	1.1	7.8	5.7	1.13

* S.D of the 24 month mean.

Isothermal conditions were found more frequently at low water when wind velocities were highest.

The mean water column DO showed in all lakes a highly significant negative relationship with water depth (L. Playa Blanca : r = −0.93; L. Orsinera : r = −0.87; L. Jobera : r = −0.89; L. Lagoven : r = −0.85; L. Castillos : r = −0.77) (Fig. 5). While lowest DO values were always recorded near the bottom at low water, the magnitude of the DO stratification varied among lakes. L. Jobera showed the largest DO stratification at low water, while L. Castillos generally showed the least severe stratification. All lakes were generally below saturation for DO at all depths. However, anoxic conditions rarely developed in the lakes. Figs. 6-7 show the DO values of Lagoven and L. Castillos recorded for several weeks during the high water and falling water phases. Although in September, hypoxic conditions prevailed near the bottom of both lakes, during subsequent

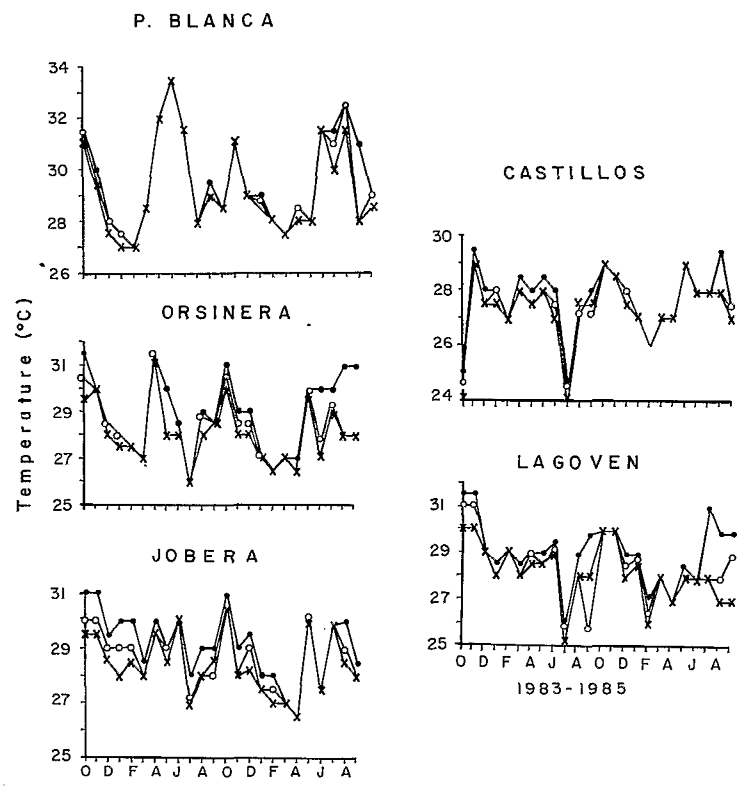

FIG. 4. — Temperatures in the Orinoco lakes (filled circles : surface, empty circles : middle, x : bottom).
Température de l'eau dans les lacs (cercles noirs : en surface; cercles clairs : au milieu et, x : bas de la colonne d'eau).

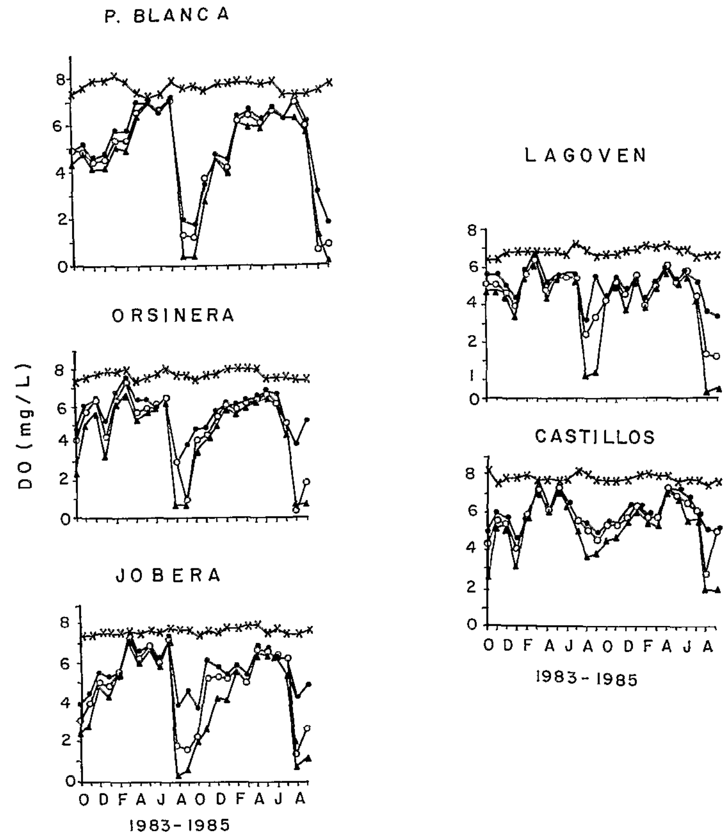

FIG. 5. – Dissolved oxygen concentrations in the Orinoco lakes (filled circles : surface ; empty circles : middle ; triangles : bottom ; asterisks : concentration of dissolved oxygen at saturation determined from in situ surface temperatures).
Concentrations en oxygène dissous dans les lacs de l'Orénoque (cercles noirs : en surface ; cercles clairs : au milieu ; triangles : au fond ; x : concentration à saturation pour la température de surface).

weeks there was a gradual increase in DO values near the bottom. In L. Castillos, higher DO values were reached sooner compared to L. Lagoven where persistent DO stratification lasted longer. This difference may be partly explained by adventive currents of inflowing water from the Supamo River which, together with the Orinoco waters, would contribute to the more rapid increase of DO in L. Castillos.

The diel cycles of temperature and DO measured at high water in L. Lagoven in an open water section of the lake and below a floating macrophyte mat are shown in Figs. 8-10. The open water cycle sometimes showed high surface water temperatures during the day. In 1984, only slight temperature gradients were observed ($\leq$ 1.0 °C); in 1986 the gradients were larger. At 18:00 hrs, for example, the range was 3.5 °C. The DO showed a marked stratification in the open water section of the lake. In August of 1984, the highest DO values extended from the surface down to 1.8 m and sharply decreased toward the bottom. The oxycline gradually deepened and weakened in subsequent profiles (midnight through morning). In August 1986, hypoxic conditions developed around 2.5 m and persisted without weakening or deepening. The highest gradients of DO (up to 5.4 mg/l) were observed during the day.

Temperature and DO profiles under the floating mat of aquatic macrophytes revealed higher superficial temperatures during day with a persistent thermal stratification that never weakened during the period of observation. DO was persistently stratified. At 6:00 hrs (August 28, 1986), anoxic conditions developed from a depth of 2.4 m to the bottom of the lake. While thermal and DO stratification was a common feature of L. Lagoven at high water, the river and the interconnecting channel showed isothermal conditions and lack of DO stratification (Fig.11).

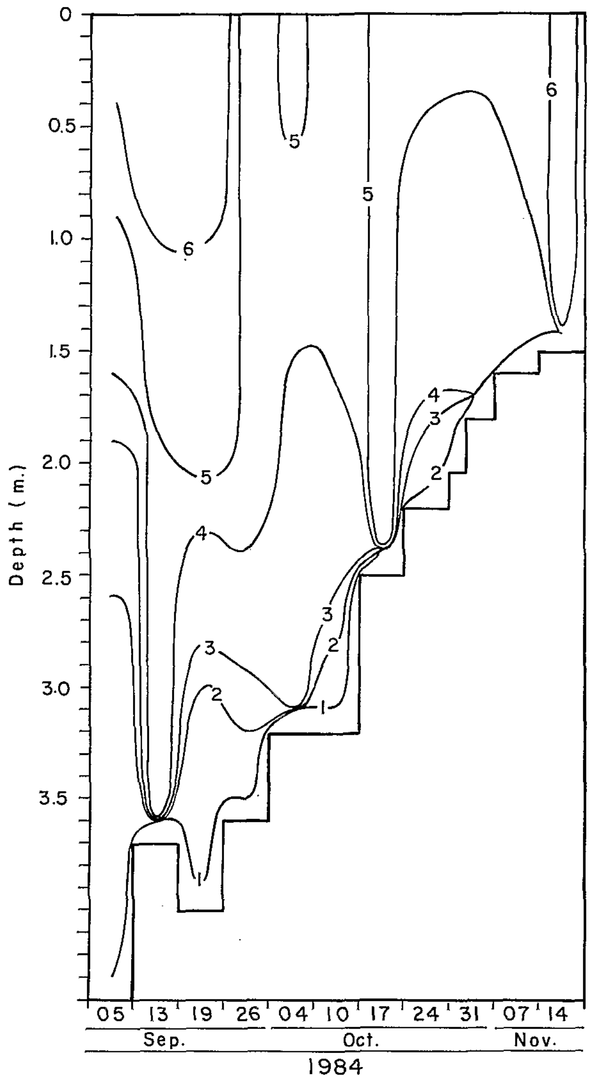

FIG. 6. — Variations of dissolved oxygen measured in Lake Lagoven during the high and falling water phases.
Variations de l'oxygène dissous dans le Lac Lagoven en période de hautes eaux et de récession.

Diel measurements of temperature and DO for lakes Lagoven and Castillos revealed that both lakes were always isothermal to the bottom. DO concentrations paralleled the temperature profiles without any stratification suggesting a continuous mixing of the water column (Fig. 12).

DISCUSSION

Thermal stratification of the lakes was generally weak as a result of reduced lake depths at low water, which also coincide with the maximum wind velocities. At high water, when lake water levels increase and wind velocities are low, the entrance of river water would erode stratification.

Although the Orinoco floodplain lakes show no relationship between mean temperature and depths, Amazon floodplain lakes do show an inverse relationship between water temperature and depth (SCHMIDT, 1973; RAI and HILL, 1981a, 1981b). The seasonal fluctuation of temperature in the Amazon lakes may be explained as a result of their greater depth as compared to Orinoco lakes where the greater depth was 5.8 m (maximum depths of Amazon lakes : L. Calado, 2-12 m, FISHER *et al.*, 1983; L. Jacaretinga, 1-6 m, TUNDISI et al., 1984; L. Cristalino, 4-8 m, TUNDISI *et al.*, 1984; L. do Arroz, 1-7 m, LOPES *et al.*, 1983; L. do Rei, 1-12 m, COLLART and MOREIRA, 1989). In some of these lakes, persistent thermal stratification and anoxic conditions develop

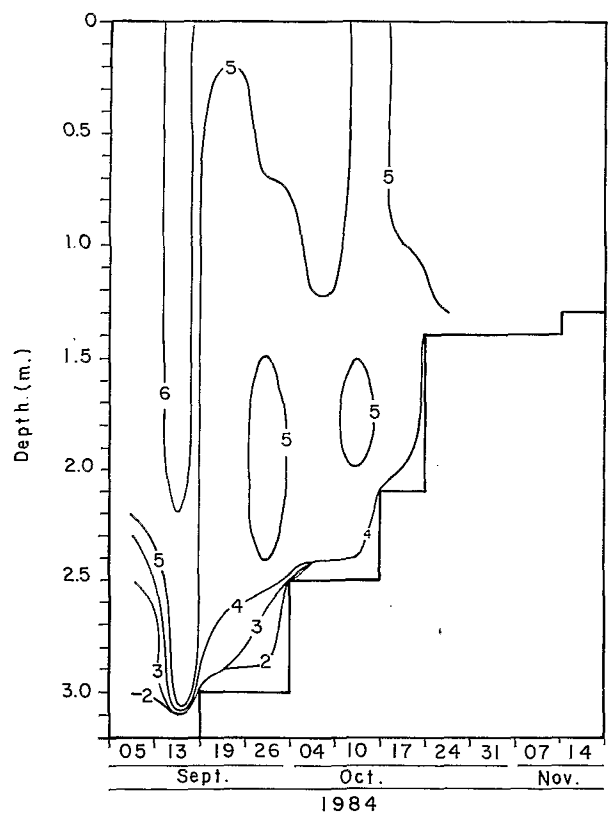

FIG. 7. — Variations of dissolved oxygen measured in Lake Castillos during the high and falling water phases.
Variations de l'oxygène dissous dans le lac Castillos en période de hautes eaux et de récession.

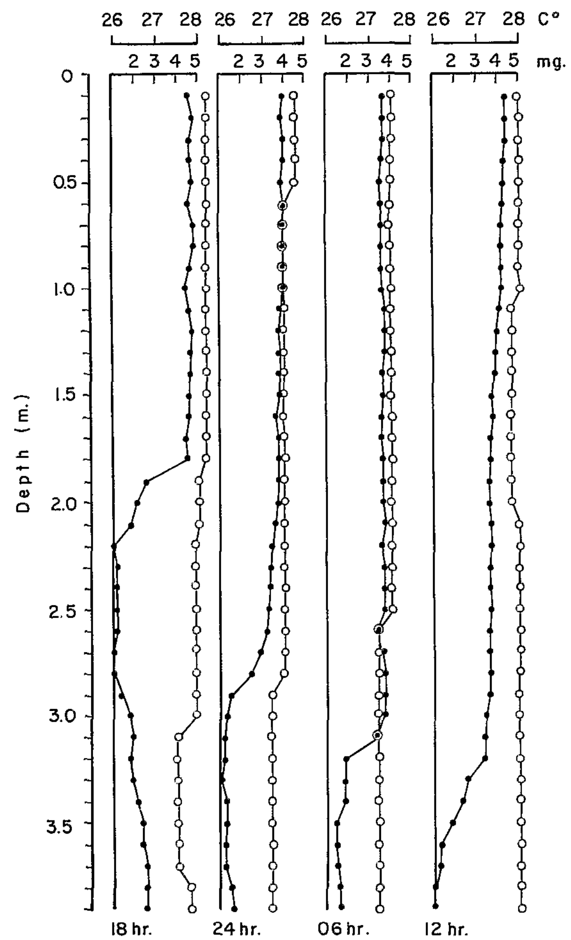

FIG. 8. — Diel cycle of temperature (empty circles) and dissolved oxygen (filled circles) measured at high water (August 29-30, 1984) in an open water section of Lake Lagoven.
Évolution nycthémérale des profils de température (cercles clairs) et d'oxygène dissous (cercles noirs) en période de hautes eaux en 1984 dans les eaux libres du Lac Lagoven (29-30 août 1984).

when the depth is above 5-6 m (MELACK and FISHER, 1983). On The Paraná floodplain, however, lakes are generally shallow (DRAGO, 1989). In one of these lakes (L. La Cuarentena, maximum depth 5 m), DRAGO and PAIRA (1987) found stratification to be occasional and weak. In this lake, similar to the Orinoco lakes, the shallowness of the lake basins, wind action, and the strong influence of river water during inundations continuously works against thermal stratification. The lakes of the Orinoco may be classified as continuous warm polymictic (*sensu* LEWIS, 1983) as is L. La Cuarentena on the Paraná floodplain (DRAGO and PAIRA, 1987), whereas many Amazon lakes show strong monomictic tendencies.

The DO of the Orinoco lakes was inversely related to lake depth. A similar observation was reported by VÁSQUEZ and SÁNCHEZ (1984) in Lake Mamo, the largest lake on the Lower Orinoco floodplain. A drastic decrease of DO takes place when lake water levels are high and large amounts of land and forest are inundated, thus increasing the amount of organic material available for decomposition. Also, wind velocities tend to be lower during this time of the year, thus reducing the movement of waters by the winds. In the Orinoco lakes, DO showed a typical clinograde pattern at high water which persisted for several weeks (though differentially) along the high and falling water phases. As reported by MELACK and FISHER (1983) for an Amazonian floodplain lake, injection of nutrients to superficial layers of the water column could be expected during the falling water phase when DO mixes vertically. This input of nutrients would favor the growth of phytoplankton, as observed in Orinoco lakes at low water (VÁSQUEZ and SÁNCHEZ, 1984). In fact, in one floodplain lake of the Orinoco, HAMILTON and LEWIS (1987) found the concentration of ammonium to be consistently higher during the inundation and early falling phases.

The strong seasonality and stratification pattern of DO in the lakes of the Orinoco floodplain have been found in Amazon lakes (JUNK, 1984). Anoxic conditions were rarely observed in the Orinoco lakes. A similar observation was reported by HAMILTON and LEWIS (1990b), who studied a number of different lakes on the Orinoco floodplain. On the Amazon, however, anoxic conditions are generally found at high water (MELACK and FISHER, 1983; TUNDISI *et al.*, 1984), which may lead to fish mortalities (SANTOS, 1979). Undersaturation seems to be a general characteristic of both the Orinoco and Amazon floodplain lakes. The seasonal and diel oxygen variations in the Orinoco lakes seem to support the observations of MELACK and FISHER (1983) who found in the Amazon Lake Calado strong evidence for the predominance of respiration over planktonic photosynthesis.

Mean DO values showed the following sequence of concentration in Orinoco lakes : Castillos > Lagoven > Orsinera > P. Blanca-Jobera. On the other hand, the mean of the ratio Area/$_{max}$at high and low water revealed the following sequence : Castillos > Lagoven > Jobera > P. Blanca > Orsinera. Therefore it seems that lakes with higher water surfaces and smaller depths tend to show the highest mean DO values. Considering the major input of atmospheric oxygen into the lakes, morphometric data would usefully explain that at larger lake sur-

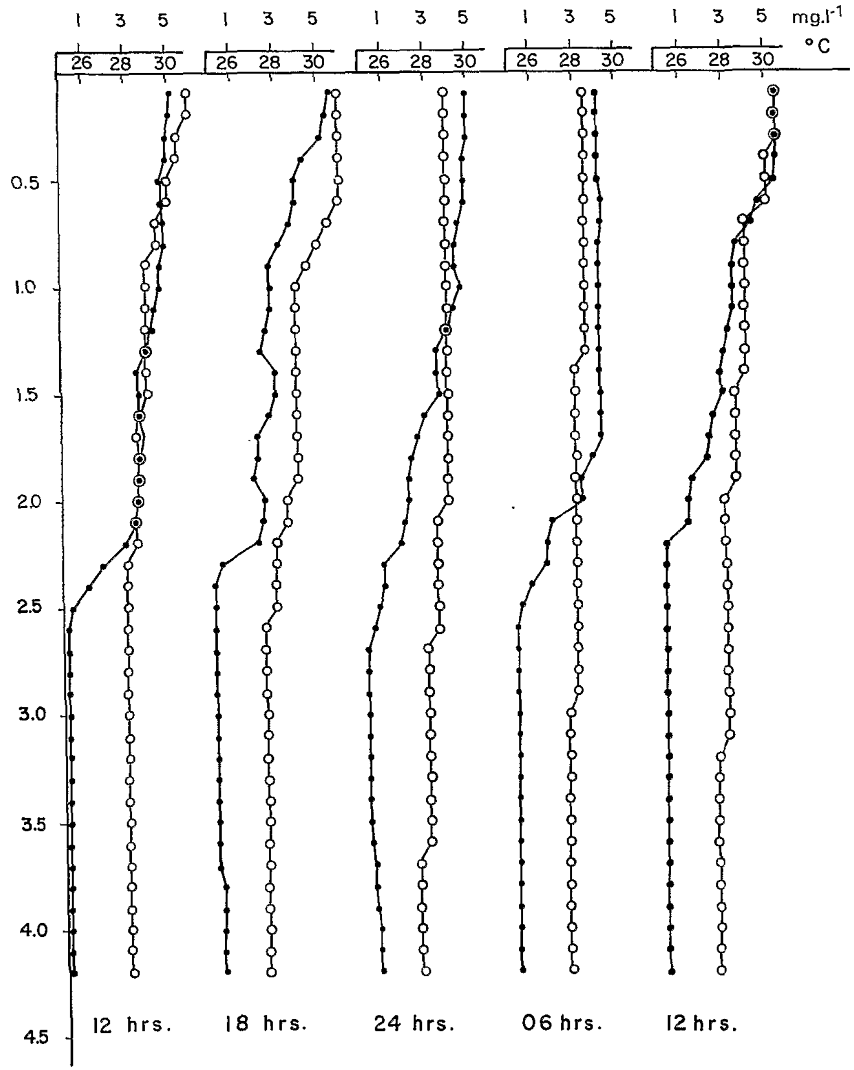

FIG. 9. — Diel cycle of temperature (empty circles) and dissolved oxygen (filled circles) measured at high water (August 27-28, 1986) in an open water section of Lake Lagoven.
Évolution nycthémérale des profils de température (cercles clairs) et d'oxygène dissous (cercles noirs) en période de hautes eaux en 1986 dans les eaux libres du Lac Lagoven (27-28 août 1986).

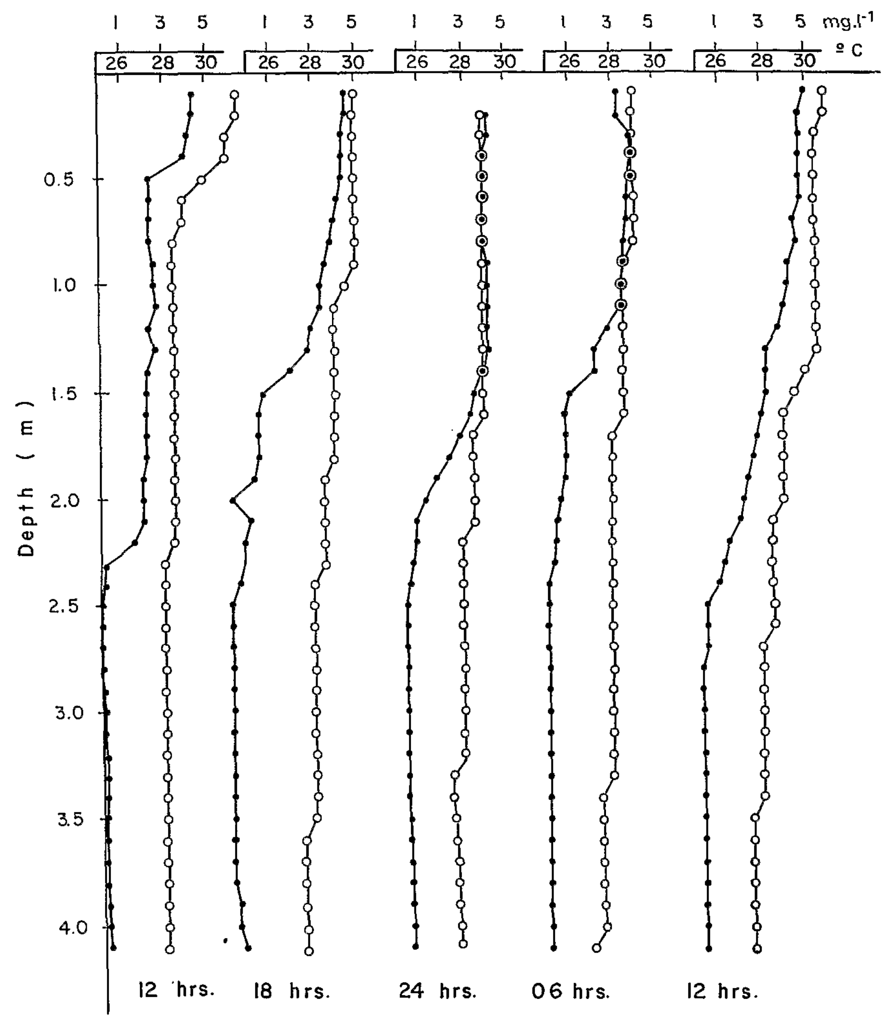

FIG. 10. — Diel cycle of temperature (empty circles) and dissolved oxygen (filled circles) measured at high water (August 27-28, 1986) under a mat of floating vegetation of Lake Lagoven.
Évolution nycthémérale des profils de température (cercles clairs) et d'oxygène dissous (cercles noirs) en période de hautes eaux sous un matelas de végétation flottante (27-28 août 1986).

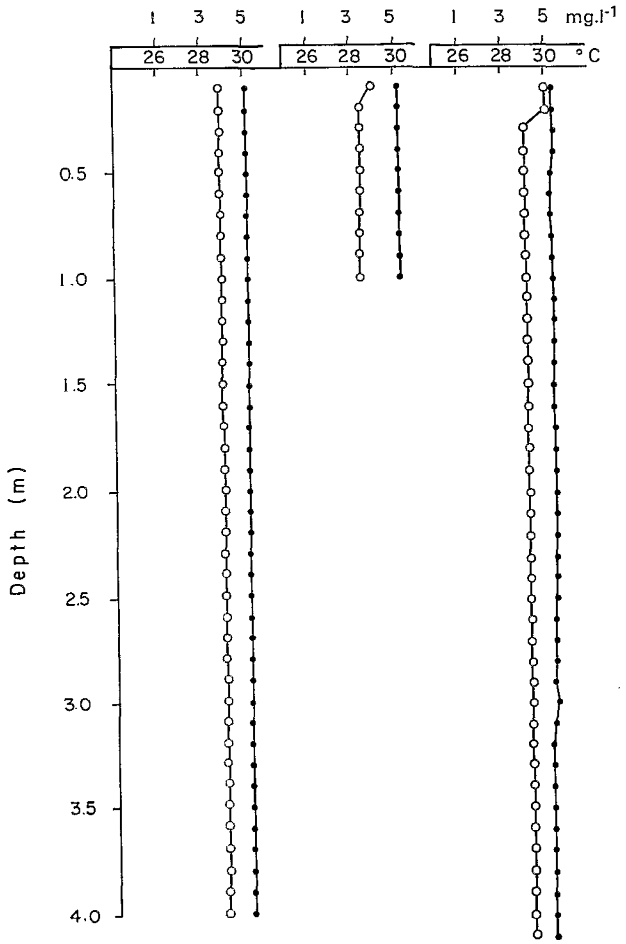

FIG. 11. — Profiles of temperature (empty circles) and dissolved oxygen (filled circles) recorded at 12:00 hours at high water (August 27, 1986) in the Orinoco River (profiles to the left of the figure), in a section of river ca. 20 m away of the coast (profiles in the center of the figure) and in the channel which connects the river and Lake Lagoven (profiles to the right of the figure).

Profils de température (cercles clairs) et d'oxygène dissous (cercles noirs) relevés à midi, en période de hautes eaux (27 août 1986) dans trois milieux : à gauche, Fleuve Orénoque ; au milieu, dans une section du fleuve à environ 20 m du bord ; à droite, dans le chenal de liaison entre le fleuve et le Lac Lagoven.

faces and lower depths diffusion of oxygen would be higher in the lakes.

Overall, the data illustrate that while the Orinoco lakes are influenced by the pulsing regime of the river, insofar as the floodwave determines the seasonal hydrograph and therefore the pattern of inundation, the properties of individual lakes actually seem to reflect their morphometries, quite independently of the floodwave. In this sense each lake could be regarded as a separate ecosystem (LEWIS *et al.*, 1990). The hydrological dominance of the river affects the geomorphological processes (erosion and deposition) that take place in floodplains, leading to the formation of a complex array of water bodies or cluster of ecosystems (*sensu* LEWIS *et al.*, 1990) . Morphometric characteristics of floodplain lakes represent useful elements to interpret the thermal and chemical behavior of these particular type of

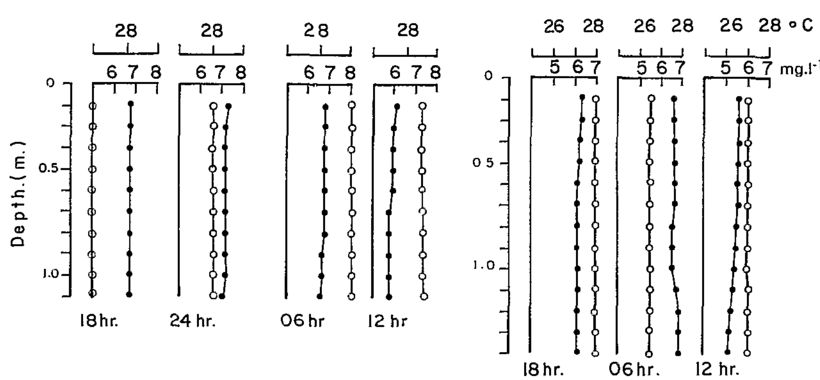

FIG. 12. — Diel cycles of temperature (empty circles) and dissolved oxygen (filled circles) measured at low water (April 16-17, 1985) in an open water section of Lake Lagoven (left panel) and Lake Castillos (right panel).

Profils de température (cercles clairs) et d'oxygène dissous (cercles noirs) en période de basses eaux (16-17 avril 1985) dans les zones d'eau libre du Lac Lagoven (à gauche) et du Lac Castillos (à droite).

lakes which probably best represent lowland tropical lakes (TUNDISI *et al.*, 1984).

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