Empirical Results on Groundwater Seepage – a Key Determinant for Hydrochemical Seasonality of Lake Camaleão, a Central Amazonian Floodplain Lake

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Synopsis

For Lake Camaleão, an island channel lake subject to the 10 m annual floodpulse of the lower Solimões River, groundwater seepage driven by stage level dynamics has recently been suggested as a major factor causing the characteristic peak in cation concentrations occurring during its low-water (isolation) phase. To test this hypothesis, a time series of hydrological and hydrochemical variables was recorded focusing on two out of the lake's four hydrological phases which are filling, through-flow, drainage and isolation. In 1995, Ca concentrations during through-flow were down to the low values observed in the river water, confirming that river water dominated lake hydrology during this phase. The seasonal pattern in cation concentration was qualitatively similar to results reported for the early 1980s. However, peak concentrations during isolation were lower than previously reported. Lake water cation loading was initiated after the start of the falling-water period and continued for two weeks after the onset of hydrological isolation. After nearshore hydraulic gradients turned negative, and consequently the influx of groundwater terminated and efflux of lake water into the aquifer occurred, cation concentrations ceased to increase. This pattern was observed for Ca, Mg, and Na. For K, the increase continued until termination of the recordings, which supports the view of decomposing macrophyte vegetation as an additional factor for the seasonality of this particular cation. Compared to the early 1980s, the stage level of hydrological isolation of the lake rose from 18.6 m above mean sea level to 22 m. Thus, the stage level range over which bank seepage occurs was reduced by 3.4 m or roughly 50%. It is suggested that the lower peak concentrations of major cations are due to this reduced range and the increased water volume of the isolated lake. Our results comprise the first field evidence that groundwater seepage is a key determinant for Lake Camaleão's hydrochemical seasonality and thus highlight a previously underrated factor in the lake's nutrient dynamics.

floodplain lake, tropical, Amazon, hydrochemistry, seasonality, groundwater, seepage

1 Introduction

Characterized by annual flooding, the fringing floodplains of the Amazon main stem cover close to 100.000 km^2 in its Brazilian reach, 10% of which are covered by permanent floodplain lakes (SIPPEL & al. 1992). Although considerable local variation exists, the main stem floodplains generally show elevated levels of primary production compared to permanent water bodies unaffected by flooding (JUNK & PIEDADE 1997). The annual delivery of nutrient-rich sediments with flooding is perceived as a major control of floodplains with predictable, low-frequency flooding favoring biotic adaptations and thus high levels of primary productivity (JUNK & al. 1989). Due to this high productivity, Amazonian floodplain ecosystems are increasingly subject to anthropogenic impacts (JUNK 1997). In order to assess the consequences of anthropogenic impacts but also to provide a basis for definition of management goals a sound understanding of the ecological functioning of floodplains is required. In this context, our study aims at improving our understanding of nutrient dynamics in a particular floodplain lake, representative for a considerable share of the total population of floodplain lakes on the Amazon mainstem (SIPPEL & al. 1992).

Located on Marchantaria Island in the Amazon mainstem 20 km upstream from the confluence with the Negro River, Lake Camaleão lacks an upland drainage basin and thus provides a study site of reduced hydrological complexity. The Lake shows a distinct seasonality with four hydrological phases namely isolation, filling, through-flow and drainage (WEBER & al. 1996). During filling, river water enters from a channel connecting lake and main river on the downriver side of the island. With further rise, increasing through-flow of surface water occurs due to channels on the upriver island shore connecting lake and river, and at extremely high river stages, the whole island can be flooded. The lake's annual hydrochemical evolution is also characterized by a distinct seasonal pattern with low solute concentrations during through-flow, a rapid increase by one order of magnitude during drainage, and a fast decrease during subsequent filling (WEBER & al. 1996; KERN 1995; FURCH 1984; FURCH & al. 1983; FURCH

1982). For major cations, this pattern is most clearly expressed, whereas for nitrogen or phosphorous, the evolution shows a much larger variability on the seasonal as well as on the annual timescale (KERN 1995; FURCH & JUNK 1993). The simple and regular pattern of their seasonal evolution, render major cations a subject well suited for studies on the basic causal factors and processes of lake nutrient dynamics.

In the tropics, extreme seasonal fluctuations of physical, chemical and biotic characteristics of aquatic floodplain habitats (JUNK 1997; SIOLI 1984) contrast markedly with the relative environmental constancy of many other types of tropical waterbodies. However, the underlying abiotic and biotic causes of seasonality are still poorly understood and frequently left to speculation, since quantification of hydrology and mass transport is difficult and has rarely been attempted. In earlier studies, biotic nutrient fluxes originating from rapid decomposition of the large standing macrophyte biomass (PIEDADE & al. 1991) were considered as major causal factors for the lake's characteristic solute concentration peak during drainage (FURCH 1984; FURCH & al. 1983; FURCH 1982). However, studies in the 1980s did not attempt quantitative assessments of the underlying hydrological processes.

Based on a lumped dynamic mass balance model incorporating surface water flow paths as well as biogenic nutrient fluxes originating from growth and decomposition dynamics of local macrophyte vegetation spatially assigned to distinct elevation zones (WEBER 1997), the first quantitative approach towards the lake's hydrochemical seasonality showed that except for potassium, biogenic fluxes could not possibly explain lake water cation loading during drainage (WEBER & al. 1996). For a floodplain lake further upstream from our study site, LESACK (1995) reported that bank seepage during rapidly falling stage level – when water levels in the surface water bodies fall much faster than in the surrounding groundwater – contributed a significant share in the lake's water budget. LESACK's findings, and reports on local properties of Lake Camaleão such as high cation concentrations in groundwater samples (FURCH & JUNK 1997) and soils draining well after reemergence (WORBES 1986) led WEBER & al. (1996) to the suggestion that loading might be due to seepage of local groundwater. WEBER (1997) adapted an empirical seepage model by LESACK (1995), and demonstrated with a dynamic mass balance model that seepage of cation-rich groundwater during drainage might quantitatively explain the lake's characteristic concentration peaks.

The purpose of this study was to provide empirical evidence for the contribution of seepage fluxes in the lake's characteristic pattern of hydrochemical seasonality. Based on the working hypothesis that cation loading during drainage is generated by seepage influx, we expected that upon termination of seepage influx cation concentrations in the lake water would not increase further. To test this hypothesis we recorded a time series of hydrological, and hydrochemical variables during late falling water and early isolation phase in 1995 targeting at closely identifying the timing of seepage flux reversal and peaks of cation concentrations.

2 Methods

Local stage level in Lake Camaleão was recorded with a staff gauge with Manaus harbor gauge as reference point. River stage levels were obtained from Manaus harbor recordings.

Nearshore hydraulic gradients were measured at up to nine locations with piezometers installed at a depth of 60 to 100 cm into the sediment. The piezometers were made of commercially available 17 mm water pipes. For installation a lag bolt was inserted to the bottom end of the pipe and knocked out with a rod after driving the piezometer to the depth of interest. The tops of the piezometers were underwater, and the hydraulic head was therefore measured relative to the surface of the lake by connecting a U-tube manometer as described by LEE & CHERRY (1978). Hydraulic conductivity was measured by attaching plastic bags to the submerged piezometers (LEE & CHERRY 1978) and recording the occurring flux rate. To complement the measurements of hydraulic gradients, two observation wells were drilled 100m to the north, and to the south of the shoreline in the mid lake section.

Seepage flux between groundwater and lake water was measured with seepage meters designed according to LEE (1977). The diameter of the seepage cylinders was 20 cm, similar to the devices used by LESACK (1995) in Lake Calado. Seepage influx is measured by connecting a deflated plastic bag to the seepage cylinder, whereas efflux can be measured by connecting a plastic bag filled with a defined volume of water. Up to 30 seepage meters were installed into the nearshore sediment in depths ranging from 20 to 70 cm. For a total of 99 seepage measurements, recording time was approximately 1 day. In some additional cases groundwater influx rate was too high to allow for more than several minutes of recording time, due to the limited volume of the collection bags.

Hydraulic conductivity of the top 50 cm of the emerged soils was measured by sampling nine locations in each of three different vegetation types with permeameters as described by LAMBE & WHITMAN (1969). We distinguished stands of *Echinochloa poly-*

stachya, a highly productive semiaquatic grass, at an elevation of 22–23 m, agricultural cropping sites of the local population at an elevation of 24–26 m, and the inundation forest at elevations above 27 m. Laboratory measurements of hydraulic conductivity was performed with a constant head of 300 cm.

From May through November 1995 river and lake water was sampled in intervals of 1 week to 1 month. During falling water, groundwater samples were collected from nearshore boreholes on the emerged sediment. The lake was sampled at three locations on a longitudinal transect. However, here we give the results for the central lake station, which are considered representative for average water quality (WEBER & al. 1996). FURCH & JUNK (1993) could not detect a pronounced vertical hydrochemical stratification in Lake Camaleão, and therefore we sampled the lake surface. Samples were filtered with 0.45 µm membrane-filter (Sartorius, cellulose nitrate filter), and acidified with ultrapure HCl (1 ml l^{-1}). The filtered samples were analyzed by flame atomic absorption (AAS 300, Perkin & Elmer) for the major cations Ca, Mg, K, and Na.

3 Results and Discussion

The hydrographs of river and lake show that hydrological isolation of the lake was reached at a stage of ca. 22 m above mean sea level on September 1, 1995 (Fig. 1). Following hydrological isolation, rates of stage level change in Lake Camaleão decreased from ca. 20 cm day^{-1} to an average of 1.4 cm day^{-1} during September and October. River stage level continued to fall with a high rate of up to 25 cm day^{-1}, and by the end of October the difference in stage level between lake and river reached ca. 6 m.

In 1995, the stage level of hydrological isolation was ca. 3.4 m higher than reported for the early 1980s (WEBER & al. 1996). Thus, due to sedimentation in the downstream channel connecting lake and river, the lake's stage level amplitude is greatly reduced compared to the 1980s. Consequently, the stage level range over which bank seepage occurs was diminished by more than 3 m, resulting in a reduced total seepage influx. Considering furthermore that the residual water volume of the isolated lake was larger than a decade ago, we would expect a seepage generated cation concentration peak to be smaller than in the 1980s.

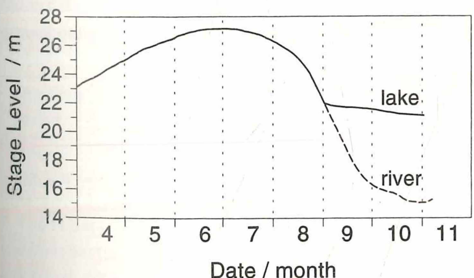

Fig. 1

Hydrographs of the Amazon River and Lake Camaleão in m above mean sea level during 1995.

After the onset of hydrological isolation, mean nearshore hydraulic gradients were positive during the first fortnight in September, but thereafter switched to the negative (Fig. 2B). Accordingly, mean seepage rates were positive during the first fortnight in September, and switched on September 15, when mean nearshore hydraulic gradients were negative for the first time (Fig. 2C). Results from the observation wells were consistent with the measured hydraulic gradients and seepage fluxes. At the end of September, groundwater levels in the two wells were below the lake stage, with an increasing difference throughout October (Fig. 2A).

With maximum rates of ca. 0.05 mm hr^{-1} seepage influx was low compared to reports from Lake Calado, a floodplain lake with a large upland drainage basin further upstream on the Amazon main stem. However, the high seepage rates with an overall mean of 1.62 mm hr^{-1} measured in Lake Calado (LESACK & MELACK 1995) were recorded during falling-water with changes in lake stage level of up to 10 cm day^{-1}. In Lake Camaleão, seepage recordings commenced at the end of the lake's drainage phase only, when daily lake stage changes and stage level differences between lake and surrounding groundwater surface were small already. Additionally, the smaller hydraulic conductivity in the lower lying soils of Lake Camaleão would lead to smaller influx rates.

Hydraulic conductivity in the sediments of the three emerged vegetation classes differed greatly, ranging from ca. 4 µm sec^{-1} in the inundation forest to 93 µm sec^{-1} in the sites utilized for agricultural crops (Tab. 2). With 34 µm sec^{-1} stands of *E. polystachya* showed an intermediate hydraulic conductivity. Conductivity of submerged sites derived from piezometer flux measurements was comparatively low with 1 µm sec^{-1}. Results from the piezometer and seepage meter measurements are consistent, since the observed and the expected seepage fluxes are fairly close. For example, on the last observation in October the mean hydraulic gradient was – 0,23. With this gradient and a mean hydraulic conductivity of the submerged sediment of k = 1 µm sec^{-1} (Tab. 2), we would expect a seepage flux of – 0,82 mm hr^{-1} from the Darcy equation, which is close to the observation of – 0,72 mm hr^{-1}.

In lake Calado, LESACK (1995) reported hy-

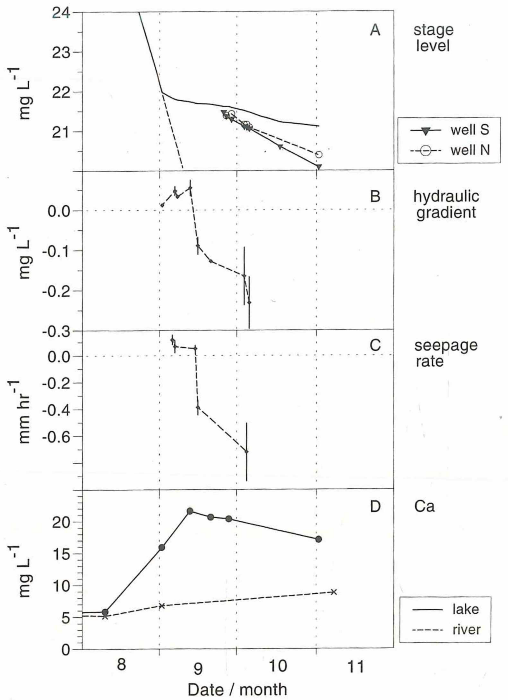

Fig. 2
A: stage level of lake, river, and two observation wells to the north and south of the central lake section. B: Mean nearshore hydraulic gradients. C: Mean seepage rates. D: Ca concentration in the river and the central lake station.

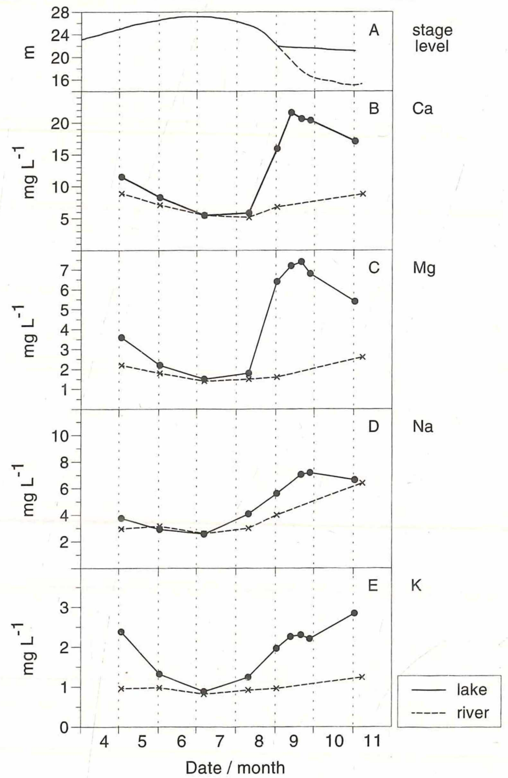

Fig. 3
A: hydrographs of lake and river. B–E: Cation concentrations in the river and at the central lake station.

draulic conductivity for an annually flooded forest soil in the lower reach of a typical stream valley of 15 µm sec^{-1}, and for shoreline soils along the main body of the lake 8.2 µm sec^{-1}. In Lake Camaleão, mean conductivity in the inundation forest was somewhat lower with 4 µm sec^{-1} but ranged in the same order of magnitude. However, with 34 and 93 µm sec^{-1} in two vegetation zones characteristic for the elevations between 22 and 26 m in the Camaleão basin, hydraulic conductivity is high. When lake stage level passes through this range during drainage, lake stage level changes correspond to the high rates occurring in the main river (Fig. 1) and a higher hydraulic gradient between lake and surrounding groundwater surface will be maintained during this period. Hence, given the highly permeable sediments in this elevational range, we would expect high seepage influx rates at stages above the isolation threshold of 22 m. This expectation is confirmed by discernable positive seepage rates even during early isolation (Fig. 2), when seepage occurred through less permeable sediments below the level of 22 m.

Groundwater samples collected prior to September 15, the period when seepage influx occurred, showed high cation concentrations (Tab. 1) which were close to the values reported by FURCH & JUNK (1997), except for the higher concentration of Mg in our samples. Except for potassium, groundwater samples collected after mid September, when seepage efflux occurred, showed lower cation concentrations compared to the samples collected during seepage influx (Tab. 1).

During high-water, lake and river water showed similar cation concentrations (Fig. 3). After the start of the falling-water period cation concentrations in the lake water increased. Except for K, peak concentrations were reached around mid September approximately two weeks after the lake had entered hydrological isolation from the river (Fig. 3). For K, the increase continued until the end the sampling period (Fig. 3E). The basic seasonal pattern in cation concentration reported by FURCH & al. (1983) and WEBER & al. (1996) for 1981 and 1982 is still observed in Lake Camaleão. However, with the exception of K, peak concentrations observed in 1995 are greatly reduced. For example, for Ca, peak concentration was 86 mg l^{-1} (WEBER & al. 1996) and 21.6 mg l^{-1} in 1982 and 1995, respectively. Hence, our results confirm the reduced maximum concentrations expected for a mainly seepage generated cation loading of lake water.

Cation loading did not continue after the hydraulic gradient and the seepage flux had turned negative (Fig. 2). Thus, the reversal of the seepage fluxes marked the time of peak cation concentrations in lake water, except for K (Fig. 3). Decreasing concentrations subsequent to the time of seepage flux reversal can be explained with the lake's water budget in particular with the diluting effect of rainfall. However, a quantitative analysis of the hydrochemical evolution during isolation is not required for our purpose and is beyond the scope of this study. For three out of the four cations studied, timing of flux reversal and concentration peaks agree with our working hypothesis, and thus confirm the key role of seepage flux for hydrochemical seasonality in Lake Camaleão suggested by WEBER & al. (1996) and WEBER (1997).

For K, loading of lake water ceased during the first days following seepage flux reversal (Fig. 3 E), but at the final sampling date K concentration was higher than at the temporary peak following flux reversal. We consider this as a further stone in the mosaic of findings from empirical and modelling studies attributing biogenic fluxes an important role in the lake's seasonal evolution of K (WEBER & al. 1996; FURCH 1984; FURCH & al. 1983; FURCH 1982). The temporary halt of K loading of lake water subsequent to seepage flux reversal supports the assump-

Table 1
Mean cation concentrations (mg / L) in nearshore groundwater samples .

Sampling period	Ca	Mg	Na	K
influx [1)]	97.00 a [3)]	38.75 a	20.90 a	2.47 a
efflux [2)]	33.55 b [3)]	18.20 a	13.05 b	2.25 a

[1)] up to September 14, 1995 = during seepage influx
[2)] from September 15, 1995 on = during seepage efflux
[3)] T-Test, different letters mark significantly different mean concentrations (p = 0.05)

Table 2
Hydraulic conductivity *k* (mean, standard error) in Camaleão basin.

Method	Vegetation	Elevation / m	*k* / µm sec^{-1}
piezometer [1)]	decomposed [3)]	< 21.6	1.0 ± 0.2
permeameter [2)]	*E. polystachya*	22 – 23	34.1 ± 15.7
	crops	24 – 26	92.6 ± 36.2
	forest	> 27	3.7 ± 1.3

[1)] depth below sediment surface 60 – 90 cm
[2)] top 50 cm of the soil
[3)] mainly *E. polystachya* on submerged sediment

tion that initially seepage influx dominates K loading whereas at a later stage of the isolation phase, decomposition of macrophytes is initiated and comprises a second source of K loading.

Our results inevitably lead to a new question: what is the cause of cation loading of local groundwater? During flooding, sediments are recharged with water which is basically river water with low solute concentrations. During subsequent storage this water is enriched in solutes by one order of magnitude or more. Whereas IRION (1983) could not detect changes in the mineralogical composition of the upper sediments of Marchantaria Island due to weathering, the authors claimed that there was iron and manganese release to a considerable extent. This apparent contradiction could be due to the geologically small age of these upper layers of at most several centuries (IRION & al. 1983). Thus, it cannot be excluded, that weathering of clay minerals constitutes the ultimate source of cation loading in Lake Camaleão.

With an annual deposition rate of 2–5 mm of riverine sediments reported for Marchantaria Island (IRION 1997) the input might be high enough to offset the losses due to groundwater seepage and hence to maintain Lake Camaleão's characteristic hydrochemical seasonality over decades. However, sedimentation events in the connecting channels can alter lake stage dynamics and consequently the stage level ranges of seepage fluxes abruptly. Within roughly a decade we observed a three meter rise in the ingression stage levels of Lake Camaleão. If seepage is a crucial process for the annual evolution of lake water quality with respect to limiting nutrients (N, P) as well, we would expect that the altered lake hydrograph affects local primary production to a considerable extent. In order to further improve our understanding of floodplain nutrient dynamics, long term studies including lake hydrology as well as quantification of primary production would be of great interest. However, due to the unpredictability of sedimentation events comparative studies of lakes with different local hydrographs might hold the greater promise to this end.

4 Conclusion

A short time series of hydraulic variables allowed the identification of the timing of seepage flux reversal in Lake Camaleão. Seepage flux reversed in mid September 1995, two weeks after the lake had entered in its isolation phase. Once seepage influx had ceased and lake water had started seeping into the sediment, no more cation loading of lake water occurred, except for potassium towards the end of the sampling period. We conclude that Lake Camaleão's characteristic peak of major cation concentrations is due to seepage influx of cation rich groundwater during the lake's drainage phase, when the rapidly falling surface water level generates and maintains positive hydraulic gradients in the surrounding groundwater surface. Due to the sensitivity of lake water quality towards seepage influx, we expect that the evolution of other solutes, e.g. nitrogen and phosphorous-compounds will also be influenced by seepage fluxes. Hence, any quantitative understanding of nutrient dynamics in Lake Camaleão requires quantification of both surface and subsurface flow paths of water and solutes.

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