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Assessment of sedimentary Phosphorus mobility in Zone II of the Ébrié Lagoon system using an Optimized Sequential extraction method

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Abstract

The present study aims to assess the mobility of sedimentary phosphorus in Zone II of the Ébrié Lagoon system by employing an optimized sequential extraction method specifically adapted to these sediments. Five samples were collected monthly over a one-year (January to December 2024), yielding a total of 60 samples. The seasonal mobility of sedimentary phosphorus in this estuary was assessed using the method proposed by Abbas et al. The results highlight a predominance of phosphorus bound to iron, followed by phosphorus bound to aluminum, with mean seasonal concentrations ranging respectively from 366.7 ± 14.5 to 493.3 ± 5.3 mg/kg and from 271.5 ± 5.1 to 351.9 ± 6.8 mg/kg. In contrast, phosphorus associated with (oxy) hydroxides, authigenic phosphorus, and detrital phosphorus exhibited the lowest mean seasonal concentrations, all below 10 mg/kg. Overall, sedimentary phosphorus mobility proved to be substantial during the study period and is likely to exert a significant influence on the trophic status of the estuarine waters.

Keywords: Côte d'Ivoire, Eutrophication; Ébrié Lagoon, Sedimentary Phosphorus; Sequential phosphorus extraction.

Introduction

Phosphorus in surface waters is influenced by a combination of sources such as diffuse agricultural pollution, wastewater discharges, and fuels[1]. Once introduced into the water column, this nutrient interacts with sediments, where it may be trapped or act as an additional source promoting eutrophication[2]. This ecological issue manifests through the massive proliferation of aquatic vegetation of various types, leading to ecological imbalance within these environments. Consequently, phosphorus, together with carbon, is among the most extensively studied nutrients in aquatic ecosystems[3,4].

Sedimentary phosphorus occurs in several distinct forms (inorganic phosphorus, organic phosphorus, and bioavailable phosphorus)[5]. Mineral phosphorus primarily consists of orthophosphates bound to iron, aluminum, or calcium oxides and hydroxides. These fractions often represent the major portion of sedimentary phosphorus and may remain relatively stable under oxic conditions. However, under anoxic conditions, the reduction of ferric iron (Fe^{3+}) releases iron-bound phosphorus, thereby triggering phosphorus remineralization and internal loading into the water column. This process is recognized as a key driver of internal eutrophication[5,6]. Organic phosphorus originates from the decomposition of aquatic organisms, allochthonous or autochthonous organic matter, and anthropogenic inputs. Although certain forms are refractory, a significant proportion of organic phosphorus is labile and can be converted into orthophosphate through microbial mineralization or enzymatic hydrolysis, thereby increasing phosphorus availability for algae[7]. The so-called bioavailable phosphorus fraction encompasses all forms that are directly assimilable or potentially mobilizable in the short term by aquatic organisms. It includes labile inorganic phosphorus, a portion of hydrolyzable organic phosphorus, and certain fractions adsorbed onto Fe/Al oxides that are readily desorbable. This fraction plays a predominant role in algal bloom dynamics, as it represents the truly utilizable share of aquatic phosphorus[8]. Thus, the distribution and mobility of these different forms determine the potential for phosphorus release and, consequently, the intensity of the eutrophication process. A high proportion of bioavailable phosphorus or fractions sensitive to redox conditions indicates an elevated risk of internal loading, even in the absence of external inputs. Therefore, sedimentary phosphorus speciation is now considered a key indicator for assessing the trophic vulnerability of aquatic environments[9,10].

Zone II represents the largest estuary within the Ebrié Lagoon system. It is characterized by remarkable biodiversity, yet threatened by intense anthropogenic pressures exerted on its watershed. Severe metal pollution of these superficial sediments, with serious ecological implications, was documented prior to the reopening of the Grand-Bassam inlet[11]. Similar findings were reported following the reopening of this channel[12,13]. Overall, studies have highlighted a state of hypereutrophication in the waters of this estuary before the

reopening of the inlet[14]. However, investigations addressing the mobility of sedimentary phosphorus in this lagoon zone and its potential sanitary and ecotoxicological implications remain nonexistent. To address these gaps, an optimized sequential phosphorus extraction method specifically adapted to these sediments was developed, namely the method of Abbas et al.[15]. The present study builds upon the work of these authors. Its primary objective is to assess the mobility of sedimentary phosphorus in this estuary using the aforementioned method after the reopening of the Grand-Bassam inlet, with particular focus on its confluence zone characterized by strong sedimentary dynamics. Secondary objectives include the physicochemical characterization of surface sediments and the evaluation of their impacts on sedimentary phosphorus dynamics.

Materials and Methods

Presentation of the Study Area: Zone II of the Ebrié Lagoon system covers an area of 87 km², with mean dimensions of 17.143 km in length and 5.714 km in width. It encompasses primarily the Ebrié Lagoon (82.5 km²), which extends from the Grand-Bassam inlet to Abouabou Bay, and the Ouladine Lagoon (4.5 km²) located at Grand-Bassam. Dominated by the Ebrié Lagoon, this zone constitutes the most significant estuary of the Ebrié Lagoon system due to the mouth of the Comoé River[11-13]. The zone is distinguished by the Grand-Bassam inlet, the only natural connection between the Ebrié system and the Atlantic Ocean. After a long period of siltation, this passage was permanently reopened in 2022. The intervention pursued three major objectives: the evacuation of pollutants (particularly those transported by the Comoé River), local socio-economic development, and the mitigation of recurrent flooding in Grand-Bassam[12] (Figure-1).

The hydrology of this estuary is dominated by the Comoé River, the Mé River, and the Atlantic Ocean. Marine influence on Zone II of the EbriéLagoon system has considerably increased following the reopening of the Grand-Bassam inlet[12,13], which is expected to affect the dynamics of sedimentary phosphorus in this lagoon zone.

The hydrological seasons in this lagoonal zone since the reopening of the Grand-Bassam inlet are as follows: Hot Season (HS) (December to April), Rainy Season (RS) (May to June), Great Cool Season (GCS) (July to August), and Flood Season (FS) (September to November)[11,12].

Sample Collection and Processing: The sampling campaign of superficial sediments was conducted over a one-year period (January to December 2024), based on five collection stations. The selection of these sampling points enables a strategic temporal comparison through the assessment of the influence of different hydrological inputs on the dynamics of sedimentary phosphorus within the lagoonal confluence zone (Figure-2).

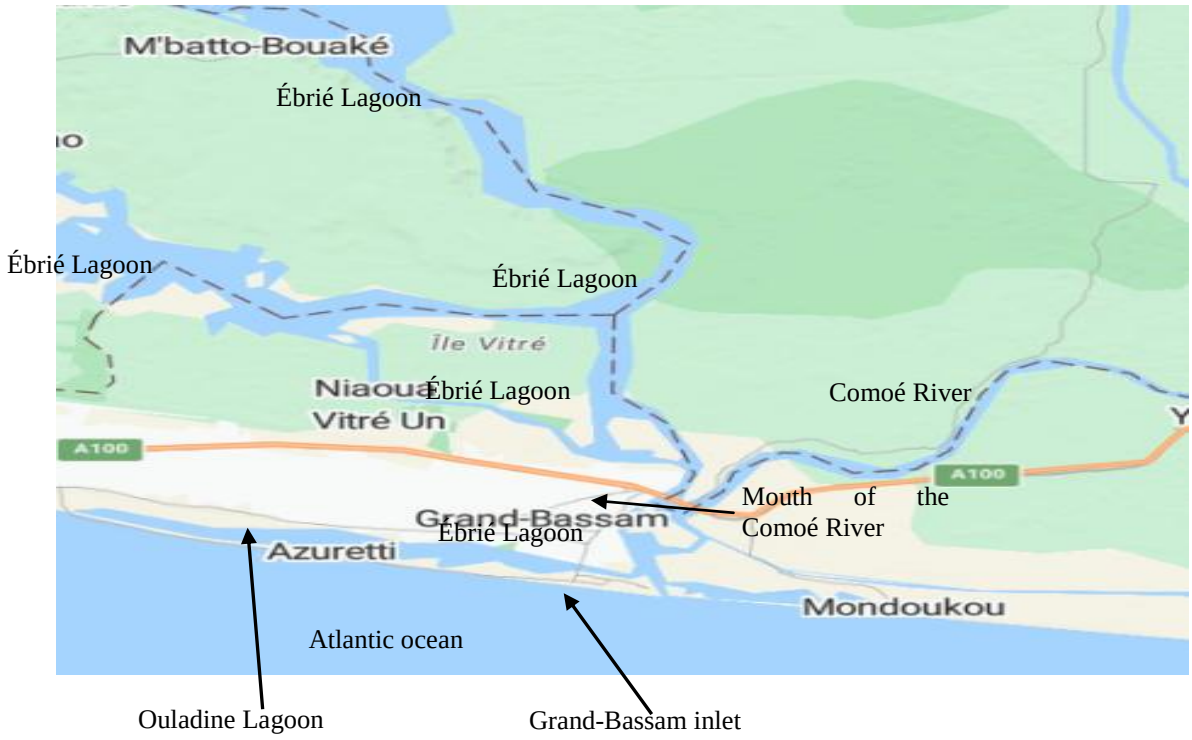

Figure-1: Location of the Ebrié Lagoon, the Ouladine Lagoon, the Grand-Bassam inlet, and the mouth of the Comoé River within the confluence zone of this estuary.

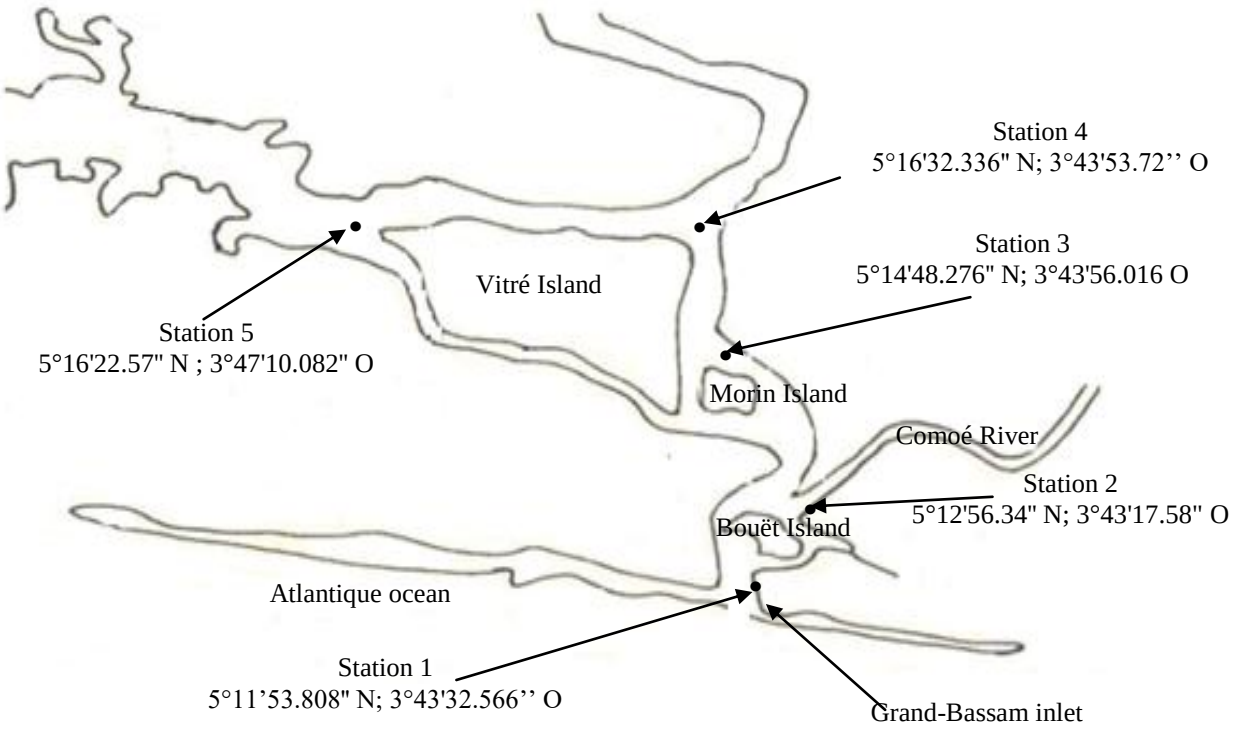

Figure-2: Geolocation of surface sediment sampling stations for the study period[11,13].

Superficial sediments (0 to –5 cm) were collected monthly using a Van Veen grab, yielding a total of 60 samples for the study. To ensure sample integrity, the sediments were immediately stored in polyethylene bags, in accordance with NF ISO 5667-15[16].

In the laboratory, sediments were first sorted to remove coarse debris. A 10 g fraction was isolated to determine relative moisture content, while the remaining material was processed following NF ISO 11464[17]. This treatment involved oven-drying at 25°C until constant weight, a low temperature chosen to preserve the chemical speciation of phosphorus. Finally, the dried samples were ground with an agate mortar, sieved through a 0.63 µm mesh to ensure homogeneity, and stored in airtight polyethylene containers.

Determination of Selected Physicochemical and Structural Characteristics of Sediments: During the study period, the physicochemical and structural properties of the sediments were characterized. pH, redox potential, conductivity, and salinity were measured in accordance with established standards. pH and redox potential were assessed following NF ISO 10390[18]. Conductivity and salinity were determined according to NF ISO 11265[19]. Relative moisture content was analyzed following NF ISO 1097-5[20], while organic matter content was evaluated based on NF ISO 11465[21]. Finally, particle size distribution was established according to the protocol of NF ISO 17892-4[22].

Assessment of Sedimentary Phosphorus Mobility: The mobility of sedimentary phosphorus in this estuary was evaluated during the study period using the method of Abbas et al.[15]. This method enables the quantification of nine distinct phosphorus fractions: Soluble Organic Phosphorus (SOP); labile Phosphorus (labile-P); phosphorus bound to iron (oxy) hydroxides (Fe-P); phosphorus associated with humic acids (HA-P); phosphorus bound to aluminum (oxy) hydroxides (Al-P); phosphorus bound to manganese (oxy) hydroxides, as well as residual aluminum and iron (oxy-P); Authigenic Apatite Phosphorus (AAP); Detrital Apatite Phosphorus (DAP) and; Residual Organic Phosphorus (ROP) (Figure-3).

From these nine fractions of sedimentary phosphorus, the concentrations of total mineral phosphorus (Pmin), Total Organic Phosphorus (TOP), mobilizable Organic Phosphorus (MOP), and the Total Mobilizable Fraction (TMF) were calculated according to the following relationships:

$$\mathrm{Pmin} = \mathrm{labile} - \mathrm{P} + \mathrm{Fe} - \mathrm{P} + \mathrm{Al} - \mathrm{Al} + \mathrm{oxy} - \mathrm{P} + \mathrm{DAP} \quad (1)$$

$$\mathrm{TOP} = \mathrm{SOP} + \mathrm{HA} - \mathrm{P} + \mathrm{AAP} + \mathrm{ROP} \quad (2)$$

$$\mathrm{MOP} = \mathrm{SOP} + \mathrm{HA} - \mathrm{P} + \mathrm{AAP} \quad (3)$$

$$\mathrm{TMF} = \mathrm{labile} - \mathrm{P} + \mathrm{Fe} - \mathrm{P} + \mathrm{Al} - \mathrm{P} + \mathrm{HA} - \mathrm{P} + \mathrm{oxy} - \mathrm{P} + \mathrm{AAP} + \mathrm{DAP} \quad (4)$$

Statistical Treatment of Results: In addition to descriptive statistics (mean (m), standard deviation (SD), coefficient of variation (VC), minimum (Min), and maximum (max)), both univariate and multivariate analyses were performed,

specifically one-way ANOVA. The one-way ANOVA was used to determine whether significant differences existed among seasonal means for a given parameter. In cases where significant differences were observed, Fisher's LSD, Tukey's HSD, and Dunnett's post hoc tests were applied to identify differentiating means and homogeneous subgroups. Results were considered statistically significant at $p < 0.05$.

Results and Discussion

Physicochemical and Structural Characterization of Sediments: One-way ANOVA revealed no significant differences among stations for physicochemical and structural parameters ($p > 0.05$); therefore, results are presented as overall seasonal means. This approach allows the discussion to be streamlined by focusing on temporal variations across the entire study site. The sediments consistently exhibited an acidic character (ranging from 5.4 ± 1.0 in FS to 5.7 ± 0.3 in HS, RS, and CS) and an oxidizing state (ranging from 58.5 ± 15.8 mV in RS to 112.5 ± 37.6mV in FS) throughout the study. While pH remained statistically stable across seasons ($p>0.05$), redox potential displayed significantly higher values during FS compared to other periods ($p>0.05$). Despite elevated conductivity (ranging from 3.7 ± 1.4mS/cm in RS to 4.9 ± 3.2 mS/cm in CS), salinity remained low (ranging from 2.2 ± 1.3 mg/L in RS to 3.6 ± 2.2mg/L in CS). Although substantial intra-seasonal variations were observed, seasonal means showed no statistically significant differences ($p > 0.05$).

The environment was characterized by consistently high relative moisture (>70% in all seasons) and stable organic richness (>83% in all seasons). Seasonal fluctuations were not statistically significant ($p > 0.05$). Sediment structure was stably dominated by medium and coarse sands (proportions >56% in all seasons), with fine fractions remaining minor. Although proportions of very coarse sands increased during FS, overall texture remained statistically homogeneous throughout the study period ($p > 0.05$).

Seasonal Evolution of the Different Forms of Sedimentary Phosphorus: One-way ANOVA revealed no significant differences among stations for the mean concentrations of each phosphorus fraction ($p > 0.05$); therefore, results are presented as overall seasonal means. This approach facilitates the discussion by focusing on temporal variations across the entire study site. Within the sediments analyzed, Fe-P predominates, followed by Al-P. ROP represents the third most abundant fraction. Conversely, oxy-P, AAP, and DAP remain minor fractions, with seasonal mean concentrations below 10 mg/kg (Figure-4). Intra-seasonal variations of each sedimentary phosphorus form were generally low (Table-1).

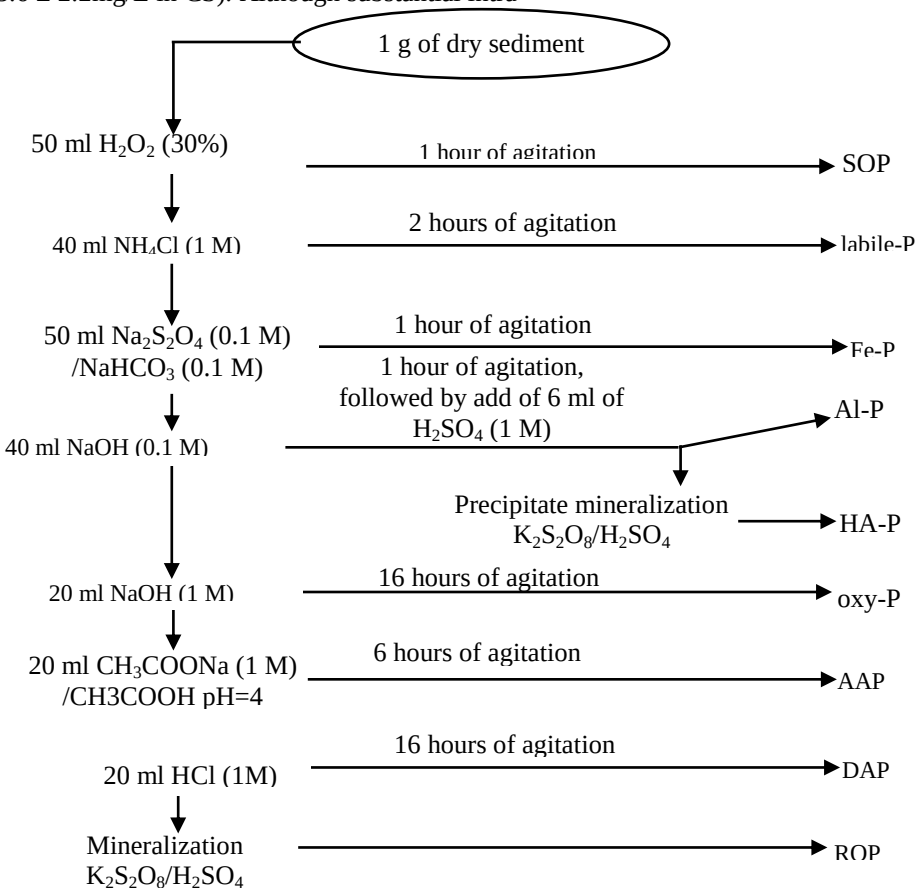

Figure-3: Optimized Sequential Extraction Protocol Specifically Adapted to These Sediments by Abbas et al. [15].

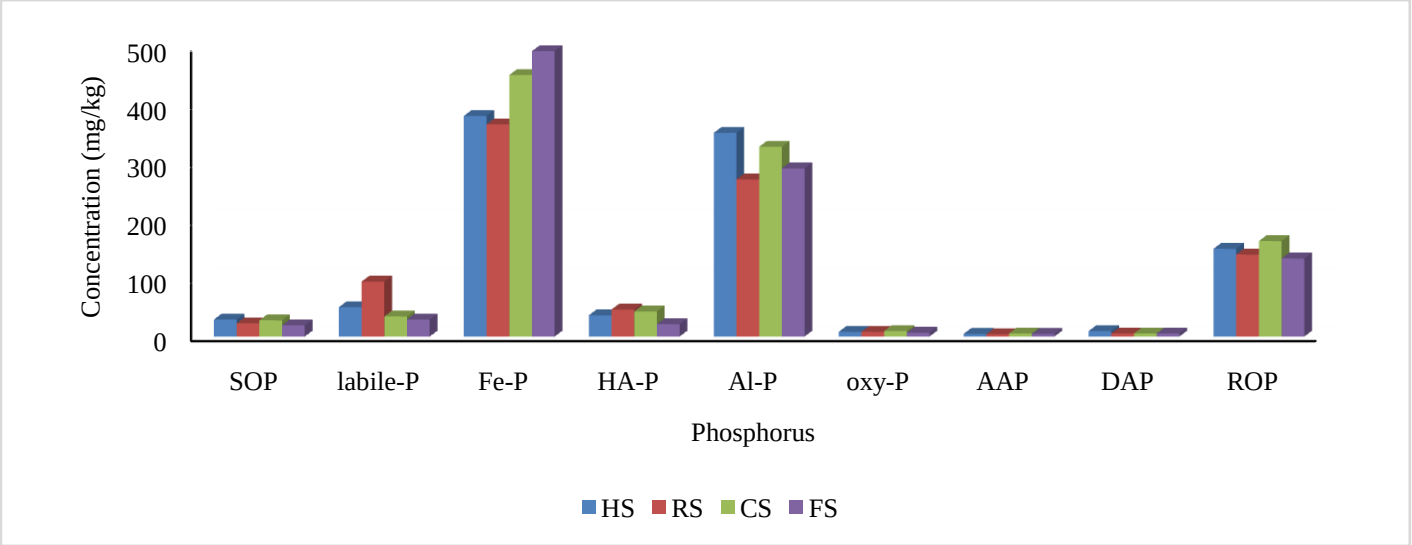

Figure-4: Seasonal evolution of the mean concentrations of the different forms of sedimentary phosphorus in the sediments of the estuarine confluence zone.

Table-1: Mean concentrations (±SD) of the different forms of sedimentary phosphorus in the estuarine confluence zone over the study period (n = 3).

Phosphorus forms	Statistical parameters	Seasons				Annual
		HS	RS	CS	FS	
SOP	m±SD	29.3±10.4	22.7±6.8	28.0±9.1	19.3±4.4	24.8±8.4
	VC (%)	35.4	30.1	32.2	22,5	33.9
	Min-Max	13.3-40.0	16.7-33.3	16.7-40.0	13.3-23.3	13.3-40.0
labile-P	m±SD	50.7±5.3	94.9±10.8	34.7±4.2	29.3±3.8	52.4±27.1
	VC (%)	10.5	11.3	12.2	12.9	51.8
	Min-Max	45.3-58.7	80.0-106.7	29.3-40.0	24.0-34.7	24.0-106.7
Fe-P	m±SD	381.3±7.7	366.7±14.5	451.9±9.1	493.3±5.3	423.3±53.8
	VC (%)	2.1	3.9	1.9	1.1	12.7
	Min-Max	373.3-393.3	349.9-383.3	439.9-463.3	486.7-499.9	349.9-499.9
Al-P	m±SD	351.9±6.8	271.5±5.1	327.9±5.9	290.7±5.7	310.5±32.7
	VC (%)	1.9	1.9	1.8	1.9	10.5
	Min-Max	343.9-359.9	263.9-277.3	319.9-335.9	285.3-298.7	263.9-359.9
HA-P	m±SD	36.7±5.3	46.7±7.1	43.3±15.6	21.3±7.7	37.0±13.4
	VC (%)	14.4	15.2	36.1	35.9	36.3
	Min-Max	30.0-43.3	36.7-53.3	26.7-66.7	13.3-33.3	13.3-16.7
oxy-P	m±SD	8.0±2.1	8.0±2.1	9.3±2.1	6.7±2.1	8.0±2.1
	VC (%)	26.4	26.4	22.6	31.6	27.0
	Min-Max	5.3-10.7	5.3-10.7	6.7-12.0	4.0-9.3	4.0-12.0
AAP	m±SD	4.5±1.5	4.0±0.9	5.3±0.9	4.5±0.7	4.6±1.1
	VC (%)	33.5	23.6	17.7	16.1	23.9
	Min-Max	2.7-6.7	2.7-5.3	4.0-5.3	4.0-5.3	2.7-6.7
DAP	m±SD	9.3±2.1	5.3±2.1	5.3±0.9	5.3±0.9	6.3±2.3
	VC (%)	22.6	39.5	17.7	17.7	36.7
	Min-Max	6.7-12.0	2.7-8.0	4.0-6.7	4.0-6.7	2.7-12.0
ROP	m±SD	151.6±3.5	141.7±2.6	164.9±4.3	134.9±5.3	148,3±12,2
	VC (%)	2.33	1.9	2.6	3.9	8,2
	Min-Max	146.7-154.9	138.3-144.9	159.9-169.9	128.3-141.7	128,3-169,9

The one-way ANOVA revealed overall significant differences among the mean concentrations of the different phosphorus forms within a given season. However, post hoc tests showed that no statistically significant differences were observed between the mean concentration of oxy-P and those of AAP and DAP across all seasons (p> 0.05). Similarly, no significant differences were found between AAP and DAP in these seasons (p> 0.05). In addition, no statistically significant difference was detected between SOP and labile-P during the CS season (p> 0.05). Finally, during the FS season, no significant differences were observed between HA-P and the concentrations of labile-P and SOP, respectively (p> 0.05).

The hierarchical ranking of seasonal mean concentrations of the various phosphorus fractions was established as follows. During HS and RS, the order was Fe-P > Al-P > ROP > labile-P > HA-P > SOP, with oxy-P, AAP, and DAP showing pair wise equivalences. In the CS season, the hierarchy was Fe-P > Al-P > ROP > AH-P > labile-P = SOP, while oxy-P, AAP, and DAP again exhibited statistical equivalence. For the FS season, the ranking was Fe-P > Al-P > ROP > labile-P = HA-P = SOP, with oxy-P, AAP, and DAP remaining indistinguishable in terms of mean concentration. Across the entire study period, the hierarchical order was consistently maintained as Fe-P > Al-P > ROP > labile-P > HA-P > POS, with oxy-P, AAP, and DAP showing pairwise equivalence.

Total mineral phosphorus (Pmin), Total Organic Phosphorus (TOP), Mobilizable Organic Phosphorus (MOP), and Total Mobilizable Fraction (TMF): The one-way ANOVA did not reveal any statistically significant differences among the stations with respect to the seasonal mean concentrations of Pmin, TOP, MOP, and TMF as determined by each of the four analytical protocols (p> 0.05). Consequently, the results are presented in the form of aggregated seasonal means. This approach facilitates a streamlined discussion by focusing on the temporal variations observed across the entire study site.

The seasonal mean concentrations of Pmin and TMF in these sediments were, a priori, expected to be highest in FS and lowest in RS over the study period. The one-way ANOVA revealed overall statistically significant differences among the seasonal means (p< 0.05). Nevertheless, post hoc pairwise comparisons indicated that no significant differences were detected between the mean concentrations of Pmin and TMF in FS and those in HS and CS (p > 0.05).Accordingly, the hierarchical ranking of seasonal concentrations was established as follows: HS = CS = FS >RS. This outcome highlights that, although global differences were statistically significant, the pairwise equivalences observed among HS, CS, and FS suggest that the temporal variability of Pmin and TMF concentrations is primarily driven by the contrast with RS, rather than by differences among the other seasons.

With regard to the mean concentrations of TOP and MOP in the sediments, they were, a priori, expected to be higher in CS and lower in FS. The one-way ANOVA further revealed overall statistically significant differences among their seasonal mean concentrations (p< 0.05). However, post hoc analyses indicated that no statistically significant pairwise differences were detected between the mean concentrations of POT and POM in SC and those in RS and CS, respectively (p> 0.05).Accordingly, the hierarchical ranking of their seasonal mean concentrations in these sediments during the study period was established as follows: HS = RS = CS >FS. This outcome highlights that, although global differences were statistically significant, the pairwise equivalences observed among HS, RS, and CS suggest that the temporal variability of TOP and MOP concentrations is primarily driven by the contrast with FS, rather than by differences among the other seasons.

The seasonal mean concentration of Pmin was consistently higher than that of POM, and consequently higher than that of POT, across all seasons during the study period (Figure-5).

Intra-seasonal variations in all these phosphorus fractions were minimal (Table-2).

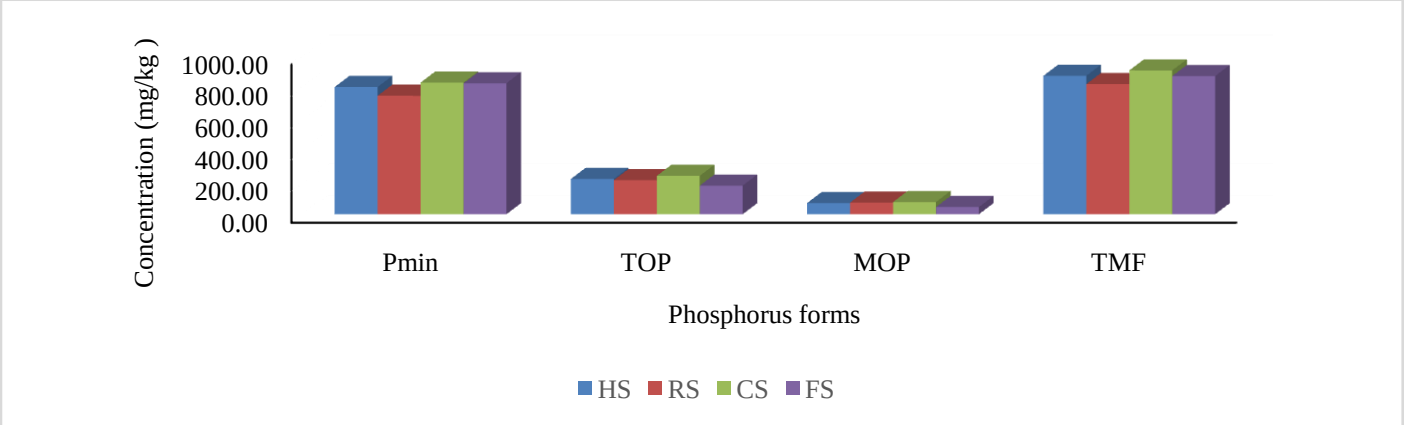

Figure-5: Seasonal dynamics of Pmin, POT, POM, and the mobilizable fraction in surface sediments of the study area over the investigation period.

Table-2: Mean concentrations (± SD) of Pmin, TOP, MOP, and TMF in superficial sediments in the estuarine confluence zone over the study period (n = 3).

Phosphorus forms	Statistical parameters	Seasons				Annual
		HS	RS	CS	FS	
Pmin	m±SD	801.3±14.3	746.4±20.6	829.3±12.4	825.3±9.7	800.6±36.5
	VC (%)	1.8	2.8	1.5	1.2	4.6
	Min-Max	784.6-819.9	720.6-771.9	720.6-771.9	814.6-837.9	720.6-842.6
TOP	m±SD	222.2±10.5	214.9±10.9	241.6±20.9	180.2±13.2	214.8±26.4
	VC (%)	4.7	5.1	8.7	7.4	12.3
	Min-Max	206.9-235.6	203.9-232.7	223.7-265.3	165.7-193.7	165.6-265.3
MOP	m±SD	70.5±11.1	73.3±10.4	76.7±19.2	45.2±12.3	66.4±17.9
	VC (%)	15.7	14.2	25.0	27.2	26.9
	Min-Max	52.0-80.7	64.0-89.3	55.3-98.7	30.7-62.0	30.7-98.7
TMF	m±SD	871.8±16.8	819.7±30.2	905.9±17.1	870.5±7.4	867.0±36.3
	VC (%)	1.9	3.7	1.9	0.8	4.2
	Min-Max	857.3-900.6	784.6-861.3	885.3-929.9	859.9-878.6	784.6-929.9

Discussion: In general, the seasonal dynamics of phosphorus in tropical lagoonal estuaries are closely correlated with the hydrological, biogeochemical, and hydrodynamic cycles of the waters. These aquatic ecosystems represent the interface of fluvial and marine processes that jointly regulate the distribution of chemical compounds, particularly phosphorus[23]. Consistent with previously reported findings, estuaries in such environments function as effective geochemical traps for phosphorus. The substantial inputs from catchment areas, enriched in (oxy) hydroxides, combined with rapid sedimentation and mineralization processes, sustain elevated stocks of mineral phosphorus and maintain its mobility within the sediment[24,25]. This outcome reinforces the conceptual framework of phosphorus retention in estuarine sediments, highlighting the dual role of these systems as both reservoirs and regulators of phosphorus fluxes. The present study corroborates this mechanism, thereby situating its results within the broader context of tropical estuarine biogeochemistry.

The marked presence of Fe-P and Al-P in the sediments confirms their enrichment in Fe and Al immediately following the reopening of the Grand-Bassam inlet[12]. Such enrichment is consistent with previously reported findings in tropical estuaries, where Fe- and Al-bound phosphorus fractions are recognized as dominant components of sedimentary phosphorus pools[26]. The strong affinity of phosphates for Fe (oxy) hydroxides, together with the formation of stable "Fe–organic matter–phosphate" complexes, explains the substantial accumulation of Fe-P in superficial sediments after flocculation, precipitation, and subsequent retention within the interstitial spaces of sand grains[27].

These processes are enhanced under conditions of increased salinity, ionic strength, and oxygen availability, which act as catalysts in the stabilization of Fe-bound phosphorus[27-29]. The substantial inputs of Fe and phosphates from the Comoé River are therefore efficiently trapped in the superficial sediments of this estuary, functioning as a geochemical sink for Fe-P before reaching the Atlantic Ocean[14]. From a biogeochemical perspective, this trapping mechanism highlights the critical role of tropical estuaries in regulating nutrient fluxes at the land–ocean interface. The elevated concentrations of Fe-P observed during HS and RS, when marine intrusion is more pronounced, reflect the capacity of estuarine sediments to immobilize phosphorus under oxic and saline conditions. Conversely, the decline in Fe-P concentrations from CS to FS, statistically significant between these two seasons, illustrates the destabilization of Fe–phosphate complexes under more acidic and slightly reducing conditions, which favor the dissolution of Fe (oxy) hydroxides[27,32].

Phosphates also exhibit strong affinities with Al (oxy) hydroxides[27]. The substantial continental inputs of Al and

phosphates lead to the pronounced presence of Al-P in these sediments following flocculation and precipitation, subsequently accumulating within the interstitial spaces of sand grains. This process is further enhanced by increases in salinity. Likewise, the stability of this fraction is maintained within the pH range of 5 to 7 in estuarine waters[27,30]. These processes explain the elevated concentration of Al-P observed during HS (the highest recorded over the study period), a season characterized by marine intrusion that increases estuarine salinity, while riverine inputs induce slight alkalinity. The subsequent decline in salinity, driven by continental freshwater inflows, correlates with reduced Al-P concentrations during seasons of intense meteoric inputs. However, variations in Al inputs from the Comoé River during these seasons resulted in statistically significant differences in Al-P concentrations: the highest values were recorded during CS, whereas the lowest were observed in RS.

The high seasonal concentrations of ROP in the sediments are indicative of a long-term accumulation of highly stable organic matter within the watershed of this estuary[31]. In general, riverine inputs transport substantial amounts of allochthonous terrestrial organic matter (plant debris, humic substances) derived from soils. This organic matter, often highly stable, is particularly rich in ROP[31,32]. In the case of this estuary, the continental input of this phosphorus fraction is largely modulated by the flooding regime of the Comoé River. The results suggest that the Central-Eastern and Southern portions of the river's watershed are richer in ROP than the Northern sector. This is reflected in the highest ROP concentration observed during CS, corresponding to the onset of the flood, when the river flushes the Central-Eastern and Southern regions of its watershed. Conversely, the lowest concentration of this phosphorus fraction was recorded during FS, when the river drains allochthonous organic matter originating from the Northern watershed, which is comparatively poorer in ROP than the meteoric inputs from the Southern watershed during RS. These meteoric contributions are particularly influenced by inputs from the Mé River, located in the southern part of the Comoé watershed, together with seasonal runoff. Furthermore, the intrusion of oceanic waters during SC promotes an increase in estuarine salinity. This rise in salinity induces rapid flocculation of organic particles, with large flocs settling quickly and enriching the sediments in ROP[33]. This process explains the elevated ROP concentration observed during SC, the second highest recorded throughout the study period. The contrasting effects of continental inputs during seasons of intense meteoric inflows and the salinity-driven processes during HS resulted in seasonally distinct ROP concentrations that were statistically differentiated from one another.

The markedly low concentrations of labile-P in sediments during the Comoé River flood, particularly in CS and FS, stand in sharp contrast to the relatively elevated concentrations observed in HS. This pattern may appear paradoxical, as river floods are theoretically expected to enrich sediments with this phosphorus fraction, whereas biological processes and chemical trapping mechanisms (namely the transfer of phosphates to Al and Fe oxy (hydroxides)) tend to reduce its sedimentary concentration[34]. During the flood period (CF and FS), when labile-P concentrations in sediments are not statistically distinct, this depletion can be primarily attributed to three processes. First, there is a rapid transfer of labile-P from sediments to the water column through accelerated desorption. Second, the sediments are diluted by coarse inputs naturally poor in this phosphorus fraction, resulting from intense leaching under high river discharge. Finally, substantial phytoplanktonic uptake within the water column further contributes to the observed depletion[34,35]. In addition, the strong hydrodynamic regime of estuarine waters induced by the river during these seasons facilitates the direct export of labile-P to the Atlantic Ocean[35]. This dynamic is, however, attenuated in RS due to contributions from the Mé River and southern tributaries of the Comoé watershed. Consequently, labile-P concentrations during RS are higher than those recorded in CS and FS. The intrusion of oceanic waters into the estuary during HS further promotes substantial internal phosphorus production, driven by enhanced mineralization of organic matter under conditions of elevated temperature and reduced turbidity[39]. The concomitant increase in salinity and slight alkalinity associated with these oceanic waters favors efficient chemical trapping of labile-P released through mineralization within sediments[40]. The combined action of these processes explains why sedimentary labile-P concentrations reach their maximum during HS and are statistically distinct from concentrations observed in other seasons.

The low concentrations of DAP observed in sediments during the study period are primarily explained by the acidic nature of the sediments (originating mainly from the Comoé River), which promotes the solubilization of calcium phosphate minerals ($Ca_5(PO_4)_3X$)[41]. During seasons of intense meteoric inputs, particularly during the Comoé River flood in CS and FS, fluvial contributions transport sediments diluted by siliciclastic material (clays, quartz, and Fe/Al (oxy) hydroxides) and depleted in calcium carbonates due to their acidic character[42]. The slightly acidic nature of the estuary during these seasons, resulting from the presence of such waters, further contributes to the instability of this phosphorus fraction. This is reflected in the lowest DAP concentrations recorded during RS, CS, and FS, which are statistically indistinguishable. In contrast, during HS, the intrusion of oceanic waters into the estuary induces a slight alkalinity, conferring stability to this phosphorus fraction[41]. As a result, DAP concentrations increase, reaching their highest levels of the study period and becoming statistically distinct from those observed in the other three seasons.

The low concentrations of oxy-P observed during the study period confirm the relative abundance of Fe and Al (oxy) hydroxides compared to those of Mn in the sediments of this estuary. This pattern is characteristic of tropical lagoonal estuaries[43]. Mn (oxy) hydroxides are unstable under anoxic

conditions[44]. Furthermore, the water chemistry, ranging from slightly acidic (RS to FS) to very slightly basic (HS), promotes Mn solubilization, as reflected in its relatively low sedimentary concentrations in this ecosystem, as reported by Drida and Yao[13]. This is particularly evident during CS, when the low concentrations of this phosphorus fraction are linked to reduced salinity, acidity, and low silt and clay content in the sediments. Accordingly, the consistently low concentrations of oxy-P observed across all seasons, with no statistically significant differences among them, can be explained. This finding also highlights a reduction of biases associated with the non-selectivity of extract ants toward Fe and Al (oxy) hydroxides, achieved through protocol optimization.

The low concentrations of the different organic phosphorus fractions (SOP, AAP, HA-P) measured in sediments using this protocol are largely explained by the accelerated mineralization of these phosphorus forms, followed by the transfer of the released phosphate into more stable phases that effectively immobilize it, particularly Al and Fe (oxy) hydroxides. These processes occur intensively both in fluvial input especially those from the Comoé River and within the estuary itself, owing to the tropical setting of the study area[36,37,41]. This is especially true for HA-P, due to the slight acidity of fluvial inputs and sediments during the Comoé River flood, particularly in FS. In addition, the prior use of H_2O_2 for SOP determination contributes to this process[42,43]. In the specific case of AAP the slight acidity of the environment during seasons of intense meteoric inputs, combined with the slight alkalinity during the warm season, hinders its formation[44]. This further explains the consistently low concentrations of AAP in sediments across all seasons. Consequently, the low concentrations of SOP and AAP observed throughout the year show no statistically significant seasonal differences. The same applies to HA-P, which remains low across all seasons; however, its concentration during FS is the lowest and statistically distinct from those measured in the other three seasons.

The high concentrations of Pmin, and consequently of TMF, contrasting with the low concentrations of TOP, particularly MOP, observed in this study, are characteristic of estuarine environments. This finding was confirmed by our results, where Fe-P and Al-P accounted for the bulk of Pmin, and thus of TMF, regardless of season. The seasonal balance of inputs of these two phosphorus forms produced similar effects across all seasons, with the exception of RS. Indeed, the simultaneous and substantial contributions of Al-P and Fe-P from the Mé River and the Comoé River (originating from the southern part of its watershed) resulted in the highest Pmin concentration during RS. This concentration was statistically distinct from those of the other three seasons, which showed no significant differences among themselves. Furthermore, massive inputs of particulate organic matter during the Comoé River flood in FS led to the highest TOP concentration recorded for this period. This value was also statistically distinct from those observed in the other three seasons, which were statistically equivalent. During FS, the oxidizing and acidic nature of the sediments favored the formation of organic phosphorus fractions. This process was reinforced by reduced salinity, which limited the interference of chloride ions with phosphate adsorption[41,27,28]. In addition, intense hydrodynamics induced leaching of fine particles (silt and clay), which are otherwise highly reactive, thereby enhancing the redistribution of phosphorus initially bound to sediments[34].

Conclusion

This study demonstrates that sedimentary phosphorus dynamics in the tropical lagoonal estuary are strongly governed by physicochemical sediment properties, notably acidic pH, oxidizing conditions, high organic matter content, and elevated moisture. The predominance of Fe-P and Al-P highlights the central role of geochemical control and preferential retention under oxidizing conditions, while the presence of POR points to a potential for remobilization under changing environmental regimes. These findings underscore the importance of integrating hydrodynamic processes, sediment characteristics, and phosphorus speciation to better understand mobility mechanisms in tropical estuaries. They further emphasize the need for long-term monitoring and holistic management approaches to anticipate eutrophication risks associated with hydrological variability and anthropogenic pressures.

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