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Interstitial Nutrient Fluxes in Niger Delta Soft-Bottom Tidal Flats: Implications for Interfacial Regeneration and Local Productivity

[1]N. Zabbey, [2]A.I. Hart and [3]E.N. Ezekiel

[1]Department of Animal Science and Fisheries, Faculty of Agriculture,
University of Port Harcourt, P.M.B. 5323, East-West Road, Choba, Rivers State, Nigeria
[2]Department of Animal and Environmental Biology, Faculty of Science,
University of Port Harcourt, Choba, Rivers State, Nigeria
[3]School of Applied Science, Rivers State Polytechnic, Bori, Rivers State, Nigeria

Abstract: This study examined spatio-temporal changes and seasonality of nutrients (nitrate-nitrogen, phosphate-phosphorus and sulphate) in soft-bottom tidal flats of Bodo Creek. Interstitial water samples were assessed every month on five intertidal flats during low tide for 2 years (May 2006 – April 2008). Nitrate-nitrogen and phosphate-phosphorus concentrations range between 0.088-3.53 mg/L and 0.004–1.38 mg/L respectively, while sulphate fluctuated between 55.04 mg/L and 1169 mg/L. NO_3-N mean values between stations 1 and 4 varied significantly, while stations 2, 3 and 5 had equivalent values (ANOVA = 0.88 < P $(2.46)_{0.05}$). PO_4-P did not vary significantly between the sampled locations in both first (ANOVA = 0.90 < P $(2.56)_{0.05}$) and second year (ANOVA = 0.28 < P $(2.56)_{0.05}$). The inter-annual difference in PO_4-P mean concentrations was not also significant (ANOVA = 0.54 < P $(2.11)_{0.05}$), But significant variation occurred in mean sulphate concentration between seasons (ANOVA = 4. 63 > P $(2.11)_{0.05}$). The rich benthic nutrient content as precursor for prodigious phytobenthos, column water phytoplankton and ancillary organic production is discussed on the basis of bottom-up inter-transference.

Key words: Inter-Transference · Phytobenthos · Regeneration · Variability · Water Column

INTRODUCTION

Nitrogen and phosphorus are major nutrients required for growth and organic production of terrestrial and aquatic plants as well as phytoplankton [1-3]. On the other hand, sulphate is a minor component of proteins and the principal available form of sulphur in water bodies that is reduced by autotrophic plants and incorporated into proteins [4, 5]. In terms of composition, nitrate and phosphate largely dominate the net nitrogen and phosphorus of surface waters. Nitrate, for instance, comprises 84% of dissolved inorganic nitrogen in surface waters [6]. Thus concentrations of nitrate, phosphate and sulphate largely reflect total inorganic nitrogen, phosphorus and sulphur, respectively, present in a given hydro-system. These nutrients can precipitate from overlying water column into sediments [2]. In turn, the nutrient demand in the water column is significantly augmented by benthic regeneration and transport across the sediment-water interface [7]. In spite of the ‘bentho-pelagic’ coupling, many water quality investigations focusing on nutrient variability in the Niger Delta have been limited to the overlying water column [8].

Factors that govern spatial and temporal variability of these essential nutrients in aquatic ecosystems include geological content, exogenous inputs (sewage, fertilizer, industrial effluents, drainage from feedlots, etc), weathering of rocks, sediment particle sizes, flow velocity and microbial mineralisation [2, 9, 10]. Studies on rivers in the Niger Delta region have shown that naturally the systems are nutrient poor due to high activity rate of pelagic organisms and the bedrock of the drainage basin is not rich in phosphate and nitrate [11, 12].

Corresponding Author: Zabbey, Department of Animal Science and Fisheries, Faculty of Agriculture, University of Port Harcourt, PMB 5323, East-West Road, Choba, Rivers State, Nigeria.

Recent studies on Bodo Creek provided some baseline information on the configuration, hydrology, physico-chemistry, macrozoobenthos (surface, tree and infauna) structural assemblages and biomass and production of a Niger Delta endemic lucinid bivalve [13-17]; none of these examined the dynamics of nutrients in interstitial water of the creek.

The objective of the present study was to evaluate variability in nitrate, phosphate and sulphate content in interstitial waters of Bodo Creek in the lower Niger Delta, in respect to space, time and season. The dynamics is also situated in the context of inter-compartment transference and local organic production.

MATERIALS AND METHODS

Study area: Occupying approximately 9230 ha [18], Bodo Creek is a network of brackish water creeks flanking Bodo community on the upper reaches of the Andoni-Bonny estuarine system in Rivers State, Nigeria. Four major channels conduct saline waters in and out of Bodo Creek: Dor Nwezor, Kpador, Koola Tobsoi and Koola Seato. These major waterways are interconnected by myriad of feeder channels, some of which terminate blindly in mangrove swamps [13]. This study was conducted at a protected mangrove swamp (Sivibilagbara) and four open, unvegetated low intertidal flats along the Dor Nwezor channel of Bodo Creek; approximately between latitude 4° 36' 29.7''N, 4° 35' 26.3''N and longitude 7° 15' 30.2''E to 7° 16' 50.9''E (Fig. 1). Detailed information on some physicochemical parameters of the creek had been documented [13, 16, 17]. Salinity of the creek interstitial water fluctuates between mesohaline (5 psu) and polyhaline (28 psu), while surface water values range between 6.2 - 22.7 psu. Surface and interstitial water temperature varied from 26.7 to 30.1°C and 25°C-34°C, respectively.

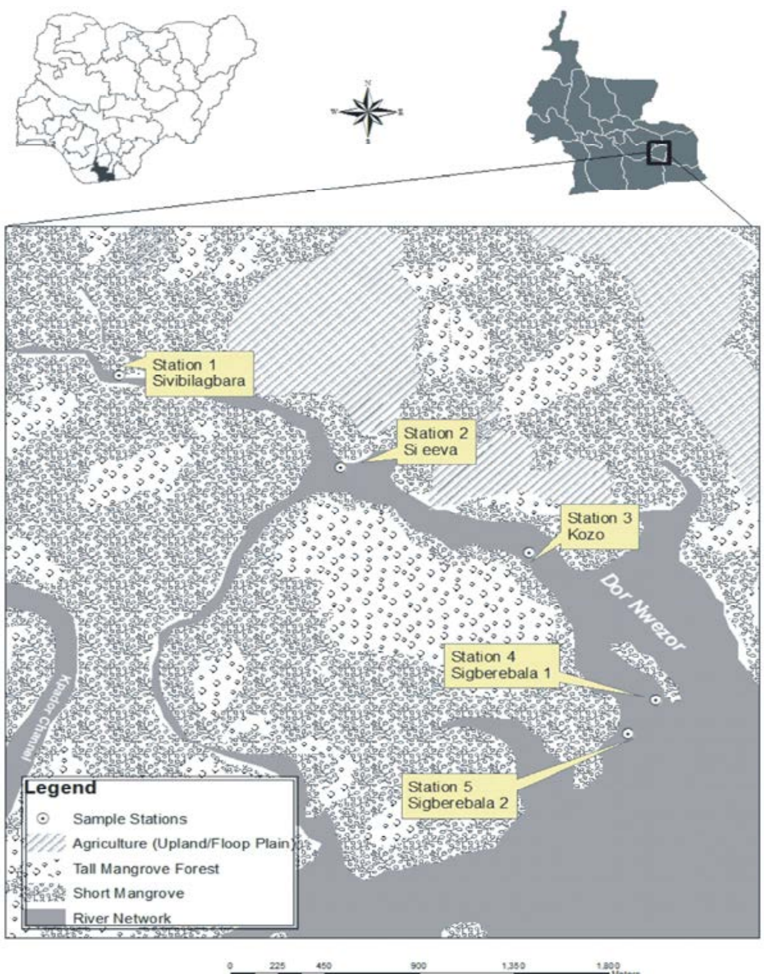

Fig. 1.0: Map of Bodo Creek Showing Sampled Stations at Dor Nwezor Channel (See stations coordinate in the text)

Station 1: This was the most upstream station and was located in the Sivibilagbara protected mangrove swamp (approximately latitude 4° 36' 29.7''N and longitude 7°15' 30.2''E – see Fig. 1). The vegetation of Sivibilagbara was homogenously red mangrove (*Rhizophora racemosa*), with knitted structural architecture of prop roots and thick intertwined crowns. The swamp dimension is approximately 4,410m^2. The sediment type was peaty clay (dominated by silt and clay)

Station 2: This was located approximately 1,280m downstream from station 1 (Fig. 1) on an open, unvegetated tidal flat locally called Si Eeva. Facing downstream, the station lay to the left of Dor Nwezor main channel (latitude 4° 36' 12.7'' N and longitude 7° 16' 08.1" E). The riparian vegetation of this station was mainly stunted red mangrove and dwarf, aged and unproductive coconut trees at the edges of the supralittoral shores. The substratum was sandy mud.

Station 3: This was located approximately 956m downstream from station 2, on a right-flanked tidal platform. The station was sited opposite a sprawling fishing settlement called Kozo (lat. 4°35' 55.3'' N and longitude 7° 16' 33.8" E). The marginal vegetation was dominated by red mangrove (*R. racemosa*), with few stands of the white mangrove (*A. germinas*) and mangrove sedge (*P. vaginatum*) at the high intertidal zone. The palm (*Phoenix reclinata*) and mango are amongst the mosaic admixture of plants at the supralittorial zone. The bottom was muddy sand.

Station 4: This was located 994m downstream from station 3, having expansive unvegetated intertidal flat (latitude 4° 35' 32.4" N and longitude 7° 16' 56.6" E). The sediment was sandy mud. Predominantly black mangrove and few stands of red mangrove and nypa palm characterise the marginal vegetation.

Station 5: Located on an expansive tidal mudflat (sandy mud) parallel to station 4. The marginal vegetation is dominantly black mangrove. The distance between stations 5 and 4 is approximately 256m and they are separated by the main creek channel. Station 5 was geo-located at latitude 4° 35' 26.3" N and longitude 7° 16' 50.9" E).

Sampling and Laboratory Procedures: Samples for the determination of nitrate-nitrogen, phosphate-phosphorus and sulphate were collected at each location during low tide from infauna sampled pits at each station every month for 2 years (May 2006 – April 2008). A 20cm x 20cm quadrant was thrown on the tidal flat and the sediment of the area of the quadrant dug with spade to a depth of 20cm. Three random replicates were collected per station per trip. Interstitial water samples for the determination of some priority physicochemical variables were collected from the infauna dugout pits (*see description above*). Data on Temperature, conductivity, salinity, pH, dissolved oxygen and biological oxygen demand are documented in Zabbey [16]. The samples were preserved in ice-chest and transported to the University of Port Harcourt Hydrobiology laboratory. The parameters were subsequently analyzed following standard procedures [19].

Nitrate-nitrogen (mg/l) was measured with brucine reagent, while phosphate-phosphorus (mg/l) was determined by the Ascorbic acid method. Sulphate was determined by the Turbidimetric Method.

Statistical Analysis: Variations in the parameters were analyzed as completely randomized design (CRD) using the procedures of Statistical Analysis Systems [20]. And where significant differences were recorded, mean separation was done at the 5% probability level using least significant difference (LSD) among stations, season and year differences and the New Duncan's Multiple Range Test (DNMRT) between month differences.

RESULTS

Nitrate-nitrogen and phosphate-phosphorus concentrations range between 0.088 -3.53 mg/L and 0.004–1.38 mg/L respectively, while sulphate fluctuated between 55.04 mg/L and 1169 mg/L. Spatially, nitrate-nitrogen (NO_3-N mg/l) mean values did not vary in the first (ANOVA = 0.14 < P $(2.56)_{0.05}$) and second year (ANOVA = 0.59<P $(2.56)_{0.05}$) (Table 1). While NO_3-N average was least (1.16 mg/l) at station 4 in the first year, the lowest mean value (1.10 mg/l) was measured at station 2 in the second year. Sustained maximum values were recorded at station 1 in both years. Cumulatively, NO_3-N mean values between stations 1 and 4 varied significantly, while stations 2, 3 and 5 had equivalent values (ANOVA = 0.88<P $(2.46)_{0.05}$). This peaked at station 1, followed by station 4. Monthly fluctuations in NO_3-N across the sampled stations are presented in Table 2 and Fig. 2. Apparently, mean NO_3-N values varied between months, having peak values in March (first year) and June (second year) at all locations except at station 4, where the

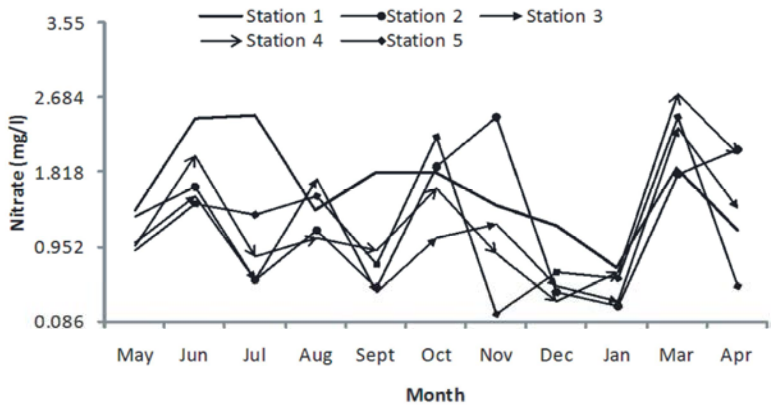

Fig. 2: Mean monthly variations of nitrate-nitrogen (mg/l) in interstitial water of Bodo Creek (May 2006 to April 2008)

Table 1: Variations in mean spatial nutrient contents of Bodo Creek interstitial water

	May 2006-April 2007			May 2007-April 2008		
Station	NO_3-N (mg/l)	PO_4-P (mg/l)	Sulphate (mg/l)	NO_3-N (mg/l)	PO_4-P (mg/l)	Sulphate (mg/l)
1	1.65	0.27	427.8	1.55	0.23	208.30
2	1.22	1.04	381.8	1.10	0.44	182.42
3	1.20	0.18	484.6	0.98	0.31	242.04
4	1.16	0.16	468.8	1.40	0.33	213.24
5	1.07	0.19	430.4	1.23	0.31	198.46

Table 2: Variations in monthly nutrient parameters in interstitial waters of Bodo Creek (May 2006-April 2008)

	May 2006-April 2007			May 2007 - April 2008		
Month	NO_3-N (mg/l)	PO_4-P (mg/l)	Sulphate (mg/l)	NO_3-N (mg/l)	PO_4-P (mg/l)	Sulphate (mg/l)
May	0.24^{d}	0.13^{b}	969.3^{a}	1.97^{ab}	0.08^{b}	277.20^{ab}
June	1.08^{bcd}	0.23^{b}	385.2^{bc}	2.57^{a}	0.05^{b}	211.42^{ab}
July	0.90^{bcd}	0.15^{b}	83.9^{e}	1.41^{bc}	1.25^{a}	144.25^{cde}
Aug	2.33^{a}	0.39^{b}	1102.2^{a}	0.42^{d}	0.08^{b}	162.03^{cd}
Sept	0.23^{d}	0.13^{b}	354.0^{bcd}	1.53^{bc}	1.04^{a}	161.60^{cd}
Oct	1.08^{bcd}	0.20^{b}	498.8^{b}	2.37^{a}	0.30^{b}	127.86^{de}
Nov	1.73^{abc}	0.35^{a}	146.4^{cde}	0.22^{d}	0.21^{b}	79.22^{e}
Dec	0.88^{bcd}	0.26^{b}	372.8^{bc}	0.36^{d}	0.03^{b}	220.17^{bc}
Jan	0.79^{cd}	0.03^{b}	467.0^{b}	0.22^{d}	0.11^{b}	299.37^{a}
Mar	2.65^{a}	0.08^{b}	121.9^{de}	1.84^{ab}	0.38^{b}	340.04^{a}
Apr	1.94^{ab}	0.14^{b}	324.0^{bcd}	0.85^{cd}	0.02^{b}	214.66^{bc}

$^{a-e}$ Means with the same superscript letters in the same column are not significant (P>0.05)

Table 3: Variations in seasonal nutrient parameters of Bodo Creek interstitial water

May 2006-April 2008				May 2006-April 2008			
Season	$N0_3$-N	PO_4-P	Sulphate	Year	$N0_3$-N	PO_4-P	Sulphate
Rainy	1.35	0.30	362.60^{a}	1	1.26	0.37	438.69^{a}
Dry	1.09	0.43	255.87^{b}	2	1.25	0.32	208.89^{b}

$^{a-b}$ Means with similar superscript letters in the same column are not significantly different (P>0.05)

peak concentration was attained in March in the second year. Cumulatively, NO_3-N fluctuated significantly (ANOVA = 9.56 > P $(2.13)_{0.05}$)) between months, having maximum values in March (Fig. 2). As shown in Table 3, variation in NO_3-N between dry and rainy seasons was insignificant (ANOVA = 1.93<P $(2.11)_{0.05}$). Inter-annual mean NO_3-N values were similar (ANOVA = 0.97<P $(2.11)_{0.05}$) (Table 3).

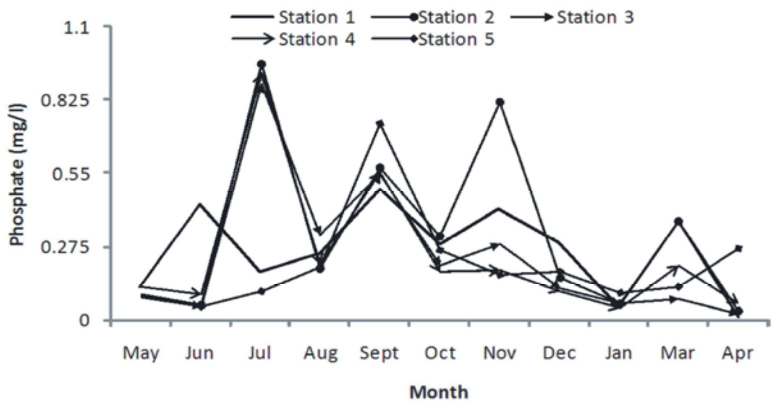

Fig. 3: Mean monthly variations of phosphate (mg/l) in interstitial water of Bodo Creek (May 2006 to April 2008)

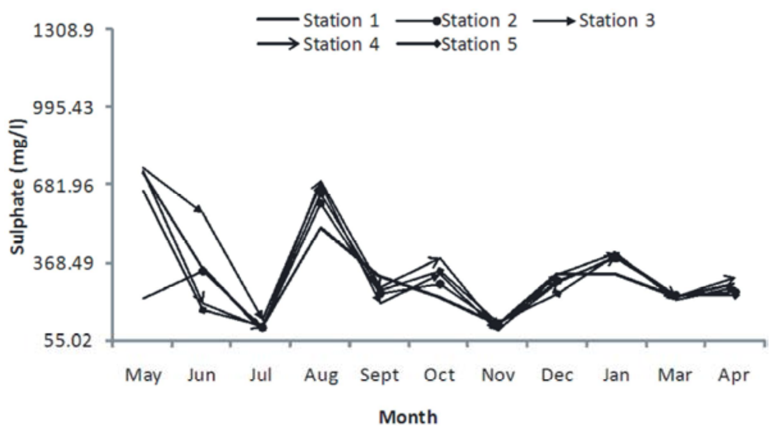

Fig. 4: Mean monthly variations of Sulphate (mg/l) in interstitial water of Bodo Creek (May 2006 to April 2008)

Phosphate-phosphorus (PO_4-P mg/l) did not vary significantly between the sampled locations in the first (ANOVA = 0.90 < P $(2.56)_{0.05}$) and second year (ANOVA = 0.28<P $(2.56)_{0.05}$) (Table 1). Numerically, in the first year, the highest (1.04mg/l) and lowest (0.16mg/l) mean phosphate concentration was recorded at stations 2 and 4 respectively. In the second year however, while station 2 had the highest mean phosphate concentration, station 1 had the lowest value (Table 1). As presented in Fig. 2, the highest cumulative mean value (0.742 mg/l) was recorded at station 2 and the least at station 3. Temporally, in the first year (May 2006 – April 2007) PO_4-P did not differ markedly (ANOVA = 1.34<P $(2.25)_{0.05}$) except in November when maximum mean concentration (2.35mg/l) was recorded (Table 3). In the second year, July and September had equivalent values which were comparatively higher (ANOVA = 14.20>P $(2.25)_{0.05}$) than other months (Table 2). The 2-year average monthly mean values varied only between July, September and November. PO_4-P concentrations were generally higher between July and November and lowest in April (Fig. 3). Seasonal PO_4-P concentrations varied only numerically (Table 3). The difference in PO_4-P yearly mean concentrations was not significant (ANOVA = 0.54 < P $(2.11)_{0.05}$) (Table 3).

Sulphate (SO_4 mg/l) values recorded in the first and second year did not vary significantly between stations (ANOVA = 0.14 < P $(2.56)_{0.05}$; 0.59 < P $(2.56)_{0.05}$) (Table 1). The parameter lowest values 381.8 mg/l and 182.42mg/l were recorded at station 2 in the first and second year respectively. In contrast, station 3 had maximum mean value in both years (Fig. 2). The highest biennial mean sulphate (363.34 mg/l) was recorded at station 3, followed by station 2, while stations 1, 4 and 5 had equivalent mean values (ANOVA = 0.29<P $(2.46)_{0.05}$). Monthly changes in mean sulphate are presented in Fig. 4. Sulphate concentration had a general inter-site trend whereby its average values peaked in August and was lowest in November. Significant variation occurred in mean sulphate concentration between seasons (ANOVA = 4. 63 > P $(2.11)_{0.05}$) (Table 3). There was significant difference (ANOVA = 23.20 > P $(2.11)_{0.05}$) between annual mean sulphate concentrations (Table 3).

DISCUSSION

Naturally, concentrations of NO_3-N and PO_4-P of surface water rarely exceed 0.1mgl^{-1} and 0.02mgl^{-1}, respectively [10]. Thus, the interstitial waters of Bodo Creek studied were comparatively rich in NO_3-N and PO_4-P, compared with surface water records of the delta river systems [13, 21]. Nitrate, in particular, was lower than 12.44 to14.56 mg/l measured in Maheshara Lake in Gorakhpur, India [22]. The rich nutrient status of the interstitial waters will, greatly, support high epipelic algal productivity (23, 24) and by extension, high turn-over rates of phytoplankton since about a quarter of nitrogen demand in the water column is usually provided by benthic regeneration and transport across the sediment-water interface [7]. Planktivores and epipelic-grazers which dominated macrozoobenthos of the studied flats [15, 17] presumably, had sufficient access to the rich epipelic or pelagic microflora food species, occasioned by the enriched nutrient elements.

The values for NO_3-N and PO_4-P were considerably higher than surface water concentrations measured in a recent study of the Kpador section of Bodo Creek [13]. They attributed the rich primary nutrients measured to fertilizer input contained in runoff from island farmlands in the creek basin. According to Cooney [25], rivers can be nutrient-poor at the source, but generally become nutrient-rich downstream after receiving industrial and domestic effluents and agricultural runoff. The Kpador and Dor Nwezor sections of Bodo Creek are intimately interconnected by network of creek channels and mangrove waterways. The linkages presuppose that, to an extent, the environmental quality at one section may be dynamically congruent to the other. In addition, flood waters from Bonny River draining Bodo Creek have nutrient-rich effluent inputs from industrial settlements that typify the Bonny Island coastline. Thus the rich interstitial NO_3-N and PO_4-P content implies sufficient supply of these primary nutrients to recoup losses due to phytoplankton uptake in the overlying water column. The inter-transference (interstitial-pelagic nutrient exchange) may rarely result to equilibrium conditions, particularly at daytime, during floodtide immersion, when micro-flora primary productivity in column water extends to the hitherto exposed intertidal flats studied.

The mean NO_3-N:PO_4-P (4:1) presumably corresponds to N:P ratio as the former traits broadly dominate latter forms. This indicates that nitrate releases into the water column were approximately 25% of phosphorus; meaning that NO_3-N was a limiting factor in the creek net primary nutrient supply. According to Redfield *et al*. [26] nitrogen and phosphorus occur in algal tissues in a remarkably consistent ratio of atomic weights of 16:1 and the same ratio occurs in oceanic waters [24]. However, in estuaries and near-shore waters, the N: P ratio is usually variable and much lower [7]. Ratios less than 16 N: 1P indicate nitrogen limitation per unit of phosphorus available to algae [6]; and the reverse is the case for phosphorus limitation. The ratio of nitrate to phosphate measured in this study, albeit low, was higher than 3N: 1P reported by Boynton *et al*. [27].

As noted by Tait [28], Chapman and Kimstach [10], sulphate is the prominent regeneration state of sulphur in water resulting from inorganic oxidation processes and can serve as an oxygen source for bacteria by anaerobic conversion to hydrogen sulphide [28]. The production of sulphide is not only toxic but also leads to acidity of water [5, 29]. As with the other nutrients, interstitial sulphate measured, to a large extent, influences the ion concentrations in the water column. Concentrations of sulphate determined were significantly higher than background contents of the surface creek waters [13]. Natural sulphate concentration in surface waters is usually between 2 and 80 mgl^{-1}, but may exceed 1000 mgl^{-1} near industrial discharge outfalls and areas where sulphate minerals such as gypsum are present [10]. Ballance [9] noted a tendency of abundance of sulphate in the earth's crust and that its concentration in water ranges from few milligrams to several thousand milligrams per litre; depending on local geochemistry and human activities. However, sulphate concentrations are generally low in African inland waters [30].

The concentrations of sulphate recorded in this study, though high, were not anomalous for such a dynamic brackish water system, which is supplied by Bonny estuarine waters. Imevbore and Ekundayo [31] recorded high concentrations of sulphate in the Bonny River. Microbial sequestration of sulphur in biogenic deposits and releases to the environment is vital to the element status and cycling [28]. Taylor & Glover [32] considered sulphide-oxidising symbiosis obligate in members of Lucinidae bivalves, having been confirmed in at least 30 species representing 18 genera from several distinct clades. Relatively poor density of the lucinid (*Lorepis aberrans*) reported at station 2 [33] could be attributed to the paucity of sulphate measured at the location. If this assumption is upheld, it becomes difficult to explain in the same context why station 3 had maximum mean sulphate concentration and, at the same time, low densities of *L. aberrans* relative to records for stations 4 and 5. Station 1 also had abundant *Keletistes rhizoecus*, another lucinid taxon endemic to the Niger Delta [14]. Species distribution and abundance are structured by complex environmental forcing that might be intimately coupled. Sometimes it might be difficult to isolate the integral factors and quantify their contributory influences on biological assemblages. It is most likely that elevated sulphate levels at station 3 were due to local geochemical richness and/or due to inputs associated with anthropic activities at ''*Kozo*'' fishing settlement on the opposite shores of the site. Annual anthropogenic inputs of sulphur can rival those of natural processes [5].

The influence of season on sulphate composition was obvious. Run-off derived sulphate caused an upsurge in the variable during the rainy months (Table 2 and 3), which peaked in August. Following the pattern of rainfall in the Niger Delta [34], September had the highest precipitation rate during the study and ordinarily would have had maximum sulphate concentration, corresponding to the highest volume of runoff. It is likely that rain mediated flooding had concomitant supply and subtle dilution effects on sulphate concentration. Consequently, as rain gathered momentum in May, sulphate had risen to a semi-peak concentration (Table 2; Fig. 4) and started dropping in synchrony with incremental wetting until July when the parameter had reduced to the least value. By August, however, the phenomenal two weeks temporary cessation in rainfall (August break) in the Niger Delta ensures that sulphate became more concentrated following skewed evaporation in relation to dilution by rains. This pattern had not attained stability when optimum wetting in September reversed the trend.

Recent studies have increasingly tied production and maintenance of benthic fauna, including deposit feeders and those feeding at depth within sediments, to surface productivity, even in deep waters [35-37]. The benthic nutrient recharge (inter-transference) presupposes prodigious phytobenthic and column water phytoplankton production, which, in turn, would provide zoobenthos nutrition, leading to the rich diversity and abundance of fish food species documented in the study area [15].

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