

Islands in the Okavango Delta as Sinks of Water-Borne Nutrients

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Abstract

Groundwater under islands in the Okavango Delta is a known sink of inorganic dissolved minerals, preventing salinisation of this virtually enclosed evaporation-dominated hydrological system. The Okavango Delta is an oligotrophic, yet very productive system, and it is important to understand sources, pathways and recycling of nutrients in order to fully comprehend its ecology. In order to investigate the role of islands as nutrient sinks, concentrations of nitrogen and phosphorus, as well as major inorganic ions were measured in island and floodplain groundwater. The electrical conductivity was found to be up to 50 times higher in the island centre groundwater than in the surrounding floodplain groundwater. The amount of total phosphorus was found to be up to 400 times higher and total nitrogen up to five times higher in the interior of the island than in the surrounding floodplain. These show that major nutrients are, like other inorganic ions, accumulated under islands. Importantly, the ratio of nitrogen to phosphorus was 5:1 in floodplain water and water in island fringe soils, but 1:4 in island centres. This indicates an intensive removal of nitrogen along the floodplain-island groundwater flow path by the floodplain fringe and riparian biota, resulting in a relative enrichment in P.

Introduction

The Okavango Delta is a large inland wetland fed by the annual flood of the Okavango River. This flood pulse causes the inundated area in the Delta to expand from an annual low of 4,000-6,000 km² to an annual high of 8,000-12,000 km². The permanent and seasonal flooding creates a wetland ecosystem in stark contrast to the surrounding rain-fed semi-arid savannah of the Kalahari. This makes the Okavango the basis for subsistence livelihoods of the local population, and the main attraction of Botswana's tourism industry. In 1997 the Okavango Delta was declared a Ramsar site - a wetland of international importance.

The two primary sources of nutrients in the Okavango Delta are the inflowing Okavango River and atmospheric aerosol deposition.

The deposition of atmospheric aerosols is a quantitatively important source of nutrients in the Okavango (Garstang *et al.*, 1998), and one which is characterized by a relatively uniform spatial distribution. N and P in aerosols originate from dust and ash from fires in the region and are primarily transported by large-scale anticyclonic circulation occurring during late winter (August). For the Etosha Pan in Namibia, deposition rates of 0.2-21.7 g·ha⁻¹·day⁻¹ for NO₃⁻ and 0.06-1.1 g·ha⁻¹·day⁻¹ for PO₄³⁻ were calculated based on a large scale atmospheric aerosol mass budget (Swap, 1996). At smaller scales, N and P are redistributed between dry islands and wet floodplains as a result of wind-induced movement of dust (Krah *et al.*, 2004).

The concentrations of nitrogen and phosphorus in the Okavango River at the inlet to the Delta are similar to global average concentrations in river water. Cronberg *et al.* (1996) found

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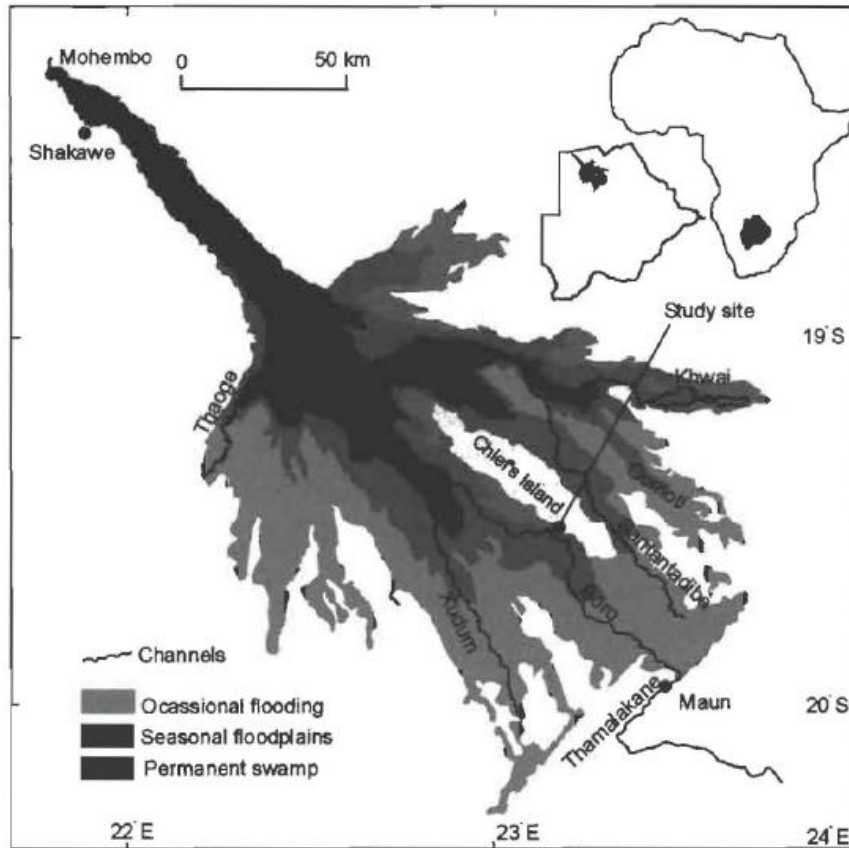


Figure 1. The Okavango Delta, Botswana.

0.35-0.88 mg·dm⁻³ of total N with 0.012-0.030 mg·dm⁻³ of NO₃⁻ and 0.024-0.044 mg·dm⁻³ of total P in the Okavango river water, while the global average is 0.2 mg·dm⁻³ total N and 0.02 mg·dm⁻³ of total P (Mitsch and Gosselink, 2000). In the permanent swamp, plant-available N and P compounds brought by the Okavango River are scavenged by bank vegetation, primarily the giant sedge papyrus (*Cyperus papyrus*) flanking the main distribution channels, when the floodwater seeps from these channels to feed the downstream system of seasonal floodplains (Garstang *et al.*, 1998). Nutrients are very tightly internally cycled by papyrus, being relocated from senescing culms to new growing shoots (Denny, 1985). Small quantities of recalcitrant organic N and P may be trapped in peat. Until the peat is oxidised through exposure to air, or burning, this recalcitrant portion of nutrients is immobilized and is available neither to papyrus nor to downstream seasonal floodplains, aside from a fraction which may be microbially mineralised.

The N and P present in the water of the seasonal floodplains downstream, therefore, have either escaped nutrient “stripping” by aquatic macrophytes taking place in the permanent swamp by being in non-plant available forms, were released from senescing plant material along the flow path, or were delivered to the floodplains as atmospheric deposition. The contributions of these various sources, however, have not to date been quantified. The water of the seasonal floodplains is characterised by a relative enrichment of both N and P compared to the main Okavango River. In the floodplains of the middle Boro system values of 0.98-3.1

mg-dm⁻³ of total N (0.016-0.183 mg-dm⁻³ of NO₃⁻) and 0.042-0.466 of total P were recorded by Cronberg *et al* (1996) and Hoberg *et al* (2002).

In the seasonal floodplains there is an intensive cycling of nutrients controlled by the seasonal cycle from reducing to oxidising conditions in the sediments. During the flood recession, under oxidising conditions, the organic (soluble and to a lesser extent particulate) N and P (ON and OP) present in the senescent plant material and in the soil are mineralised by microbial action and oxidation into the plant-available forms PO₄³⁻ and NO₃⁻. The ON is transformed in a two-stage process via NH₄⁺ (ammonification) and thence to NO₂⁻ and NO₃⁻. OP is transformed by degradation of organic material and then by oxidation and some microbial action to form soluble PO₄³⁻. At the arrival of the flood, these enter into solution in addition to the P and N brought in with the flood water.

Phosphorus cycling is not significantly microbially mediated in anaerobic conditions. When oxidising or low pH conditions pertain, P is in the form PO₄³⁻, orthophosphate, or the form soluble organic phosphate (SOP). Orthophosphate tends to form strong complexes with clays, calcium/magnesium carbonates, and metal hydroxides (Fe or Al); these complexes effectively immobilise P, making it unavailable to plants, but also removing it from solution (Axt and Walbridge, 1999; Mitsch and Gosselink, 2000; Wetzel, 2001). SOP, having no charge, is not prone to complexing, and although soluble is not a plant-available form.

During the flood, N and P are actively taken up in the floodplain sediments through processes of complexation, microbial activity, and directly from pore water by rooted emergent plants. Additionally, infiltrating flood water carries dissolved N and P to the island fringe soil supplying bacterial processes in the hyporheic zone. Some N may be mineralized into to gaseous NH₃, N₂O and N₂ and effectively removed from the system. All these processes contribute to a decrease in total N concentration in floodplain water, a phenomenon observed by Hoberg *et al* (2002) and Krahl *et al* (2005).

One of the paths of movement of nutrients from the seasonal floodplains in the Okavango Delta mentioned above is advection with infiltrating water. Infiltration is an important element of floodplain water balance: up to 90% of floodplain water input can be removed that way (Ramberg *et al*, 2005). Some nutrients carried by the infiltrating water may be utilized by bacteria in the hyporheic zone or in shallow groundwater in the direct vicinity of floodplains. For example, Ramberg *et al* (2000) showed that there were high concentrations of *Nitrosomonas* and *Nitrobacter*, which produce plant available NO₃⁻ from organic N, in the groundwater along the perimeter of an island (Figure 2).

In the Okavango Delta, advection and movement with groundwater is the process responsible for immobilization of inorganic chemicals described in detail by McCarthy and Ellery (1994). In this process, a cone of groundwater depression under an island is created by island vegetation transpiring shallow groundwater (Figure 3). This induces radial flow of groundwater towards the island centre, maintained by infiltration of surface water in the surrounding floodplains. Concentrations of solutes in the island groundwater are subject to evaporative and transpirative enrichment, and as a result, high salinity brines are formed in the island centre. A groundwater salinity gradient develops, which affects island vegetation: the island centre is bare or supports only salinity tolerant grasses, while the island fringe, where groundwater is fresh, supports lush riparian woodland. Concentrations of solutes often exceed their saturation points, and precipitation of carbonates and silicates takes place, contributing to island aggradation. The process is ubiquitous in the Okavango Delta as is manifest by the conspicuous zoning of vegetation on virtually all islands in the system. The process is thought

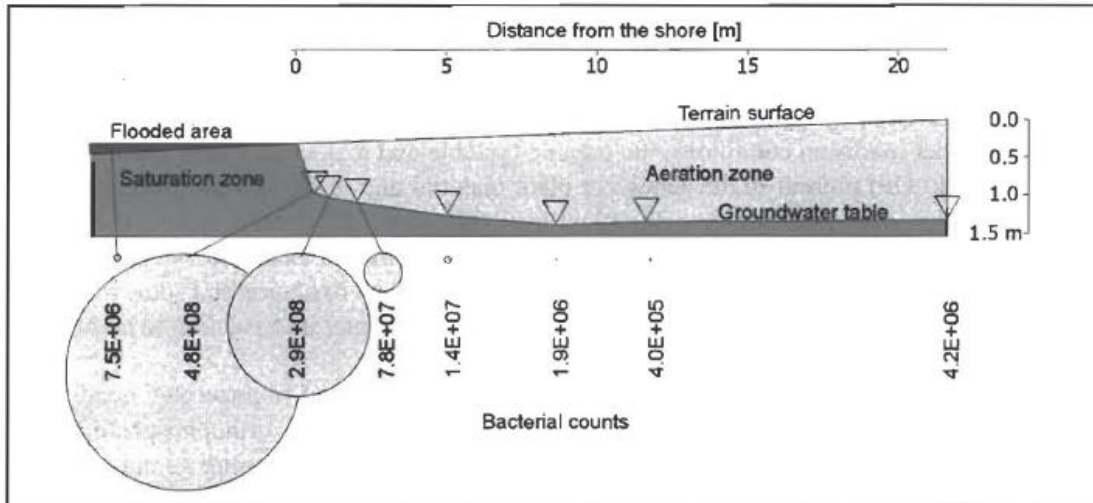


Figure 2. Bacterial counts at water table along a floodplain-island groundwater flow system (after Ramberg *et al*, 2000).

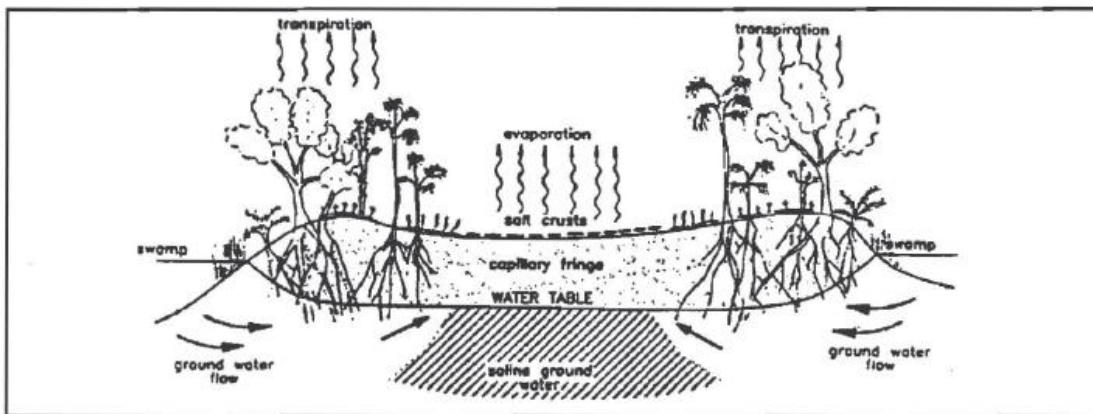


Figure 3. Model of islands' role in solute immobilization in the Okavango Delta. (after McCarthy and Ellery, 1994).

to keep solutes from the surface, which would otherwise accumulate as a result of evaporation and transpiration removing 95% of the system water input, turning the Delta into a saline lake.

This paper presents results of a short study aiming at identifying the storages of nutrients in the island groundwater and at hypothesizing a conceptual model of origin and transport of nutrients in the floodplain-island groundwater system of the Okavango Delta.

Materials and Methods

Study Site

Groundwater was sampled at two islands located in the seasonally flooded zone, along the main Boro channel. Camp Island is a medium-sized island (25,000 m²) with vegetation zoning typical of Okavango Delta islands. The outer fringe is covered with riparian woodland, followed by a palm belt, while the central part is covered by salinity tolerant grass. Regular seasonal flooding occurs on the SW side of the island, while the NE side is inundated only during high flood

years, and was not inundated during the field campaign in March-April 2003. Observation Island is a small (2,500 m²) asymmetric island. A narrow riparian belt faces the Boro River on the NW, and the remainder is covered by salinity tolerant grass. During the flood season the island is usually surrounded by water. During the field campaign the floodplain to the NE of Observation Island was dry.

Field Sampling

Groundwater samples were taken from three permanent piezometers on Observation Island and from two on Camp Island (Figure 4). Additionally, 11 augered holes constituting two transects were drilled and sampled on Camp Island. In the field, measurements of pH, temperature and conductivity were done using a YSI field meter. Samples were collected using a vacuum pump, and all auger holes and piezometers were pumped dry three times before the sampling. Samples of 1 dm³ were filtered through a 0.45 mm Millipore filter, and split into two portions: one, used for cation analysis, was acidified with nitric acid, the other, used for total nitrogen and total phosphorus analysis, was not.

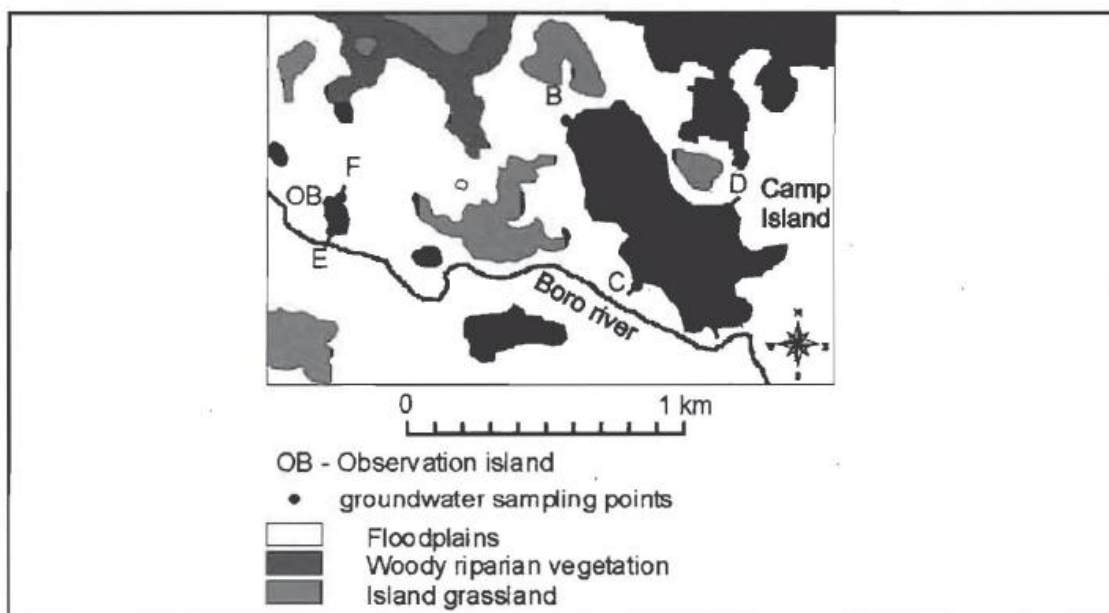


Figure 4. Location of sampled groundwater transects.

Laboratory Analyses

In the laboratory, total P and total N were measured using a Bran+Luebbe Auto Analyser III. For total P, the sample was first irradiated in a UV digester to release organically bound phosphorus. Subsequently, acid persulfate was added to break down the remaining organic compounds. Polyphosphates were converted to ortho-phosphate by acid hydrolysis at 90°C. The ortho-phosphate was determined by reaction with molybdate, antimony and ascorbic acid, producing a phospho-molybdenum blue complex which was measured colorimetrically at 880nm (Bran+Leubbe method no. G-219-98).

For total N, inorganic and organic nitrogen compounds were oxidised to nitrate by persulphate under alkaline conditions in an on-line UV digester. The nitrate was reduced to

nitrite in a cadmium column and then determined using the sulphanilamide/NEDD reaction with detection at 520nm (Bran+Leubbe method no. G-218-98).

Calcium (Ca) and Magnesium (Mg) were analysed on the acidified samples using a Varian SpectraAA 220 atomic absorption spectrometer. Sodium (Na) and Potassium (K) were analysed using a Sherwood Flame Photometer 410.

Results

In all transects the groundwater table under the island body was lower than that under the surrounding floodplains (Figures 5, 6 and 7). Groundwater electrical conductivity, pH and Na⁺ concentration increased from the floodplains towards the island centres. Conductivities of 300 to 800 $\mu\text{S}\cdot\text{cm}^{-1}$ were recorded in the floodplains, and up to 14000 $\mu\text{S}\cdot\text{cm}^{-1}$ in the island grassland area. Floodplain groundwater had a pH of 6 while values of up to 8.8 were recorded in the island centres. The concentration of Na⁺ was less than 20 $\text{mg}\cdot\text{dm}^{-3}$ in the floodplains and increased towards island centre, reaching 10000 $\text{mg}\cdot\text{dm}^{-3}$. Concentrations of Ca²⁺ and Mg²⁺, however, did not follow the same pattern. Floodplain groundwater contained 17-20 $\text{mg}\cdot\text{dm}^{-3}$ of Ca²⁺ and 5-7 $\text{mg}\cdot\text{dm}^{-3}$ of Mg²⁺. In island fringe groundwater (riparian belt) Ca²⁺ concentrations of 50-80 $\text{mg}\cdot\text{dm}^{-3}$ and Mg²⁺ concentrations of 30-50 $\text{mg}\cdot\text{dm}^{-3}$ were recorded. In island centre, however, Ca²⁺ concentrations of 8-10 $\text{mg}\cdot\text{dm}^{-3}$ and Mg²⁺ concentrations of 3-5 $\text{mg}\cdot\text{dm}^{-3}$ were measured.

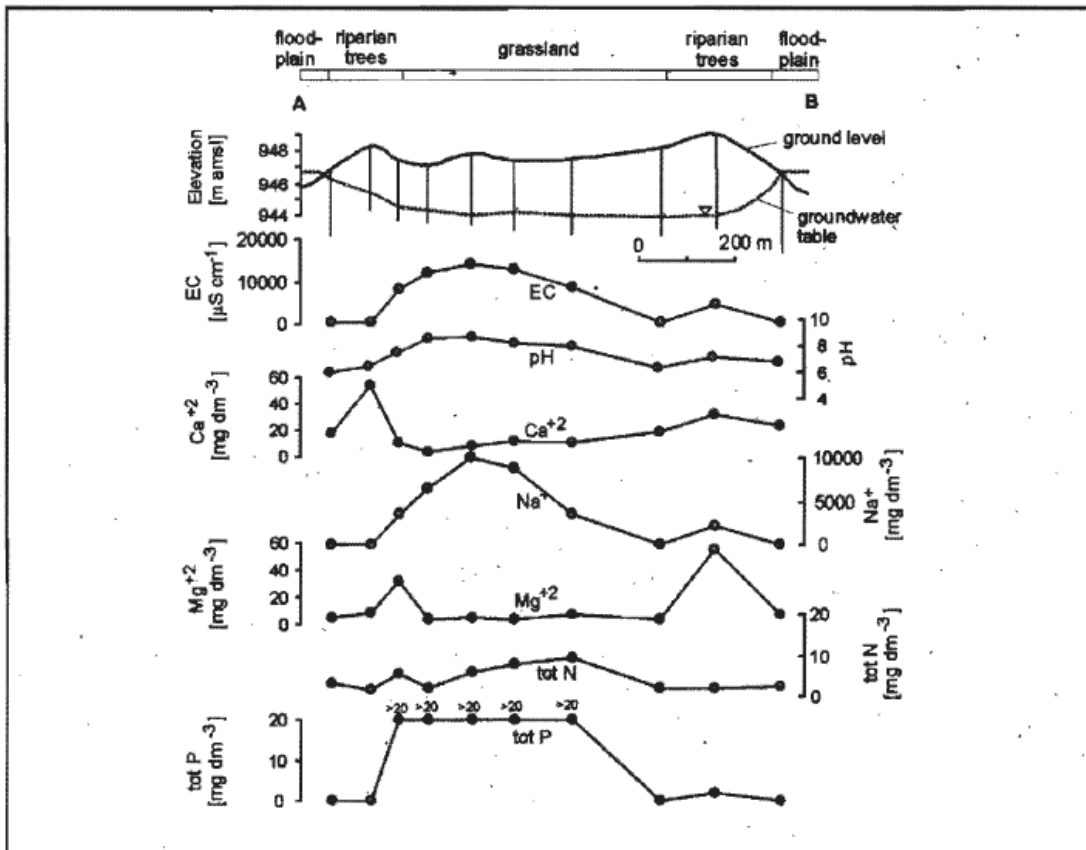


Figure 5. Groundwater table, EC, pH, concentration of major ions and N and P for A-B transect.

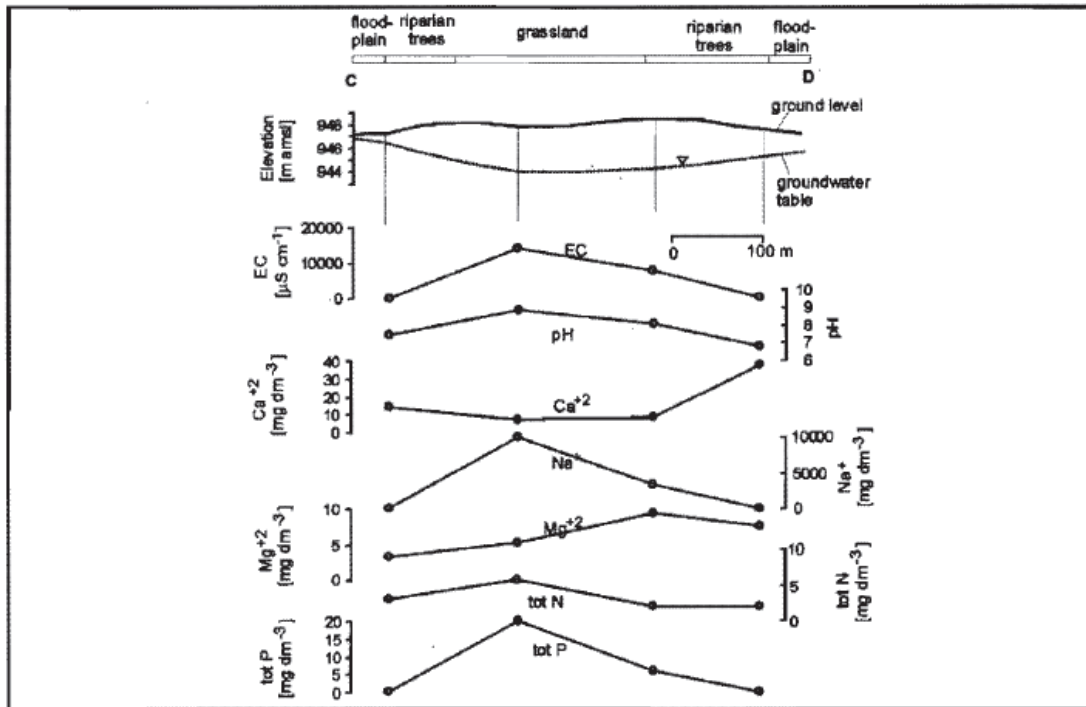


Figure 6. Groundwater table, EC, pH, concentration of major ions and N and P for C-D transect.

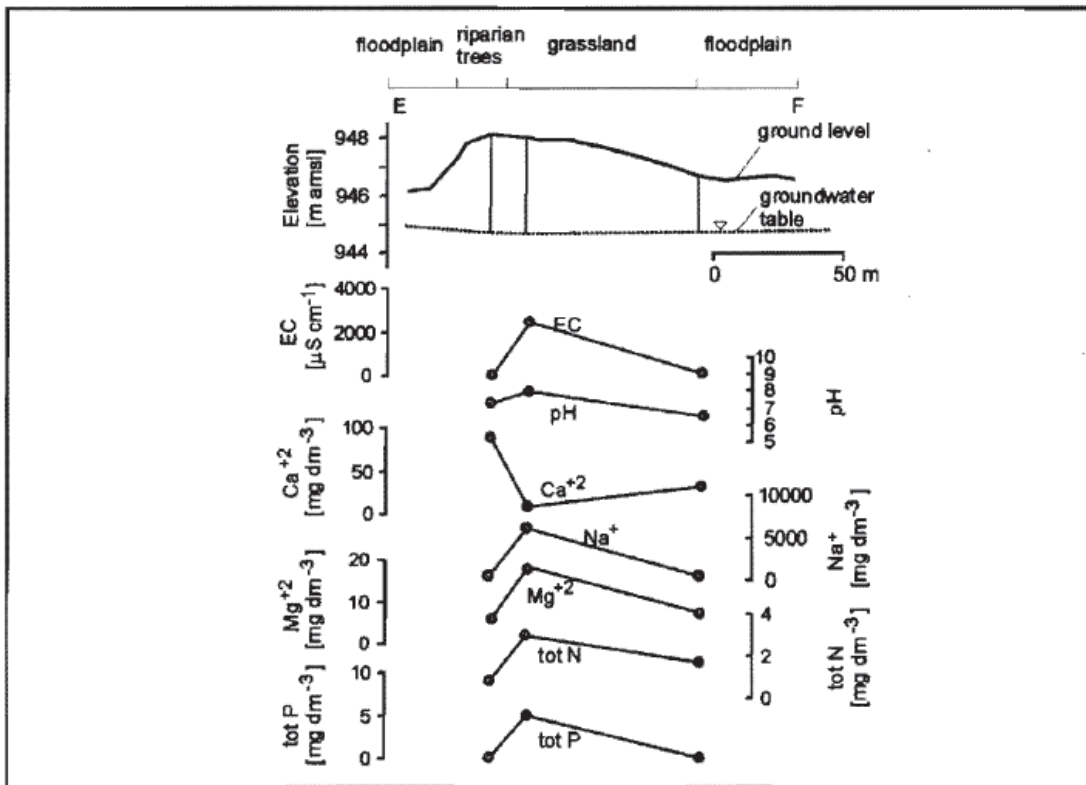


Figure 7. Groundwater table, EC, pH, concentration of major ions and N and P for E-F transect.

The concentrations of total N and total P in the transects follow the general pattern of increase towards island centre. Floodplain groundwater contains 0.005 to 0.13 mg·dm⁻³ of total P and 0.8 to 2.5 mg·dm⁻³ of total N. In the island centres total P increases to above 20 mg·dm⁻³ and total N up to 9.3 mg·dm⁻³. In general, concentrations of P are 20 to 400 times higher in the inner parts of the islands compared to the floodplain, and the concentrations of N are about 5 times higher in the inner parts compared to the outer parts of islands. Significantly, the ratio of N:P changes from 20:1 at the floodplain to 1:2-1:4 at island centre.

Interpretation and Discussion

The shape of the groundwater table under the studied islands indicates a radial flow pattern of groundwater from the surrounding floodplains towards the island centre. This agrees well with observations of island groundwater from various different parts of the Delta described earlier by Bauer (2004), Wolski and Savenije (2004), McCarthy *et al* (1998) and McCarthy (1992).

The variation of EC, pH and major ions is consistent with the model of chemical development of island groundwater described by McCarthy and Ellery (1994). In that model, evaporative concentration and precipitation of ions from solution taking place along the groundwater flow path from the floodplain toward the island's centre determine the chemical composition of the groundwater. Na⁺ is highly soluble and as a result displays the highest concentration in island's centre. Ca²⁺ and Mg²⁺ initially increase along the groundwater flow path as a result of evaporative concentration. After reaching saturation level, these ions precipitate to form carbonate soil matrix, and may form pedogenic nodules. Further down the groundwater flow path their solute concentrations are controlled by pH and ionic strength of the solute, and thus often drop to low levels.

For N and P, there appears to be a net accumulation of both nutrients *in solution* in the groundwater beneath the islands. This is apparently consistent with McCarthy & Ellery's (1994) evaporative enrichment model. In addition, a strong differential removal of N from floodplain groundwater is indicated by the change in relative concentrations of N and P between floodplain and island groundwater: N levels do show some concentration, but not to the extent shown by P.

A net loss of nitrogen is to be expected in the floodplain sediments, and in the passage through the hyporheic zone, through ammonification and denitrification. This effect has been observed elsewhere in shallow groundwater in riparian wetlands (Burns and Nguyen, 2002). Additionally, grasses along the floodplain margins and trees in the riparian zone tap plant-available N from groundwater. However, in the island centre the extremely high (toxic) levels of Na⁺ and high osmolarity of the groundwater effectively prevent access to this water by plants. Thus, once N has arrived in the island centre, it is isolated from any plant activity which might utilise it as a nutrient or a source of energy, and thus it accumulates in groundwater storage. Microbial activity in the phreatic zone of the island centre soils, however, probably results in some gasification of this N, with consequent loss to the atmosphere.

The high levels of dissolved P are more intriguing. Firstly, the biologically available PO₄³⁻ should be taken up by bacteria in the hyporheic zone and by plants along the groundwater flow path, and this uptake should be more intensive than that of N. Additionally, the solubility of PO₄³⁻ is strongly pH dependent, and its propensity to complex with Ca and Mg carbonates, Fe and Al hydroxides, and clays is strong. In the islands studied high levels of accumulation in calcareous cement and soil nodules of the riparian fringe should occur as hydroxyapatite (highly stable calcium phosphate). This is partly confirmed by the mineral content of island soils: island

riparian fringe soils contain 0.029% of total P, while floodplain soils only 0.005% and island centre soils 0.008% (McCarthy and Ellery, 1995). Moreover, PO_4^{3-} complexes with metal hydroxides. In palustrine forested wetland soils in Virginia, PO_4^{3-} sorption was strongly correlated with Al and Fe (Axt and Walbridge, 1999). Since floodplain and island soils contain 0-0.5 % of Fe and 0-2% of Al in various forms (McCarthy and Ellery, 1995), this process can also be expected to immobilize PO_4^{3-} from groundwater. In combination these processes would mitigate against large quantities of PO_4^{3-} moving past the floodplains and riparian belt zone towards the island centre, and remaining in solution there. Apart from PO_4^{3-} , there are, however, two more forms of water-borne P: soluble organic P (SOP) and particulate organic P (POP). POP represents P sorbed on large organic particles; these would be held (filtered out) in the hyporheic zone soils during infiltration. SOP usually takes the form of low-molecular weight phosphate esters, or "soluble unreactive P" (Wetzel, 2001). SOP is not prone to complexing, having no charge, and although soluble is not a plant-available form, and thus cannot be utilized by the vegetation of the riparian zone. It is therefore highly probable that P detected in island groundwater is mostly in the form of soluble organic phosphate (SOP). Unfortunately, we were not able to analyse the form of P compounds within this study, and thus confirm or reject that hypothesis. However, Wetzel (2001) points out that in most lakes, most of the P is in an organic form (87-94%), and SOP constitutes a large proportion of all P (30-60%). Although the relative contributions of PO_4^{3-} , SOP and particulate organic P (POP) in the Okavango water have never been investigated, SOP probably constitutes a large portion of P compounds in the Okavango river water, and thus its accumulation in island centres in this form is likely.

As atmospheric aerosols contain P and N (Garstang *et al*, 1998) they constitute a potential additional source of N and P for islands centre groundwater. In this case N and P would be delivered in the form of dry (dust) or wet (rainfall) deposition directly onto the island surface, and brought to the stagnant island centre groundwater with infiltrating rainwater. Although rainfall recharge in islands is insignificant in terms of quantities of water (Wolski and Savenije, 2004), the supply of dissolved chemicals may be significant in the long-term. No data presently exist, however, to quantify this process. Other additional sources of N and P contributing to the island groundwater pool include inputs from decaying island vegetation and animal excreta; for these there are also no quantitative data as present. Irrespective of source, microbial processes in island interior soils will act to increase the observed differential enrichment, because N is volatilised and can escape to the atmosphere, while P cannot be lost.

Summary

In summary, there appears to be a significant storage of N and P in the groundwater under the islands of the Delta. Given soil conditions and ionic composition of groundwater, P is probably in the form of SOP. The origins of N and P occurring in island groundwater (atmospheric aerosols or water borne), unfortunately, cannot be precisely determined at this stage, but we suggest that it is mostly the result of transport with groundwater and differential loss processes during this transport. Given the chemical composition of the groundwater, it is considered highly unlikely that these nutrients are available to macrophyte plants; they are effectively removed from the ecosystem by virtue of the extremely high EC and Na^+ content of their medium. The potential role of this sequestration process in the nutrient balance of the system warrants further investigation.

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