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Limnological conditions associated with natural fish kills in the Pantanal Wetland of Brazil

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Introduction

Fish kills resulting from natural changes in water quality sometimes occur in floodplains (WELCOMME 1985), and have been attributed to several physicochemical factors, including O_2 depletion, accumulation of H_2S, and Al toxicity (BRINKMANN & SANTOS 1973, KUSHLAN 1974, TOWNSEND 1994). Two common situations explain most of the natural floodplain fish kills reported in the literature: 1) persistent thermal stratification followed by mixing, bringing deoxygenated bottom waters to the surface (e.g., BRINKMANN & SANTOS 1973); and 2) concentration of fishes in residual water bodies during desiccation of the floodplain (e.g., KUSHLAN 1974). The former occurs at high water, when water depths are greatest, whereas the latter occurs during the drainage or isolation phase. A third, less studied situation that can result in fish kills is associated with the initial flooding of previously dry land. This phenomenon has been reported in the tropical Magela Creek floodplain of Australia (TOWNSEND 1994).

In the Pantanal wetland of Brazil, massive fish kills sometimes occur upon inundation of the floodplains by rising river waters, and tend to move in the downriver direction with the passage of the flood wave. Contact of flood waters with the extensive aquatic-terrestrial transitional zone appears to cause significant changes in the physico-chemical properties of the water. The water changes in appearance, becoming highly colored by dissolved organic carbon, and is locally called "água de diquada". The fish kills sometimes occur in distinct river basins, which suggests that point-source anthropogenic pollution is not responsible. Popular opinion maintains that contact of water with ashes from dry-season fires cause the fish kills.

This report describes the limnological conditions leading up to a fish kill that occurred in the floodplain of the Paraguay River during rising water, and identifies the most likely factors that caused the fish mortality. These measurements comprise part of a broader limnological study of the floodplain, and follow preliminary reports on the "diquada" in the main river channel by RESENDE & MOURÃO (1987) and RESENDE et al. (1990). These previous studies suggested that O_2 depletion caused by decomposition of submersed organic matter was the likely cause of fish mortality in the river. In this paper we present new data for a floodplain lake, and we summarize relevant hydrochemical data for river and floodplain waters from throughout the region to constrain the possible causes of fish kills during the "diquada".

Study site and methods

Our study site is a relatively large floodplain lake known as the "Baía do Castelo" (Lake Castelo), one of a series of large lakes along the right margin of the Paraguay River (Fig. 1). Climate in the region is tropical with marked wet and dry seasons, resulting in seasonal inundation and desiccation of extensive floodplains. The Paraguay River floodplain is one of the most deeply inundated parts of the region, but outside of river channels depths do not usually exceed 6 m (HAMILTON 1994) and are in general around 1–2 m. The fluctuation in river level is unimodal and ranges 2–5 m over the course of the year, typically peaking in April–June at the study site. This peak in river level occurs a few months after the peak rainfall (November–March) because the extensive floodplains delay the progress of the flood wave. Vegetation in the floodplain surrounding Lake Castelo is a mixture of savanna and woodland, with extensive stands of palms (*Copernicia alba*). During inundation, emergent aquatic and semi-aquatic plants colonize much of the floodplain; the most abundant species include *Scirpus cubensis, Eichhornia azurea, E. crassipes, Oryza* spp., and *Polygonum* spp.

The measurements reported here are for two sites, one in the open-water part of the floodplain lake and another in the Paraguay River adjacent to the lake (Fig. 1). These sites were selected from a larger set to illustrate the relation between the river water (the source of flood waters) and the lake water where the fish kill was observed. The lake was sampled near the surface and the bottom. Both sites were sampled mid-morning. Sampling spanned the period from the low-water conditions (December 1993) through rising water until after the occurrence of the fish kills (August 1994), and the sampling interval varied. A staff gauge in the lake (Fig. 2) confirmed that lake

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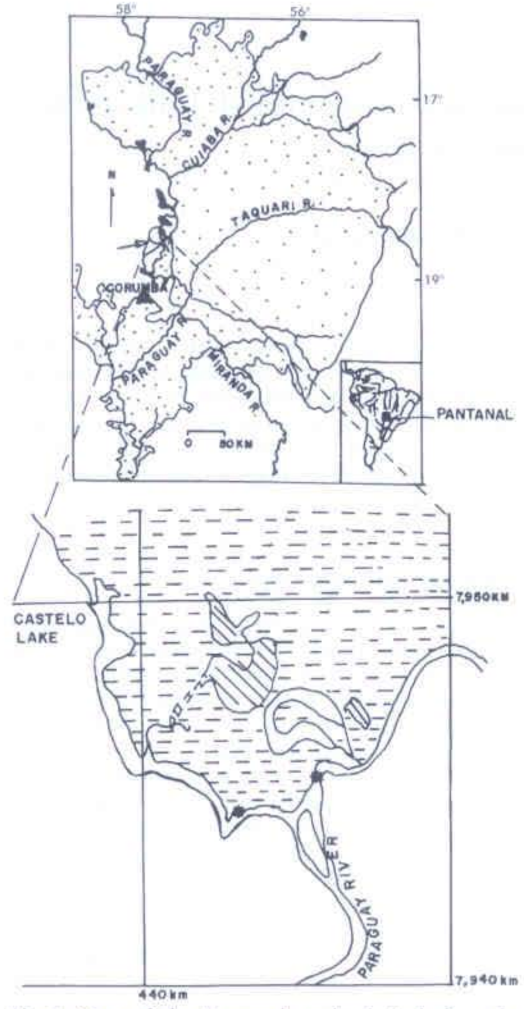

Fig. 1. Map of the Pantanal wetland, including the Castelo area. The asterisks show the sampling sites.

levels fluctuated in concert with the river level measured daily by the Brazilian Navy downriver near the city of Corumbá (Ladário).

Profiles of temperature and dissolved O_2 were measured with a thermistor and polarographic sensor. On the day of collection, pH was determined in a closed container to avoid loss of CO_2, and conductance (25 °C) was measured on unfiltered water. Within several days, we measured total alkalinity by Gran titration of unfiltered water (WETZEL & LIKENS 1991). We used the methods of KEMPE (1982) to calculate the concentration of free CO_2 from pH, alkalinity, and temperature, accounting for the average ionic strength of Paraguay River water using data from HAMILTON (1994). Chlorophyll *a* was analyzed by the method of MARKER et al. (1980).

Results and discussion

The initial sampling was performed at low water (December 1993), when the lake was still connected to the river by a narrow channel but little exchange of water took place, and the sur-

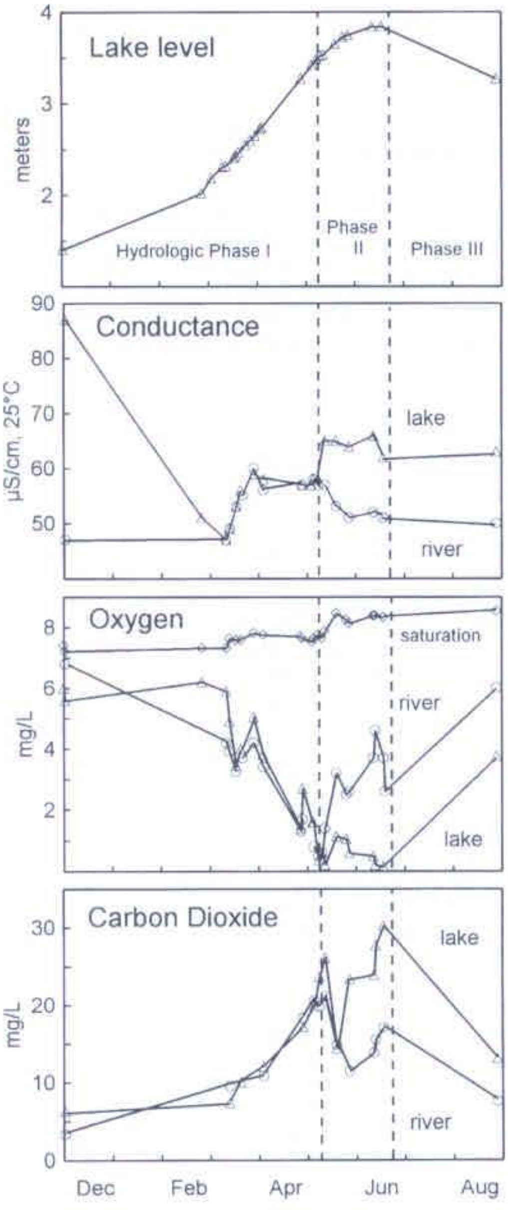

Fig. 2. Water level, conductance, and dissolved O_2 and CO_2 in Lake Castelo and the nearby Paraguay River. The saturation concentration is given for dissolved O_2.

rounding floodplain was mostly dry. Between that time and the fish kill in June 1994, three hydrological phases can be distinguished (Fig. 2), and their timing is likely to determine the occurrence and duration of fish kills in a particular year. Phase I was the initial rising-water phase, with increasing exchange of water between the lake and the river. In Phase II, river water spilled over the levee upriver from the lake entrance, passing through extensive, previously dry floodplain areas before reaching the lake, and forced lake water to exit back to the river through the connecting channel. The fish kills occurred in the latter part of Phase II, between 1–5 June. In Phase III this flow pattern continued, but the water levels gradually fell, and fish kills were not observed.

Changes in conductivity in the lake reveal the increasing proportion of river water in the lake in Phase I, and after February the lake water closely tracks the conductance of the river water (Table 1, Fig. 2). In Phase II, the lake diverges from the river. The higher conductance of water passing across the floodplain (66 µS/cm) may be explained by leaching of solutes from previously dry soils and from dead plant material, which includes abundant litter from the terrestrial plants as well as from the previous year's aquatic plant growth. There may also be significant evaporative concentration of solutes during residence of river water on the floodplain.

Dissolved O_2 and CO_2 reflect the changes in flow patterns in the lake (Table 1, Fig. 2). These gases were close to atmospheric equilibrium in the lake waters in December. Throughout Phase I, the concentration of dissolved O_2 steadily fell, accompanied by increasing concentrations of CO_2. This pattern was observed in both the river and the lake water. The lake waters reached virtual anoxia ($O_2 < 0.5$ mg/L, CO_2 up to 26 mg/L) at the beginning of Phase II, but fish kills were not observed at that time. Shortly thereafter, falling temperatures (Table 1) and increased winds associated with a cold front temporarily alleviated the situation. In the latter part of Phase II, however, the lake water once again approached anoxia, and fish mortalities occurred during the first week of June, which corresponded to a river stage of ~3.50 m at Ladário (near Corumbá).

Table 1. Hydrochemical characteristics of surface (Lk. surf.) and bottom (Lk. bot.) waters of Lake Castelo and of the adjacent Paraguay River during the three hydrological phases. Data are means with the range and number of measurements in parentheses; only one sample was collected during Phase III.

Variable	Site	Phase I	PhaseII	Phase III
pH	Lk. surf.	6.49 (6.22–6.93) (11)	6.25 (6.17–6.30) (6)	6.55
	Lk. bot.	6.39 (6.16–6.59) (9)	6.26 (6.18–6.35) (5)	6.43
	River	6.41 (6.26–6.62) (8)	6.37 (6.25–6.45) (6)	6.47
Cond. (µS/cm, 25 °C)	Lk. surf.	54.8 (47–59) (11)	64.4 (62–66) (5)	63
	Lk. bot.	58.8 (49–74) (9)	64.8 (62–67) (5)	87
	River	54.7 (47–60) (9)	52.8 (51–57) (5)	50
Alkalinity (µeq/L)	Lk. surf.	388 (313–426) (6)	447 (278–494) (6)	470
	Lk. bot.	408 (293–543) (6)	481 (465–514) (5)	691
	River	368 (315–410) (6)	374 (340–404) (6)	367
Dissolved O_2 (mg/L)	Lk. surf.	3.20 (0.35–6.20) (13)	0.55 (0.15–1.15) (7)	3.75
	Lk. bot.	2.33 (0.10–4.30) (9)	0.34 (0.10–0.60) (5)	0.30
	River	2.50 (0.50–4.20) (11)	2.81 (1.40–3.70) (7)	6.00
Secchi depth (m)	Lk. surf.	0.59 (0.47–0.79) (12)	0.65 (0.58–0.74) (5)	0.83
	Lk. bot.	–	–	–
	River	0.54 (0.39–0.71) (10)	0.81 (0.72–0.88) (5)	0.49
Water temp. (°C)	Lk. surf.	30.3 (28.5–33) (13)	25.0 (23.5–28) (7)	23
	Lk. bot.	28.6 (28–30) (9)	24.6 (22–27) (5)	21
	River	29.7 (28.5–31.5) (11)	25.6 (23–28) (8)	25
Chl-a (µg/L)	Lk. surf.	3.9 (2.2–5.6) (5)	4.4 (2.2–10.6) (5)	2.2
	Lk. bot.	2.8 (1.9–4.5) (5)	2.8 (1.7–3.9) (5)	1.1
	River	2.8 (1.9–4.1) (5)	2.1 (1.1–3.0) (5)	1.7

Table 2. Range of hydrochemical variation observed in the Paraguay River near Corumbá throughout the annual cycle (February 1992–November 1993). Analytical methods are given by HAMILTON (1994). TDS = Total dissolved solids; TSS = Total suspended solids.

Variable	Range	Variable	Range
pH	6.52–7.36	TSS (mg/L)	0.4–54
Gran Alkalinity (µeq/L)	337–468	Dissolved Fe (mg/L)	0.1–1.0
Ca^{2+} (mg/L)	3.2–4.8	Total Fe (mg/L)	0.2–3.1
Mg^{2+} (mg/L)	1.6–2.3	Dissolved Mn (µg/L)	2–5
Na^{+} (mg/L)	1.0–1.9	Total Mn (µg/L)	3–62
K^{+} (mg/L)	1.3–2.0	Dissolved Al (µg/L)	6–85
Cl^{-} (mg/L)	0.1–0.6	Diss. Organic C (mg/L)	2.0–8.3
SO_4^{2-} (mg/L)	0.04–0.6	Total diss. N (mg/L)	0.16–0.34
TDS (mg/L)	41–57	Dissolved H_2S (mg/L)	<0.02

During the fish kill, the O_2 of the surface water of the lake fell to 0.2 mg/L, and CO_2 reached 30 mg/L. By this time dissolved O_2 concentrations were higher in the river water. Persistent thermal stratification with the development of an anoxic hypolimnion was not observed during the study, although dissolved O_2 was sometimes lower in the bottom waters. The pH changed little and algal blooms were not evident during Phase II (Table 1), suggesting that algae were not a factor in the fish kills.

The fishes that died during this event were mostly individuals of the families Pimelodidae, Characidae (Myleinae, Serrasalminae), Cynodontidae, Loricariidae, Sciaenidae and Potamotrygonidae. Local fisherman quickly collected the dead and dying fishes, making quantitative observations impossible.

Interestingly, the fishes did not die during the first period of O_2 depletion, when concentrations fell as low as during the later fish kill, perhaps because there were refuges in other parts of the lake during the first period. Alternatively, another factor that covaries with O_2 could be involved as well, such as accumulation of reduced substances produced by anaerobic decomposition. Concentrations of ammonia, H_2S, and Al evidently do not approach toxic levels in these waters, as has been pointed out by RESENDE et al. (1990). Nitrite concentrations also remain low, as indicated by measurements of the sum of NO_3^- and NO_2^- (HAMILTON 1994). Table 2 summarizes additional hydrochemical characteristics of the Paraguay River near Corumbá, which provide an approximate indication of the chemistry of adjacent floodplain lakes.

The observation that many fishes were gulping air from the surface, together with the O_2 depletion and an increase in the free CO_2 concentration (Fig. 2), strongly suggest that asphyxia was the cause of the fish kill. High CO_2 acts synergistically with low O_2 to exacerbate the respiratory stress on fishes (LAGLER et al. 1977). Waters of the Pantanal may have particularly high dissolved CO_2 because of the prevalence of emergent aquatic plants with roots in the water column, which release CO_2 to the water (HAMILTON 1994).

The timing of fish kills in the Pantanal occurs after the initial contact of floodwaters with previously dry land, which causes rapid leaching of materials and stimulation of aquatic decomposition rates. A more severe dry season preceding the flooding would likely result in more dead vegetation, and in turn greater rates of decomposition upon inundation. This may explain the popular association of fish kills with burning, because more burning would occur during a severe dry season. Ashes from burning could conceivably cause fish kills if they resulted in marked pH elevation and accumulation of very high concentrations of dissolved ions, but this has not been observed in waters of the Pantanal.

This kind of fish kill has rarely been reported in the literature; the most comparable situation may be found in the floodplains of northern Australia (TOWNSEND 1994). However, such fish kills may be common in the extensive savanna floodplains of the tropics, which have received little study.

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References

BRINKMANN, W. L. F. & SANTOS, U. DE M., 1973: Heavy fish-kill in unpolluted floodplain lakes of central Amazonia, Brazil. – *Biol. Cons.* **5:** 146–147.

HAMILTON, S. K., 1994: *Aquatic biogeochemistry of the Orinoco River floodplain (Venezuela) and the Pantanal wetland (Brazil).* – Doctoral dissertation, University of California, Santa Barbara, California, USA.

KEMPE, S., 1982: Long-term records of CO_2 pressure fluctuations in fresh waters. – Mitt. Geol.-Paläont. Inst., Univ. Hamburg, *SCOPE/UNEP Sonderband* **52:** 91–332.

KUSHLAN, J. A., 1974: Effects of a natural fish kill on the water quality, plankton, and fish population of a pond in the Big Cypress Swamp, Florida. – *Trans. Amer. Fish. Soc.* **2:** 235–243.

LAGLER, K. E., BARDACH, J. E., MILLER, R. R. & PASSINO, D. R. M., 1977: *Ichthyology* – 2nd ed., Wiley, New York, 506 pp.

MARKER, A. F. H., NUSCH, E. A., RAI, H. & RIEMAN, B., 1980: The measurement of photosynthetic pigments in freshwaters and standardization of methods: conclusions and recommendations. – *Arch. Hydrobiol. Beih. Ergebn. Limnol.* **14:** 91–106.

RESENDE, E. K. & MOURÃO, G. M., 1987: Report on a fish kill that occurred in the Paraguay River (Feb. 27 to Mar. 5), Corumbá – *MS. EMBRAPA CPAP Technical Report*. (in Portuguese).

RESENDE, E. K., FERREIRA, C. J. A., CALHEIROS, D. F. & NASCIMENTO, F. L., 1990: Changes in water quality during a fish kill in the Paraguay River, Pantanal Matogrossense. – *Proceedings of III Brazilian Congress of Limnology:* 183. (in Portuguese).

TOWNSEND, S., 1994: The occurrence of natural fish kills, and their causes, in the Darwin Katherine-Jabiru region of northern Australia. – *Mitt. Internat. Verein. Limnol.* **24:** 197–205.

WELCOMME, R. L., 1985: *River Fisheries.* – FAO Fisheries Technical Paper 262. Food and Agriculture Organization of the United Nations, Rome, 330 pp.

WETZEL, R. G. & LIKENS, G. E., 1991: *Limnological Analyses.* – 2nd ed. Springer-Verlag, New York, 391 pp.

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