PHYSICAL CHARACTERISTICS OF THE FRINGING FLOODPLAIN OF THE ORINOCO RIVER, VENEZUELA

STEPHEN K. HAMILTON
and WILLIAM M. LEWIS, Jr.

Floodplains along large rivers are one of the most important types of wetland in the tropics (Melack and Fisher, 1990). Welcomme (1979) discerns three general classes of floodplains: fringing floodplains, which are relatively narrow flood zones lying along river channels; internal deltas, where lateral flooding results because drainage is blocked or slowed by some geological feature; and coastal deltaic floodplains, which are influenced by tides and seawater as well as by seasonal overbank flow from the river. Each of these floodplain types is found in the Orinoco River system of Venezuela and Colombia.

The fringing floodplain of the Orinoco resembles other large tropical floodplains in its amplitude and duration of flooding, and in many of its ecological characteristics. Such floodplains require careful management and conservation because they modulate the intensity of riverine floods (Petts and Foster, 1985), support important local fisheries (Novoa, 1982; Welcomme, 1979), can produce fertile soils for agriculture that are sustained by the annual inundation (Junk, 1982; Sioli, 1984) and provide habitat for a variety of wildlife, including endangered or threatened species (Best, 1984) as well as species of potential economic value (Ojasti, 1980).

Despite an increasing interest in neotropical wetlands among scientists and resource managers, remarkably few data have been published on their areal extent (Melack and Fisher, 1990). Estimates that do appear in the literature often lack information on how they were obtained, and their uncertainty may be high. This situation has resulted in part from the remoteness and large areal extent of many floodplain regions, and from the difficulty of surveying seasonally flooded regions. In addition, authors differ in their definitions of floodplain boundaries.

Measurements of the areal extent of the Orinoco floodplain are valuable for several reasons. Venezuela is currently beginning an ambitious program to develop the region (Ministerio del Ambiente y de los Recursos Naturales Renovables, 1983), and plans under consideration include impoundment of the main channel by a lowhead dam, expansion of mining and industrial activity along the river exploitation of petroleum along the left (northern) bank, and alteration of the present channel to facilitate navigation. Each of these projects has potentially strong negative effects on the fringing floodplain ecosystem. There is thus an urgent need for basic information on the extent and distribution of floodplain for consideration during the planning stages of these projects. Improved measurements of floodplain area are also required for studies of regional and global biogeochemical cycles (Richey *et al.*, 1988; National Academy of Sciences, 1988). For example, the accuracy of recent estimates of the role of floodplain wetlands in the global cycling of methane, a gas which contributes to climatic warming, depends directly on knowledge

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Stephen K. Hamilton **graduated from Michigan Technological University in 1981 and obtained a Master's degree in Biology from the University of Colorado at Boulder in 1985. He has participated in a variety of limnological and biogeochemical studies of the Orinoco River and its floodplain. He is currently working on his doctorate at the Department of Biological Sciences, University of California, Santa Barbara, California, 93106, U.S.A.**

William M. Lewis, Jr. **has been a Professor of Biology at the University of Colorado at Boulder since 1974, and is director of the University's Center for Limnology. He has authored several books and over 110 scientific papers dealing with a wide variety of limnological and ecological topics, with particular emphasis on tropical freshwaters. Address: Department of Environmental, Population and Organismic Biology, Campus Box 334, University of Colorado, Boulder, Colorado 80309, U.S.A.**

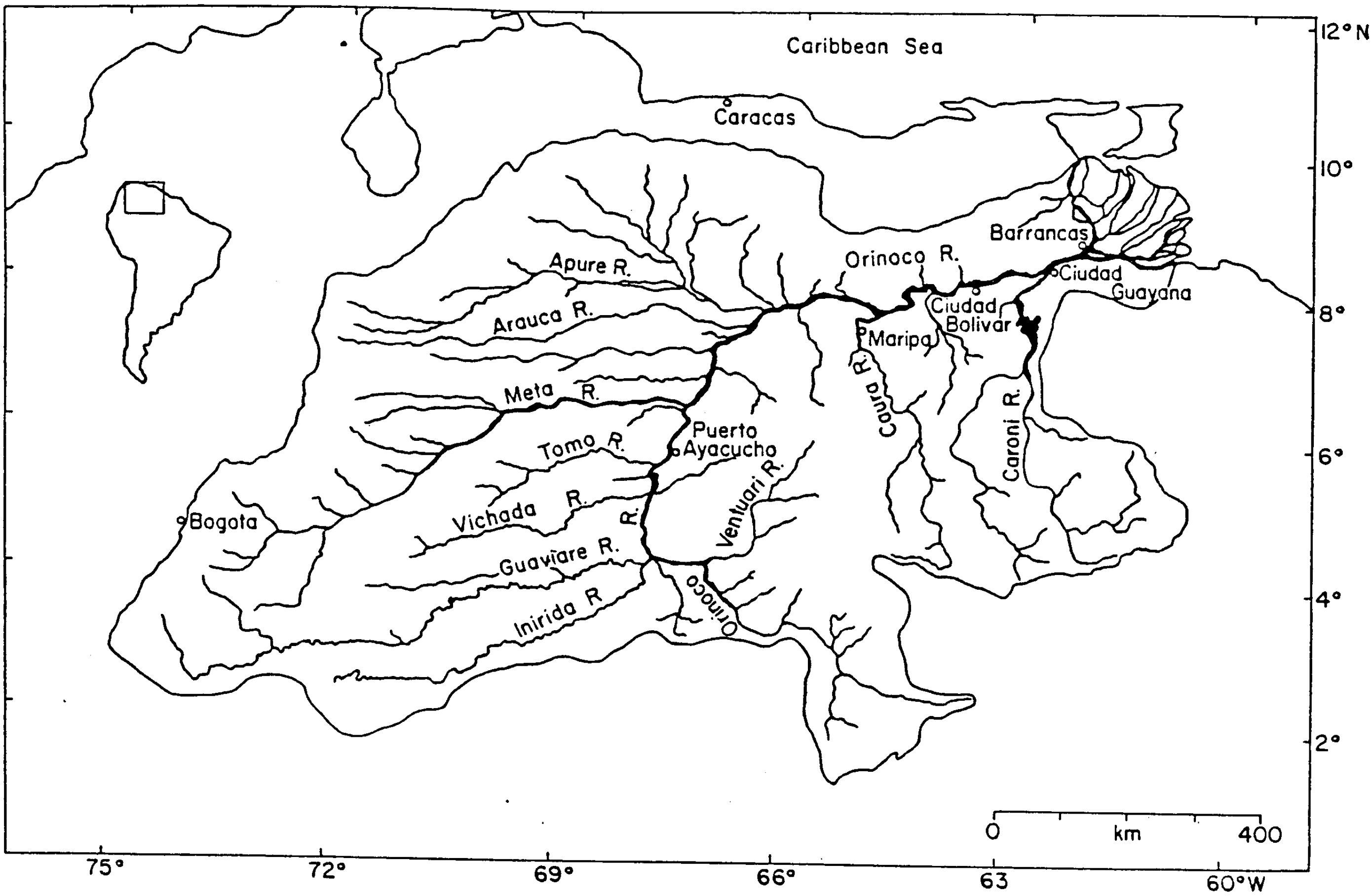

Figure 1. The Orinoco River system of Venezuela and Colombia.

of the areas of floodplain environments such as open water, forest, and floating macrophyte beds (Devol *et al.*, 1988). Data on floodplain area can also be useful for prediction of the potential yield of fish from floodplain rivers, which is related to the area of floodplain (Welcomme, 1979). To the geomorphologist, data on floodplain area and distribution provide interesting insights into the origin and dynamics of floodplain landforms (Leopold *et al.*, 1964).

We are unaware of any published estimates of the area of the Orinoco fringing floodplain. Welcomme (1979) estimated that 70,000 km² of the extensive plains west of the Orinoco are subject to sheet flooding, and described this region as an internal delta floodplain. The area of the Orinoco delta has been reported as 20,000 km² by Welcomme (1979) and as 22,500 km² by Pannier (1979). These estimates do not include the fringing floodplain, which is geologically and ecologically distinct from both the extensive areas of inundable savanna to the west and the coastal deltaic floodplain to the east.

The purpose of this study is to present data on the areal extent and spatial patterns of the fringing floodplain of the Orinoco River. We delineated the boundaries of the floodplain using a combination of large-scale maps, Landsat imagery, aerial photography, and our experience in the field during inundation of the floodplain. We discuss the effect of geomorphology on the hydrology and ecology of the fringing floodplain, and we compare the Orinoco floodplain to floodplains of other major neotropical rivers.

Description of the Orinoco River and its floodplain

The Orinoco River drains an area of 1.1 x 10^6 km² in Venezuela and Colombia (Fig. 1), and has a mean annual discharge of 36 x 10^3 m^3 s^{-1} (Meade et al., 1983). Seasonal variation of rainfall in the basin causes a pronounced annual rise and fall of the river level (Fig. 2), resulting in a unimodal seasonal inundation of the floodplain that typically lasts for 4–6 months. Precipitation is higher in the delta (140-200 cm y^{-1}) and along the upper Orinoco (200-360 cm y^{-1}) than along the fringing floodplain of the middle Orinoco (100-200 cm y^{-1}) (Ewel *et al.*, 1976). Floodplain areas experience a marked dry season between January-April, during which they receive only 10-15% of the annual precipitation.

Major geographic regions in the basin are shown in Fig. 3. The river flows between the Precambrian Guayana Shield to the south and the late-Tertiary and Quaternary alluvial plains ("Llanos") on the left bank (Case et al., 1984; Sarmiento, 1983; Tricart, 1984). Although extensive areas in the alluvial and high plains are subject to shallow inundation during the wet season, this is mostly due to poor drainage of local rainfall, rather than to overbank flow from the large rivers (Sarmiento, 1983). The alluvial plains close to the Orinoco channel are more deeply inundated, and an internal delta occurs where riverine overflow from tributaries such as the Apure and Arauca rivers covers some of this area (Herrera and Rondón, 1985).

The Orinoco Delta is distinct from the fringing floodplain upriver because of the ideal control of its water level, which dampens seasonal variation in the river level and causes penetration of seawater into the delta, particularly at low river discharge (Pannier, 1979). Mangrove forest covers much of the region. The delta is currently aggrading and retains much of the sediment transported by the Orinoco (Meade *et al.*, 1983). At the apex of the delta, the tidal fluctuation in water level is only 60 cm, compared to the seasonal river level fluctuation of ca. 9 m (van Andel, 1967).

The fringing floodplain of the Orinoco main channel extends from the apex of the delta upriver to the Meta River; above this point the floodplain is much smaller. The river channel is straight (sinuosity, ca. 1.1) and braided for about half of its total length. Much of the alluvial valley of the Orinoco is confined between granitic outcrops of the Guayana Shield and erosional scarps along the high plains. The fringing floodplain is occasionally interrupted by higher land that extends to the river channel ("control points"), particularly below the Apure River. These points have a long history as preferred sites of human settlement (Roosevelt, 1980), and some are now important cities and villages, which are the foci for current development of the region (Fig. 1). The river is often narrower and more turbulent where control points exist on both banks (personal observation), and lateral mixing of river waters may be enhanced at these points (Meade *et al.*, 1983).

The annual variation in water level of a typical floodplain lake along the lower Orinoco is shown together with the river hydrograph in Fig. 2. The Orinoco River usually begins to rise in April, and first inundates much of the fringing floodplain in May and June. Inundation of the floodplain with nutrient-rich river water stimulates the growth of floating emergent forms of vascular aquatic plants (e.g. **Paspalum repens** Berg, **Eichornia crassipes** Mart). (Sánchez and Vásquez, 1986). Plankton blooms may also occur at inundation, but dilution and flushing often keep densities low (Hamilton and Lewis, 1987; Hamilton *et al.*, 1990). Between July and October, river water flows through most floodplain areas. As the river level falls during November and December, much of the water on the floodplain drains into the river. Waterbodies reach their maximum transparency at this time, although plankton densities typically increase as flushing rates decrease (Hamilton and Lewis, 1990). After December, most of the floodplain is dry, and numerous waterbodies become isolated from the river until the following inundation. During isolation, the water level in lakes and pools is controlled primarily by evaporation and local rainfall (Hamilton and Lewis, 1987), and most waterbodies remain perched well above the level of the nearby river channel. As waterbodies become very shallow (< 1 m deep) over the course of the dry season, sediments may become resuspended by wind-driven turbulence, increasing the turbidity of the water.

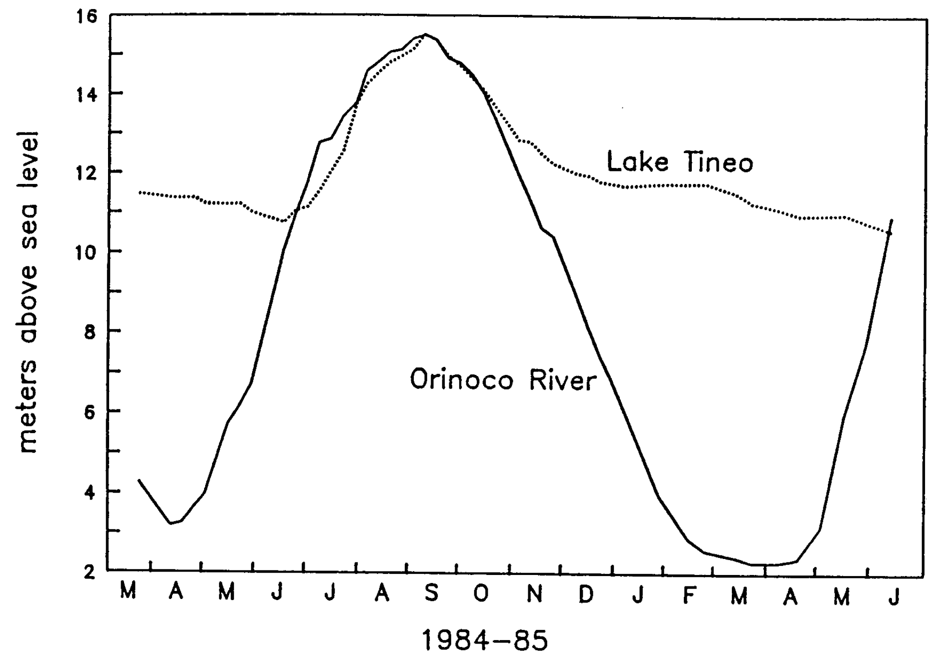

Figure 2. Hydrographs of stage height for the Orinoco River at Ciudad Bolívar (data provided by the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables) and for Lake Tineo, a floodplain lake located 14 km downriver from Ciudad Bolívar (Hamilton and Lewis, 1987).

Investigations of the geochemistry and aquatic ecology of the Orinoco River system include studies of riverine mass transport and metabolism (Meade *et al.*, 1983; Vásquez and Sánchez, 1984; Weibezahn, 1985; Stallard, 1985; Lewis, 1987; Lewis and Saunders, 1989; Saunders and Lewis, 1989), and limnological studies of several floodplain lakes along the lower Orinoco (Vásquez, 1984; Twombly and Lewis, 1987; Hamilton and Lewis, 1987). The floodplain vegetation has been studied by Sánchez and Vásquez (1986) and Colonnello *et al.* (1986), and research on the savannas in the Orinoco basin is summarized by Sarmiento (1983).

The fringing floodplain of the Orinoco has not yet been strongly altered by human activities, although most areas are affected by free-ranging livestock, and Novoa (1982) estimates that subsistence-level agriculture is practiced on approximately 400 km^2 of floodplain (mostly on the levees). Effects of a major impoundment of the Caroní River (the Raul Leoni or Guri Reservoir) on the Orinoco fringing floodplain have not been reported, although the Caroní River contributes 13% of the mean annual Orinoco discharge, and impoundment has altered the seasonal flow regime of the Caroní (Castro and Gorzula, 1986; Lewis, 1987). Industrial development in the vicinity of Ciudad Guayana has resulted in localized disturbance of floodplain environments (personal observation). Most of the Orinoco fringing floodplain is located upriver from these disturbances (Fig. 1)

Methods

We plotted floodplain boundaries on maps of 1:100,000 scale for most of the fringing floodplain, from the delta to about 70 km below the Meta River (6°40'N). These maps were produced by the Venezuelan Dirección de Cartografía Nacional between 1968-1975, and include topographic contours (20-m intervals) and general classes of vegetation as well as cultural information. We have used these maps extensively during recent field work in floodplain areas and have found them to be accurate and reliable. Forested floodplain areas do not appear to have changed significantly since the maps were made. Lake and river boundaries on these maps represent low water, and generally correspond to the vegetated shorelines.

For much of the fringing floodplain, the approximate location of high-water flood boundaries was apparent on the 1:100,000 maps as the transition between semideciduous floodplain forest and savanna-deciduous forest, and from the presence of floodplain waterbodies. However, we used Landsat imagery and aerial photography as well as our field observations to more precisely delineate the boundaries. Landsat imagery was a more important source of information for the right-bank floodplain upriver from Caicara de Orinoco, where the transition from forest to savanna is not a reliable indicator of floodplain limits, and it was the only source of information for the floodplain along 70 km of channel between 6°40'N latitude and the Meta River, for which maps of 1:100,000 scale were unavailable. Standard Landsat film negatives (Multispectral Scanner, band 7 near-infrared) from several high-water dates were enlarged in one step with a photographic enlarger to produce a positive image with a scale of 1:100,000. Comparison of the positives with the 1:100,000 maps enabled us to plot floodplain boundaries on the maps. Vertical black-and white aerial photographs of a 15-km reach of floodplain in the vicinity of Ciudad Bolívar provided additional information to aid in our interpretation of the maps and Landsat imagery. These photographs, taken in September 1974, were obtained from the Venezuelan Dirección de Cartografía Nacional.

We define the Orinoco fringing floodplain as land that is inundated seasonally by water from the main channel of the Orinoco. Permanent waterbodies are included in the area of floodplain; river channels are not. Low-lying plains lateral to the river that are inundated by local rainfall or by tributaries are not included, nor are beaches and islands without vegetation. The fringing floodplain was divided into 7 reaches for the purpose of data presentation and interpretation (Table I). Boundaries between the reaches are sites where there is no floodplain on either bank ("control points" discussed above), except for the boundary between reaches a and b, which is the southern limit of available maps. These control points are also sites of the most important villages and cities along the river. Within each reach, measurements of floodplain on the left and right banks and on islands were tabulated separately. The floodplain of the Caura River from its mouth upriver to near Aripao (7°20'N, the limit of available maps) was also measured, and data were tabulated separately.

Areal measurements were made on the 1:100,000 maps using a computerized digitizer. In addition to the area of floodplain, we measured the area of lakes (low-water boundaries that appear on the maps) and of unforested floodplain (area not marked as "bosque, monte alto" on the maps). The accuracy of our delineation of floodplain boundaries is better below Caicara de Orinoco, where the boundaries are generally well-defined by topography and vegetation, and where we have had more field experience. Between Caicara and the Meta River, the boundaries are less clear, particularly along the right bank where the transition between riverine floodplain and sheet-flooded savanna is often gradual. In some valleys on the right bank, flooded savanna extended from the river bank far up into the valley; in these places, we arbitrarily placed the floodplain boundary near the mouth of the valley. On the left bank, we used the forest-savanna boundary, together with the presence of abundant floodplain lakes, to indicate the limits of the fringing floodplain.

The placement of the boundary of the fringing floodplain was also somewhat arbitrary at the mouths of several tributaries. The Caroní River has very little floodplain at its mouth. We used information on water chemistry in the floodplain on both sides of the mouth of the Caura River (unpublished

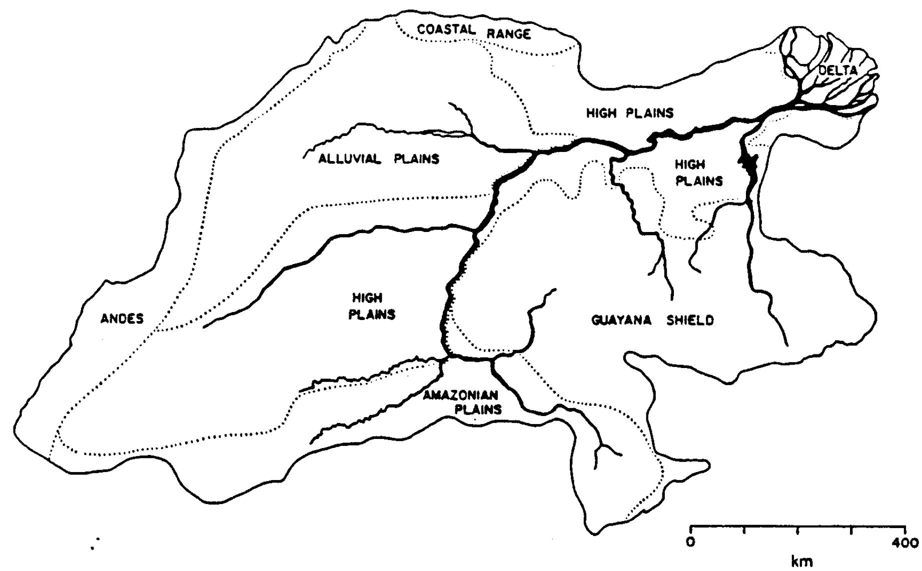

Figure 3. Major geographic regions in the Orinoco River basin.

TABLE I

DIVISION OF THE ORINOCO FRINGING FLOODPLAIN INTO LONGITUDINAL REACHES

reach	*beginning*	*end*
A	Meta River confluence	6°40'N latitude
B	6°40'N latitude	Caicara-Cabruta
C	Caicara-Cabruta	Las Bonitas-Parmana
D	Las Bonitas-Parmana	Las Majadas-Mapire
E	Las Majadas-Mapire	Ciudad Bolívar-Soledad
F	Ciudad Bolívar-Soledad	San Félix-Los Barrancos
G	San Félix-Los Barrancos	Delta apex

data) to distinguish between Caura and Orinoco floodplain. At the mouths of the other tributaries, the boundaries were arbitrarily drawn as straight lines between the mainstem boundaries above and below the confluence; our choice of boundaries in these areas does not affect our interpretation of the data, however.

Results

Areal measurements of the fringing floodplain are summarized by floodplain reach in Table II, and floodplain area in each reach is shown in Fig. 4. The floodplain is larger on the left bank of the river in all of the reaches, although the difference is small in reaches b, c and e. The amount of floodplain on islands is small compared to that along the banks. Expression of the data as floodplain area per kilometer of river channel shows that the floodplain is considerably wider in reaches b and c than in the other reaches. The floodplain is largely covered with forest, and forest cover increases downriver. Table II also shows the number of spatially discrete floodplain "units" in each reach; more units exist on the right bank, where control points are more frequent than on the left bank. The floodplain of the Caura River is similar in area between the two banks, and islands are insignificant. The Caura floodplain is a small proportion (4%) of the total fringing floodplain.

Data on floodplain lake abundance and the area are given in Table III. Reach b contains the most lakes in terms of total number, lakes per km of river channel, and total lake area. However, the overall density of lakes in reach b (both banks plus islands), in terms of both lakes per km² and percent of the total area occupied by lakes, is lower than in reaches downriver because of the scarcity of lakes along the right bank floodplain. Among the six reaches, lakes cover 5-12% of the fringing floodplain, and the median area of individual lakes varies only from 0.05-0.11 km². The Caura floodplain has few lakes, but includes several relatively large lakes on the right bank.

An example of the floodplain of the lower reaches is shown in Fig. 5. This section is located in reach f, immediately downriver from Ciudad Bolívar. Control points are frequent along this part of the river, particularly along the right bank, and there is generally an erosion scarp close to the floodplain boundary (Vásquez, 1988). Upland areas on both sides of the river,

TABLE II

AREA, FOREST COVERAGE, AND SPATIAL DISTRIBUTION OF THE ORINOCO FRINGING FLOODPLAIN. RIVER BANKS ARE DESIGNATED AS LEFT OR RIGHT AS ONE FACES DOWNRIVER. THE PERCENT FOREST COVER IS THE PERCENTAGE OF SEASONALLY INUNDATED LAND THAT IS FORESTED; OPEN-WATER AREAS (PERMANENT LAKES) WERE NOT INCLUDED IN THE CALCULATION. SPATIAL UNITS ARE EITHER DISCRETE AREAS OF FLOODPLAIN ALONG THE RIVER BANKS, SEPARATED FROM OTHER FLOODPLAIN AREAS BY HIGHER GROUND THAT IS NOT INUNDATED SEASONALLY, OR INDIVIDUAL ISLANDS. THE FLOODPLAIN OF THE CAURA RIVER (A MAJOR TRIBUTARY) IS NOT INCLUDED IN THE TOTALS FOR THE ORINOCO FRINGING FLOODPLAIN. NA = DATA ARE NOT AVAILABLE

reach	*channel length in reach (km)*	*bank*	*floodplain area (km²)*	*floodplain area (km²) per km of channel*	*percent forested*	*number of spatial units*
A	70	left	338	4.83	NA	1
		right	120	1.71	NA	4
		island	24	0.34	NA	10
		total	482	6.88	NA	15
B	175	left	1359	7.77	78	1
		right	1245	7.11	74	6
		island	226	1.29	86	32
		total	2830	16.17	77	39
C	66	left	422	6.39	80	1
		right	338	5.12	96	2
		island	26	0.39	77	12
		total	786	11.90	87	15
D	110	left	597	5.43	84	3
		right	265	2.41	94	3
		island	73	0.66	81	24
		total	935	8.50	87	30
E	185	left	385	2.08	90	7
		right	351	1.90	98	11
		island	159	0.86	81	33
		total	895	4.84	92	51
F	107	left	438	4.09	95	3
		right	86	0.80	100	15
		island	101	0.94	95	22
		total	625	5.84	96	40
G	57	left	243	4.26	100	2
		right	141	2.47	100	5
		island	27	0.47	100	6
		total	411	7.20	100	13
A-G	770	total	6964	9.04	NA	203
B-G	700	total	6482	9.26	85	188
Caura	71	left	147	2.10	86	3
		right	177	2.53	84	4
		island	1	0.01	100	3
		total	325	4.64	85	10

which are covered with *Trachypogon* savanna and deciduous forest, are generally not inundated in the wet season. Levees separate most floodplain areas from the river except at the highest stage, and the floodplain is roughly convex in cross-section. Narrow tie channels ("caños") pass through the levees and between lakes (Blake and Ollier, 1971), allowing water to flow into and out of floodplain areas when the river level is below the levees.

Fig. 6 shows the floodplain in reach b, where the river flows between high plains on both banks. In this area, water from the Meta River travels along the left bank for up to 200 km before mixing completely with the water of the main channel (Meade *et al.*, 1983; Weibezahn, 1985). Floodplain lakes are very abundant along the left bank, which carries sediment-laden water from the Meta River, but are relatively scarce along the right bank, which carries water lower in suspended solids that originates above the Meta. The right bank is flanked by occasional granitic massifs of the Guayana Shield, with intervening valleys of low relief in which the savanna is subject to sheet flooding by local rainfall. In the upper right of Fig. 6, a portion of tributary floodplain (Capanaparo River) adjoins the fringing floodplain of the main channel.

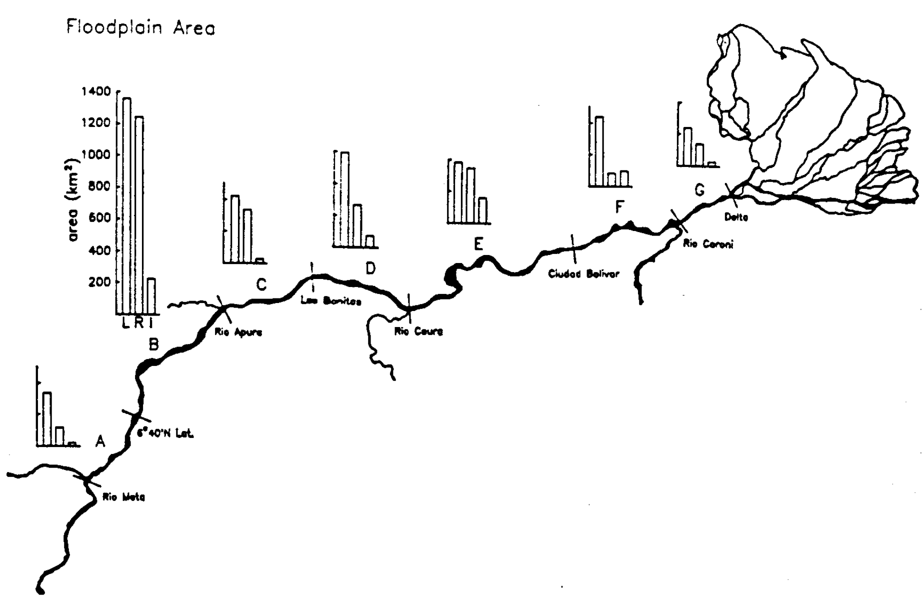

Figure 4. The area (km2) of fringing floodplain in each reach. L: left bank, R: right bank; I: islands.

Discussions

Geomorphology and hydrology of the floodplain

Geomorphologic features of particular importance to the hydrology of the fringing floodplain include elevation, lateral extent, and the existence of control points. These features control the depth and duration of inundation and the hydraulic residence time of river water on the floodplain, which in turn affect many biogeochemical, limnological, and ecological processes.

The depth of flooding at high water on the Orinoco floodplain is commonly less than 6 m, except in some of the largest lake basins (Vásquez, 1988; Hamilton, unpublished data). MacIntyre and Melack (1988) reported that a moderate-sized Amazon floodplain lake (Lake Calado) tends to develop persistent thermal stratification with anoxic bottom waters when its depth exceeds 6 m. We have measured dissolved oxygen in Orinoco floodplain waters during inundation and found that anoxic waters are less common and less persistent in lakes on the Orinoco floodplain than in the lakes that have been studied on the Amazon floodplain (Hamilton and Lewis, 1987 and 1990). In addition to the relatively shallow depth of waters on the Orinoco floodplain, high rates of riverine through-flow also act to maintain oxygen in bottom waters.

Through-flow of river water in floodplain areas is biologically important because it is a major source of dissolved and particulate nutrients to aquatic plants, it maintains high inorganic turbidity and reduces deoxygenation, and the outflow current may carry planktonic organisms out of their suitable habitat (Hamilton and Lewis, 1987; Forsberg *et al.*, 1988; Hamilton *et al.*, 1990). We have frequently observed currents of 10-20 cm s^{-1} on the fringing floodplain of the Orinoco. Through-flow of river water continually flushes most floodplain areas during inundation, and residence time of water in floodplain lakes can be on the order of days (Hamilton and Lewis, 1987; Hamilton *et al.*, 1990), although densely vegetated or isolated areas can be relatively stagnant. The residence time of river water on the Orinoco floodplain may be shorter than on larger floodplains such as that of the Amazon near Manaus because the Orinoco floodplain is relatively narrow, and the permanently backflooded tributary valleys that are common on the middle Amazon floodplain (Tricart, 1977) are not found along the Orinoco.

Control points, which define discrete spatial units of the fringing floodplain, act to force floodplain waters back into the main channel. In large floodplain units, the river water is progressively depleted in nutrients and dissolved oxygen as it travels across the floodplain. Toward the end of the hydrologic flow path across the floodplain, the fertilizing effect of riverine inundation may be lessened. It follows that smaller floodplain units may show higher overall biological production than larger ones. The existence of many discrete floodplain units defined by control points is a characteristic of the Orinoco fringing floodplain that is not shared by the well-studied floodplains of the middle Amazon and the middle Paraná rivers.

The distribution of control points is of practical interest with regard to industrial development along the river. Valuable biological resources are concentrated in floodplain environments. Floodplains may act as traps (Hart *et al.*, 1987) or as dispersal sites (Lewin, 1978) for pollutants released along the river margins. At control points, pollutants will re-enter the river and become mixed into the main channel. Future industrial development along the Orinoco will include plants to process wood pulp and bauxite as well as a major crude oil refinery (Ministerio del Ambiente y de los Recursos Naturales Renovables, 1983). These and other activities related to resource exploitation and industrialization will likely result in the release of significant quantities of pollutants into the river. The sites of release relative to floodplain units and control points will determine the effects of the release on floodplain environments, as well as the rapidity and degree of dilution of the pollutant by river water. Construction of raised highways and dikes on the floodplain can alter flow patterns, causing potentially large impacts on floodplain environments.

Processes of floodplain formation

The data on floodplain area (Tables II and III, Fig. 4) indicate that the Orinoco fringing floodplain is asymmetric, with considerably more floodplain along the left bank. Tricart (1977) attributed the asymmetry of the Amazon floodplain below the mouth of the Japura River to basin tilting, which causes the river to erode against one bank. The asymmetry of the Orinoco floodplain may be explained simply by the asymmetry in sediment loading from the tributaries. Most of the suspended sediment carried by the Orinoco main channel comes from the Meta and Apure rivers along the left bank, whose waters tend to flow considerable distances before mixing fully into the main channel (Meade et al., 1983). Dilution of suspended solids by the right bank tributaries (Caura and Caroní rivers) may enhance the asymmetric aggradation of sediment along the course of the main channel.

Figs. 5 and 6 show typical floodplain patterns. Meander scroll topography (Blake and Ollier, 1971) is not strongly developed on the Orinoco floodplain, although meander cores are occasionally found. Oxbow lakes with dimensions comparable to those of the main river channel are not found on the fringing floodplain. The uniform topography of much of the floodplain suggests that overbank deposition of sediment, as opposed to lateral accretion (Leopold *et al.*, 1964; Blake and Ollier, 1971; Gerrard, 1981), has been the primary mechanism of aggradation. This mechanism is consistent with the unimodal hydrograph (Fig. 2), the abundance of fine silts and clays in the sediment load (Meade *et al.*, 1983), and the confinement of the channel by resistant geologic formations.

Occasional floods of extraordinary magnitude have been implicated as the principal forces that create many of the geomorphologic and ecological features of the Paraná (Drago, 1977;

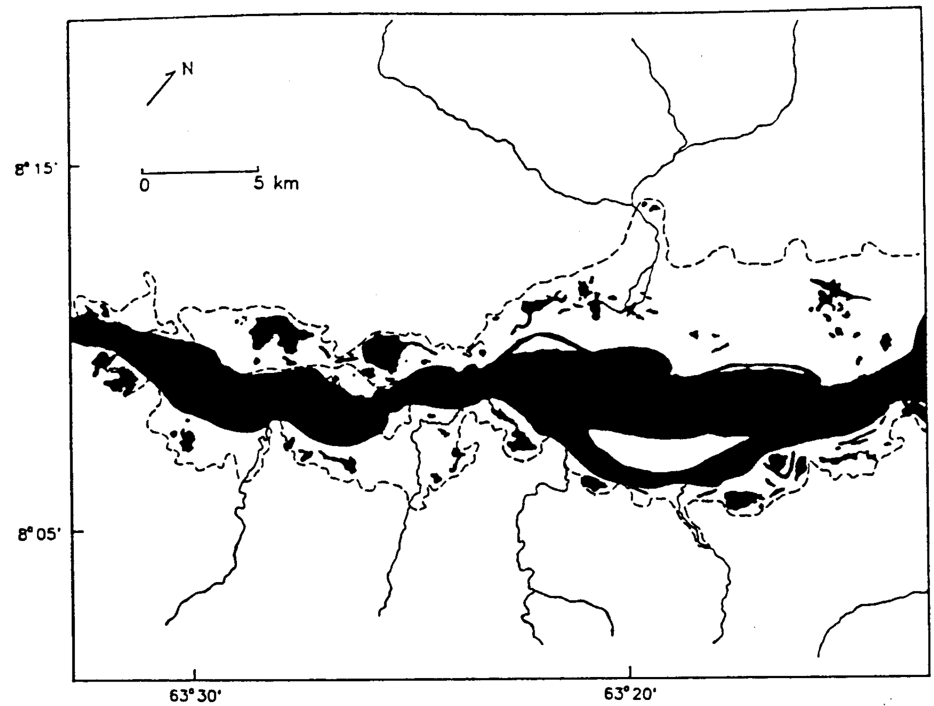

Figure 5. Example of the fringing floodplain along the lower Orinoco (reach F.) Shading indicates permanent waters; dashed line shows the floodplain boundaries.

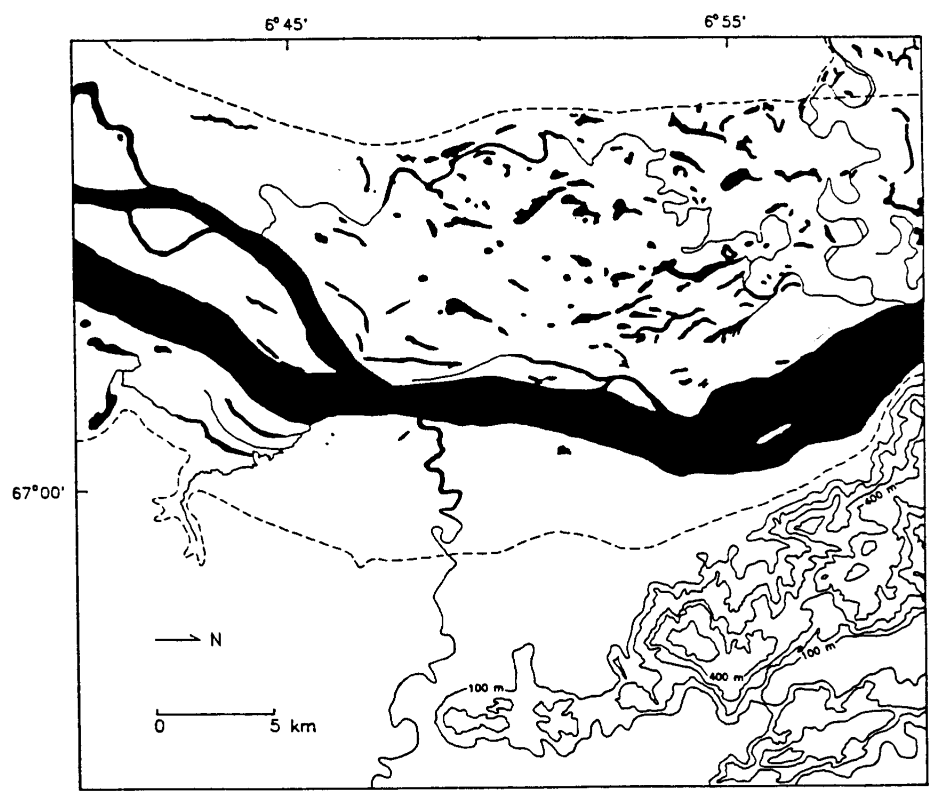

Figure 6. Example of the fringing floodplain along the upper Orinoco (reach B). Shading indicates permanent waters; dashed line shows the floodplain boundaries. The floodplain and a small distributary of the Capanaparo River bisect the Orinoco fringing floodplain in the upper right of the figure. Elevation contours are 100-m intervals.

Neiff *et al.*, 1985) and upper Amazon (Colinvaux *et al.*, 1985; Salo *et al.*, 1986) floodplains. The succession of vegetation on these floodplains is periodically reset by large floods, and floodplain forests tend to be comprised largely of pioneer species. In contrast, much of the Orinoco fringing floodplain is covered by forest that does not appear to be in an early successional state (Williams, 1941; Colonnello *et al.*, 1986; Hamilton, personal observations). Recent extraordinary floods in 1976 and 1981 did not cause extensive forest damage, and comparison of the 1:100,000 maps with recent aerial photographs shows that the shapes of floodplain lakes have changed little in over 20 years. The relative resistance of the Orinoco floodplain to geomorphologic changes during large floods is explained by the geomorphology of its valley; periodic confinement of the river channel by control points throughout the length of the river may limit the overbank flow and the river channel cannot migrate freely across a wide alluvial plain.

TABLE III

ABUNDANCE AND AREA OF PERMANENT LAKES ON THE ORINOCO FRINGING FLOODPLAIN

reach	bank	number of lakes	lakes per km channel	lakes per km² of floodplain	Σ lake area (km²)	% of area as lakes
B	left	567	3.24	0.42	114	8
	right	130	0.74	0.10	22	2
	island	61	0.35	0.27	7	3
	total	758	4.33	0.27	143	5
C	left	130	1.97	0.31	25	6
	right	117	1.77	0.35	42	12
	island	13	0.20	0.50	1	4
	total	260	3.94	0.33	68	9
D	left	191	1.74	0.32	40	7
	right	104	0.95	0.39	27	10
	island	19	0.17	0.26	2	3
	total	314	2.86	0.34	69	7
E	left	176	0.95	0.46	31	8
	right	170	0.92	0.48	29	8
	island	71	0.38	0.45	11	7
	total	417	2.25	0.47	81	8
F	left	204	1.91	0.47	60	14
	right	90	0.84	1.05	12	14
	island	38	0.36	0.38	4	4
	total	332	3.11	0.53	76	12
G	left	132	2.30	0.54	28	12
	right	58	1.01	0.41	12	9
	island	23	0.40	0.85	3	11
	total	213	3.71	0.52	43	10
B-G	total	2294	3.28	0.33	480	7
Caura	left	35	0.49	0.24	8	5
	right	17	0.24	0.10	17	10
	island	0	—	—	—	—
	total	52	0.73	0.16	25	8

Effects of tributaries and local drainage on floodplain hydrology

Differences between the left and right banks of the Orinoco fringing floodplain during inundation are enhanced by the delayed mixing of tributary inflows for long distances below their debouchure into the main channel. For example, the geomorphologic differences between the floodplain on the left and right banks (Fig. 5) are likely to be accompanied by differences in water turbidity, nutrient concentrations, and primary production because the Meta River is more turbid and has higher nutrient concentrations than the Orinoco above the Meta (Weibezahn, 1985). The waters of the Caura and Caroní rivers, which are more dilute and transparent than those of the main channel (Lewis and Saunders, 1989), will similarly affect the fringing floodplain of the right bank until they become fully mixed into the main channel.

Local rainfall and runoff are generally small components of the floodplain water budget during inundation (Hamilton and Lewis, 1990), but are likely to be more important during isolation of lakes from the river, particularly where a spring-fed stream flows into the lake and maintains its water level through the dry season. In floodplain lakes of the Amazon river, rainfall and local runoff have been found to be substantial sources of water relative to riverine inflows, even during inundation (Forsberg *et al.*, 1988; Lesack, 1988). This apparent difference between the Amazon and Orinoco floodplains may be explained by the higher precipitation along the Amazon near Manaus (ca. 200 cm y^{-1}) and by the fact that the Amazon studies have focussed on larger lakes, many of which are backflooded tributary valleys along the floodplain boundary, in which stream inflows can be larger and riverine throughflow smaller than in lakes in the center of the floodplain.

Comparisons with other South American floodplains

The fringing floodplain of the Orinoco between the Meta River and the delta covers approximately 7,000 km² (Table II). Direct comparison of this value with estimates for other neotropical floodplains is possible for cases in which the fringing floodplain has been distinguished from adjoining internal delta plains and from contiguous coastal deltaic floodplains (Table IV). The areal estimates for internal deltas of the Orinoco and Paraguay rivers include extensive areas of savanna subject to sheet flooding by local rainfall as well as areas that receive overbank flow from the main river channels. The total area of the Orinoco fringing floodplain is much smaller than that of the Amazon, and is comparable to that of the middle Paraná. The mean area of floodplain per kilometer of channel for the Orinoco (9.3 km^2 km^{-1}: Table II) is much smaller than that for the Brazilian Amazon (ca. 40: Melack and Fisher, 1990), but is similar to those for the middle Paraná (10: Drago, 1981) and the lower Paraguay (6: Drago, 1975) rivers. These ratios vary much less than the mean annual discharges of these rivers, which range from 4.5 x 10^3 m^3 s^{-1} (Paraguay) to 200 x 10^3 m^3 s^{-1} (Amazon).

TABLE IV

COMPARISON OF THE AREA (Km^2) OF THE ORINOCO FRINGING FLOODPLAIN WITH AREAS OF OTHER MAJOR NEOTROPICAL FLOODPLAINS. NA = DATA NOT AVAILABLE

river system	*mainstem fringing floodplain*	*internal deltaic floodplain*	*coastal deltaic floodplain*	*total*	*references*
Orinoco	7,000	70,000	20,000	97,000	this study and Welcomme 1979
Amazon	170,000 [a]	NA	25,000	195,000 [a]	Melack & Fisher 1990 and Welcomme 1979
Paraná	13,100	NE	12,350	25,450	Drago, 1989
Paraguay	2,000	140,000	NA	142,000	Drago 1975 and Bonetto et al., 1988

NA: Not available.
NE: Non existent.
a: includes floodplain in both Brazil and Peru.

Conclusions

The fringing floodplain of the Orinoco river covers approximately 7,000 km^2 of largely forested land that is seasonally inundated with river water. Discrete spatial units of floodplain are defined by periodic control points along the river valley. The floodplain is larger along the left bank, where sediment transport is greater because of loading from the turbid Andean tributaries. The alluvial plains (Llanos) and the Orinoco Delta are the most extensive wetland areas in the Orinoco basin, and because of these areas, the Orinoco basin ranks as a major neotropical wetland site. However, fringing floodplains such as that of the Orinoco may be disproportionately important relative to their surface areas because of their biological diversity and their hydrological and ecological linkages to the riverine systems. As industrial development and hydrologic modifications in the basin proceed in the future, management and conservation of the Orinoco fringing floodplain will require consideration of the unique geomorphological, hydrological, and ecological characteristics of floodplain environments.

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REFERENCES

Best, R. C. (1984): The aquatic mammals and reptiles of the Amazon. In H. Sioli (ed.) *The Amazon: Limnology and landscape ecology of a mighty tropical river and its basin.* Dr. W. Junk Publishers, Dordrecht: 371-412.

Blake, D.H. and Ollier, C. D. (1971): Alluvial plains of the Fly River, Papua. *Z. Geomorph. N. F., Suppl. 12:* 1-17.

Bonetto, A. A., Wais, I. R. and Arquez, G. S. (1988): Ecological considerations for river regulation of the Del Plata basin according to flatland characteristics. *Wat. Internat. 13:* 2-9.

Case, J. E., Holcomb, T. L. and Martin, R. G. (1984): Map of geologic provinces in the Caribbean region. In W. E. Bonini, R. B. Hargraves, and R. Shagam (eds), *The Caribbean-South American plate boundary and regional tectonics.* Geol. Soc. Am. Mem. 162: 1-30.

Castro, M. L. and Gorzula S. (1986): The inter-relationship of the Caroní River basin ecosystems and its hydroelectric power projects. *Interciencia 11 (6):*

Colinvaux, P. A., Miller, M. C., Steinitz-Kannan, M. and Frost, I. (1985): Discovery of permanent Amazon lakes and hydraulic disturbance in the upper Amazon basin. *Nature 313:* 42-45.

Colonnello, G. Castroviejo, S. and López, G. (1986): Comunidades vegetales asociadas al río Orinoco en el sur de Monagas y Anzoátegui (Venezuela). *Memoria de la Sociedad de Ciencias Naturales La Salle 46:* 127-165.

Devol, A.H., Richey, J. E., Clark, W. A. and King, S. L. (1988): Methane emissions to the troposphere from the Amazon floodplain. *J. Geophys. Res. 93 (D2):* 1583-1592.

Drago, E. C. (1975): Mapa geomorfológico de la llanura aluvial del río Paraguay inferior. *Revista de la Asociación Geológica Argentina 30:* 217-222.

Drago, E. C. (1977): Erosión y sedimentación en un tramo del cauce del río Paraná medio (República Argentina). *Revista de la Asociación Geológica Argentina 32:* 277-290.

Drago, E. C. (1981): Grados de conexión y fases hidrológicas en ambientes leníticos de la llanura aluvial del río Paraná (Argentina). *Ecología* (Argentina) *6:* 27-33.

Drago, E. C. (1989): Morphological and hydrological characteristics of the floodplain ponds of the Middle Paraná River (Argentina). *Rev. Hydrobiol. trop.*, 22 (3): 183-190.

Ewel, J. J., Madriz, A. and Tosi, J. A. Jr. (1976): Zonas de vida de Venezuela. Second edition. Sucre, Caracas, Venezuela.

Forsberg, B. R., Devol, A. H., Richey, J. E., Martinelli, L. A. and dos Santos, H. (1988): Factors controlling nutrient concentrations in Amazon floodplain lakes. *Limnol. Oceanogr. 33:* 41-56.

Gerrard, A. J. (1981): *Soils and landforms: An integration of geomorphology and pedology.* George Allen and Unwin, London 219 pp.

Hamilton, S. K. and Lewis, W. M. Jr. (1987): Causes of seasonality in the chemistry of a lake on the Orinoco River floodplain, Venezuela. *Limnol. Oceanogr. 32:* 1277-1290.

Hamilton, S. K. and Lewis, W. M. Jr. (1990): Basin morphology in relation to chemical and ecological characteristics of lakes on the Orinoco River floodplain, Venezuela. *Archiv für Hydrobiologie,* (in press).

Hamilton, S. K., Sippel, S. J., Lewis, W. M. Jr. and Saunders, III, J. F. (1990): Zooplankton abundance and evidence for its reduction by macrophyte mats in two Orinoco floodplain lakes *J. Plankton Res. 12 (2):* 345-363.

Hart, B. T., Ottaway, E. M. and Noller B. N. (1987): Magela Creek system, Northern Australia. II. Material budget for the floodplain. *Aust. J. mar. Freshw. Res. 38:* 861-876.

Herrera, J. I. and Rondón, J. (1985): Estudio fotogeomorfológico del río Orinoco y confluencia con el río Apure. Sector Puerto Ayacucho, río Caura. In M. Isabel Muñoz (ed.), *I Simposio Amazónico. Dirección de Geología* (Venezuela), *Boletín de Geología,* Publicación Especial Nº 10: 361-372.

Junk, W. J. (1982): Amazonian floodplains: Their ecology, present and potential use. *Revue Hydrobiol. trop. 15:* 285-301.

Leopold, L. B., Wolman, M. G. and Miller, J. P. (1964): *Fluvial processes in geomorphology.* Freeman, San Francisco, 522 pp.

Lesack, L. F. W. (1988): Mass balance of nutrients, major solutes, and water in an Amazon floodplain lake. *Ph.D. thesis, Univ. of California,* Santa Bárbara, 494 pp.

Lewin, J. (1978): Floodplain geomorphology. *Prog. Phys. Geogr. 2:* 408-437.

Lewis, W. M. Jr. (1987): Primary production in the Orinoco River. *Ecology 69:* 679-692.

Lewis, W. M. Jr. and Saunders, III J. F. (1989): Concentration and transport of dissolved and suspended substances in the Orinoco River. *Biogeochemistry 7:* 203-240.

MacIntyre, S. and Melack, J. M. (1988): Frequency and depth of vertical mixing in an Amazon floodplain lake (L. Calado, Brazil). *Verh. int. Ver. Limnol. 23:* 80-85.

Meade, R. H., Nordin, C. F. Jr., Hernández, D. P., Mejía, A. and Godoy, J. M. P. (1983): Sediment and water discharge in río Orinoco, Venezuela and Colombia. In *Proceedings of the Second International Symposium on River Sedimentation.* Water Resources and Electric Power Press, Beijing, China: 1134-1144.

Melack, J. M. and Fisher, T. R. (1990): Comparative limnology of tropical flood-plain lakes with an emphasis on the central Amazon. *Acta Limnologia Brasiliensia,* (in press).

Ministerio del Ambiente y de los Recursos Naturales Renovables (1983): Taller de trabajo: El proyecto Orinoco-Apure y sus impactos ambientales (30-31 May 1983). Caracas, Venezuela, 119 pp.

National Academy of Sciences (1988): *Toward an understanding of global change: Initial priorities for U. S. contributions to the International Geosphere-Biosphere Program.* National Academy Press, Washington, D. C., 213 pp.

Neiff, J. J., Reboratti, H. J., Gorlero, M. C. and Basaldo, M. (1985): Impacto de las crecientes extraordinarias sobre los bosques fluviales del bajo Paraguay. *Boletín de la Comisión Especial del río Bermejo* (Argentina), Nº 4: 13-31.

Novoa R., D. (1982): *Los recursos pesqueros del río Orinoco y su explotación.* Corporación Venezolana de Guayana, Editorial Arte, Caracas, Venezuela, 386 pp.

Ojasti, J. (1980): Ecology of capybara raising on inundated savannas of Venezuela. *Trop. Ecol. Dev.* 1980: 287-293.

Pannier, F. (1979): Mangroves impacted by human-induced disturbances: A case study of the Orinoco Delta mangrove ecosystem. *Envir. Management 3:* 205-216.

Petts, G. and Foster, I. (1985): *Rivers and landscape.* Edward Arnold, London, 274 pp.

Richey, J. E., Devol, A. H., Wofsky, S. C., Victoria, R. and Riberio, M. N. G. (1988): Biogenic gases and the oxidation and reduction of carbon in Amazon River and floodplain waters. *Limnol. Oceanogr. 33 (pt. 1):* 551-561.

Roosevelt, A. C. (1980): *Parmana: Prehistoric maize and manioc subsistence along the Amazon and Orinoco.* Academic Press, New York.

Salo, J., Kalliola, R., Hakkinen, I., Makinen, Y., Niemela, P., Puhakka, M. and Coley, P. D. (1986): River dynamics and the diversity of Amazon lowland forest. *Nature 322:* 254-256.

Sánchez, L. and Vásquez, E. (1986): Estudio estacional y longitudinal de la hidroquímica y fitoplancton en una sección del bajo Orinoco (Venezuela). *Memoria de la Sociedad de Ciencias Naturales La Salle 46:* 69-94.

Sánchez, L. and Vásquez, E. (1986): Notas sobre las macrofitas acuáticas de la sección baja del río Orinoco, Venezuela. *Memoria de la Sociedad de Ciencias Naturales La Salle 46:* 107-126.

Sarmiento, G. (1983): The savannas of tropical America. In F. Bourliere (ed.), *Tropical savannas. Ecosystems of the world* 13. Elsevier, Amsterdam: 245-288.

Saunders, III, J. F. and Lewis, W. M. Jr. (1989): Zooplankton abundance in the lower Orinoco River, Venezuela. *Limnol. Oceanogr. 34:* 395-407.

Sioli, H. (1984): Former and recent utilizations of Amazonia and their impact on the environment. In H. Sioli (ed.), *The Amazon: Limnology and landscape ecology of a mighty tropical river and its basin.* Junk, Dordrecht: 675-706.

Stallard, R. F. (1985): River chemistry, geomorphology, and soils in the Amazon and Orinoco Basins. In J. I. Drever (ed.). *The chemistry of weathering. Proceedings of a NATO Advanced Workshop,* July 2-6, 1984, Rodez, France. J. Reidel Publ. Co., Dordrecht, Holland.

Tricart, J. (1974): Existence de periodes seches au Quaternaire en Amazonie et dans les regions voisines. *Revue Geomorph. dynamique 23:* 146-158.

Tricart, J. (1977): Types de lits fluviaux en Amazonie bresilienne. *Ann Georgr. 86:* 1-54.

Twombly, S. and Lewis, W. M. Jr. (1987): Zooplankton abundance and species composition in Laguna La Orsinera, a Venezuelan floodplain Lake *Arch. Hydrobiol. Suppl. 79:* 87-107.

van Andel, T. J. H. (1967): The Orinoco Delta. *J. sed. Petrol. 37:* 297-310.

Vásquez, E. (1984): Estudio de las comunidades de rotíferos del Orinoco medio, bajo Caroní y algunas lagunas de inundación adyacente. *Memoria de la Sociedad de Ciencias Naturales La Salle 44:* 95-108.

Vásquez, E. and Sánchez, L. (1984): Variación estacional del plancton en dos sectores del río Orinoco y una laguna de inundación adyacente. *Memoria de la Sociedad de Ciencias Naturales La Salle 44:* 11-34.

Vásquez, E. (1988): Morfometría de un conjunto de lagunas de inundación del bajo Orinoco, Venezuela. *Pantepúi: Geografía y ciencias conexas, Nº 4* Publication of the Colegio de Geógrafos de Venezuela, Capítulo Guayana, Ciudad Guayana, Venezuela: 31-37.

Weibezahn. F. (1985): Concentraciones de especies químicas disueltas y transporte de sólidos suspendidos en el alto y medio Orinoco y sus variaciones estacionales. Informe Universidad Simón Bolívar, Caracas, Venezuela, 223 p.

Welcomme, R. L. (1979): *Fisheries ecology of floodplain rivers.* Longman, London, 31[illegible] pp.

Williams, L. (1941): Forests of the Venezuela Guiana. *Trop Woods 68:* 13-40.