



Impact of the Climate Change and the Recent Development of an Artificial Tropical Estuary on the Mobility and Distribution of Phosphorus: Case of Vridi Channel (Côte d'Ivoire)

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Authors' contributions

This work was carried out in collaboration among all authors. Author NS designed this study, performed the sampling and managed the analyses. He also wrote the first draft. Author YMK performed the statistical analysis, managed the analyses and contributed for the results discussion. Author TA contributed to the results discussion. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IRJPAC/2021/v22i230384

Editor(s):

(1) Dr. A. V. Raghu, Jain University, India.

Reviewers:

(1) Herojit Singh Athokpam, Central Agricultural University, India.

(2) Kelly Johanna Avila, Colombia.

Complete Peer review History: <http://www.sdiarticle4.com/review-history/65618>

Original Research Article

Received 20 December 2021

Accepted 22 February 2021

Published 26 March 2021

ABSTRACT

This study focused on the effects of the climate change and the recent modification of Vridi channel on the mobility and distribution of phosphorus (P) in its superficial sediments. To best estimate this fact, the annual mobility and distribution of P were followed and compared before and after this development during two different annual periods, marked differently by the climate change effects. The first annual period has covered the period from April 2014 to March 2015 and this channel presented its former hydromorphology, with hydroclimatic conditions very close to that normal of Abidjan district. The second period annual has covered the period from October 2018 to September 2019 and this channel presented its current hydromorphology and, characterized by a rainfall drop and high ambient air temperatures compared to that normal of Abidjan district. A monthly sampling has been done at 5 cm below the surface sediment in this channel during each annual period. The mobility and distribution of P was assessed in the superficial sediments of this channel according two sequential extraction protocols: the modified Van Eck method and the

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modified Olsen method. Total phosphorus was assessed according AFNOR NF X31-147. The total phosphorus contents and all P fractions contents of these superficial sediments assessed by these two sequential methods and obtained over the period from April 2014 to March 2015 are higher than those determined over the period from October 2018 to September 2019. Thus, the recent development of this estuary, with as a corollary the modification of the physical and chemical characteristics of its superficial sediments, would have had the effect of clearing P towards the Atlantic Ocean and/or accelerating its sedimentation; hence the reduction of eutrophication risk of this aquatic ecosystem.

Keywords: Côte d'Ivoire; climate change; eutrophication; marine estuary; modified van eck method; modified olsen method; water; pollution.

1. INTRODUCTION

Eutrophication is one of the worst threats for the existence of surface waters. It is a real ecological scourge. This phenomenon is visibly reflected by an anarchic proliferation of aquatic plants of all kinds in these aquatic ecosystems. It is mainly due to an excessive presence of nutrients, particularly those of nitrogen (N) and phosphorus (P). N and P are its limiting factors [1] and, P its controlling factor because of its sedimentary biogeochemical cycle [2]. So, P study in surface waters has always aroused scientific interest. The presence of P in these aquatic ecosystems remains characterized by deposition and burial in sediments. This fact explains frequent uses of these substrates to the study of the mobility and distribution of P in surface waters [3].

In sediments, P is bound to many metal cations and to many (oxy)hydroxides of metal cations. Several methods are used for the detection of some P fractions in sediments. Among them, there are the modified Van Eck method [4,5] which highlights more forms of P, and the modified Olsen method [6,7] which gives the P total bioavailable forms.

The modified Van Eck method [4,5] makes it possible to highlight the labile P fraction (PL), the exchangeable P fraction (PE), the reducible P fraction or the P bound to Fe fraction (PR), the P bound to (oxy)hydroxides of Fe, Mn, Al, etc. fraction (PO), the authigenic apatite P fraction (P-CO₃), the detrital apatite P fraction (P-Ca) and the P bound to residual organic matter fraction (POR). As for the modified Olsen method [6,7], it makes it possible to highlight the dissolved bioavailable P fraction (DBP) and the particulate bioavailable P fraction (PBP).

In general, the mobility and distribution of P in sediments depend on several endogenous and exogenous factors. Among these factors, there

are the hydrosystem of surface waters (hydromorphology, current, tide, etc.) [8] in one hand, and pH, redox potential, salinity, conductivity, nature and particle size distribution, and moisture, organic matter, carbonates, Al, Ca, Fe, Mg, Mn contents of sediments [3], on other.

The strong water hydrodynamics favors the remobilization and solubilization of all forms of P [9,10]. This fact is particularly important with a particle size distribution of sediments dominated by the fine fraction (silts and clays) [11,12] simultaneously with their high moisture content [10,13]. The nature of sediments particle size also plays an important role in the presence of P in its various forms. Indeed, sediments dominated by silts and clays have a high P fractions contents, due to their relatively high organic matter content [11,12]. Also, the high presence of heavy titanium-type minerals in sediments contributes to their relatively high P fractions contents. These minerals, mainly composed of magnetites (Fe^{II}Fe^{III}₂O₄) and hematite (Fe₂O₃), have a high capacity of P adsorption due to "organic matter-iron oxide-phosphate" complexes [14,15].

In the particular case of the P fractions determined according to the modified Van Eck method [4,5], the important roles of pH, redox potential, salinity, conductivity, nature and particle size distribution, and organic matter, moisture, carbonates, Al, Ca, Fe, Mg, Mn contents of sediments have been illustrated by recent scientific studies. In the case of pH, Ostrofsky et al. [16] mentioned that the formations of P-CO₃ and P-Ca are favored in basic environments at high temperatures in sediments rich in organic matter and nitrogen. However, Price et al. [17] noted a high remobilization of these P fractions at pH less than 5. According to N'Da et al. [3] and März et al. [18], this situation is mainly due to the reduction of the negative surfaces of sediments

simultaneously with the competition of Ca^{2+} with the other major cations (K^+ , Na^+ , Mg^+ , etc.) on the surface of these substrates. These P fractions become bioavailable under these conditions at high temperatures (Price et al., 2020). The formations of PO, PR and PL are favorable in acidic to slightly basic environments [19,20]. Regarding to the redox potential, Chen et al. [21] and Zhao et al. [22] noted that the high reducing conditions are more unfavorable to the formations of PL, PO and POR, but favorable to that of PE. As for salinity, its relatively important in these substrates inhibits the formation of PL, but is favorable to the formation of PO by conversion of P-Mn into this P form [14,15]. The high conductivity of sediments contributes to their relatively high PE content [3,18]. Also, a relatively high organic matter content of sediments contributes to their relatively high POR content, but decreases their PR content [11,23]. The relatively high Fe and Mn contents of sediments would also increase their PE, PR, PO and POR contents, but contribute to reducing their P- CO_3 content [21]. The relatively high Al content of sediments is also favor to the formation of PO [24,25]. As for the limestone character of sediments, it promotes the increase of their PE and P-Ca contents [26,27]. This is also the case for the relatively high carbonates content of sediments which contributes to the increase of their P- CO_3 and PR contents [28]. Regarding to Mg content of sediments, its relatively high importance leads to a decrease in their PO, P-Ca and P- CO_3 contents. A drop in their Mg content in limestone sediments further promotes P precipitation in the P-Ca fraction [19,29].

Vridi channel is the only way of communication between Atlantic Ocean and Ebrié system. It has a remarkable biodiversity straddling the marine, lagoon and fluvial environments. This biodiversity is highly threatened by strong anthropogenic pressures. For illustration, the studies carried out by Yao et al. [30] and Yao et Trokourey [31,32] in its former hydromorphology showed a relatively high pollution of its superficial sediments by trace metals. This is also the case with those of Konan et al. [33] who highlighted a relatively high pollution of these substrates by polycyclic aromatic hydrocarbons. As a result, this artificial estuary presented a state of high ecological risk due to these forms of chemical pollution. Also, N'Da et al. [3], by the study of the distribution and mobility of P in its superficial sediments in its former hydromorphology, showed that P was highly present in mineral form in these

substrates. P- CO_3 was the highest P fraction, and PO was the lowest P fraction of the seven P fractions determined by the modified Van Eck method [4,5]. This study highlighted that P exhibited there a relatively high PBP content, and that of relatively low DBP content. It also showed that the seasonal distribution and mobility of P in these substrates were highly impacted by water inputs through the high seasonal variations of their pH, reducing character, salinity, conductivity, moisture and organic matter contents.

In order to increase the operational capacity of the autonomous harbour of Abidjan, Vridi channel has undergone a development over two years, from 2016 to 2018. This has led to a modification of its hydromorphology. This fact has impacted its hydrochemical functioning. This was illustrated by the recent study of N'Da et al. [34], who have shown that the simultaneous impacts of this development with the climate change on the seasonal dynamics of pH, redox potential, conductivity, salinity, particle size distribution, moisture and organic matter contents of its superficial sediments. This would certainly have an effect on the biodiversity of this aquatic ecosystem, in particular on its flora and benthic fauna. Given the important socio-economic role of this ecosystem, it is important to monitor its health status for possible decisions and actions aimed at its protection for its sustainable development. It is in this context that this present study was carried out. Its main objective was to assess the effects of the recent development and the climate change of this estuary on the mobility and distribution of P in these superficial sediments. That was doing through the assessment of the impact of these facts on some physical and chemical parameters (pH, redox potential, salinity, conductivity, distribution and particle size composition, and moisture, organic matter, carbonate, Al, Ca, Fe, Mg, Mn contents) of these sediments and their influence on the mobility and distribution of P in these substrates.

2. MATERIAL AND METHODS

2.1 Generalities on the Study Area During the Study Period

Vridi Channel is located in the South of Côte d'Ivoire, precisely at $4^{\circ}0'50''$ West longitude at the North latitude of $5^{\circ}15'23''$ (DMS) (5.257636 N; 4.011545 W in decimal degrees). It results from the breakthrough of the Jacquerville dyke

during the creation of the autonomous harbour of Abidjan in 1953. It is therefore an artificial marine estuary as mentioned by Yao et al. [30] and Yao and Trokourey [31,32]. As part of the increase in traffic from this harbour, this estuary underwent hydromorphological development from 2016 to 2018. This development focused on its deepening along its entire length and the enlargement of its west jetty. The characteristics of its former hydromorphology (from 1951 to 2016) and its current hydromorphology (since 2018) are given in Fig. 1.

Vridi channel is in a subequatorial regime. Rains are the main character of this climate, characterized by four land seasons: a great rainy season (from May to June), a small rainy season (from October to November), a great dry season (from December to April) and a small dry season (August to September). The low latitudinal extension of the basin, as well as the relief of the surrounding continent, explain the geographical homogeneity of this climate: winds, sunshine and precipitation [34]. The annual normal of cumulative rainfall in Abidjan district is of 1922 mm, obtained over the period from 1961 to 2014 [35]. That of air ambient temperature is of 26.6 °C, obtained over the period from 1941 to 2000 [36]. In order to best estimate the effect of the climate and the recent development of this artificial marine estuary, this study was lead on two different annual periods. The first annual

period was covered the period from April 2014 to March 2015 and, the second the period from October 2018 to September 2019. The mean annual cumulative rainfall in this district was (1904.70 ± 169.11) mm over the period from April 2014 to March 2015, and (808.40 ± 60.70) mm over the period from October 2018 to September 2019. Regarding the ambient air temperature in this district, it was on mean of $(27.02 \pm 1.23)^\circ\text{C}$ over the period from April 2014 to March 2015 and, on mean of $(28.37 \pm 1.91)^\circ\text{C}$ for the period from October 2018 to September 2019 [37]. So, the rainfall regime in Abidjan district over the period from April 2014 to March 2015 was very close to normal. As for that over the period from October 2018 to September 2019, it was characterized by a rainfall deficit. Again, the two annual mean of the ambient air temperature are higher than the annual normal of the ambient air temperature in Abidjan district. Thus, the study period was very hot, particularly that from October 2018 to September 2019. This is due to climate change observed in recent decades around the world [38], particularly in Abidjan district. This climatic phenomenon was more evident in the second annual study period. This climatic phenomenon therefore has a great impact on the hydrochemical functioning of surface waters, particularly in the mobility and distribution of phosphorus in marine estuaries [39], such as Vridi canal.

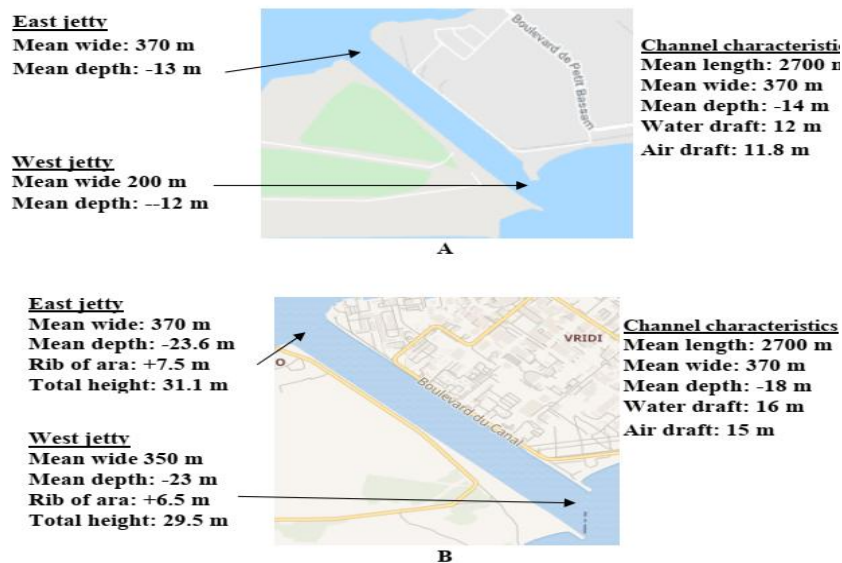


Fig. 1. The hydromorphological characteristics of Vridi channel in its former configuration (from 1951 to 2016) (A) and in its new configuration (since 2018) (B)

The water hydrodynamics of this estuary, very important in its former configuration [30-32], is amplified by its recent development [3]. Due to its position, Vridi channel has an important hydrographic network made up of Atlantic Ocean on the one hand, and Ébrié system and its hydrology, on the other. The hydrology of Ébrié system consists of Comoé river and numerous coastal rivers, the most important of which are Agnéby river and Mé river. Thus, the influence of these surface waters on Vridi channel depends on their water seasons. This leads to the definition of the water seasons of Vridi channel which result simultaneously from those of Atlantic Ocean in front of Abidjan district and those of Ébrié system. Yao et al. [30] and Yao and Trokourey [31,32] define the water seasons of this artificial estuary as follows:

- a Hot Season (HS) from February to April, the waters of this channel are essentially those of Atlantic Ocean due to the low meteorite inputs;

- a Rainy Season (RS) from May to July, where the influx of meteorites runoff and warm Guinean waters from Agnéby river and Mé river are important in this channel. However, the marine influence still remains important;

- a Great Cold Season (GCS) from August to September, characterized by the installation in this estuary of the cold marine waters from the great upwelling season of Atlantic Ocean in the Guinea gulf;

- a Flood Season (FS) from October to November, marked by the total installation in this channel of the warm Sudanese waters from Comoé river;

- a Small Cold Season (SCS) from November to December, where the hot Sudanese waters of Comoé river coexist in this channel simultaneous with the cold marine waters from the small upwelling season of Atlantic Ocean in the Guinea gulf.

The effects of the climate change, marked on the second annual period, was characterized firstly by very low inputs of Agnéby river and Mé river in this channel; secondly by a earlier and great inputs of Comoé river in this ecosystem and, started in August of this annual period; finally by a earlier and great inputs of cold water from the great upwelling season of Atlantic Ocean in this estuary and, started in June of this period. So, in the period from October 2018 to September

2019, RS was coincided with GCS and, GCS with FS.

Akobe et al. [40] note that Vridi channel is fed with sedimentary solid load by Atlantic Ocean marked by sands of coarse to very coarse fractions. It is also affected by Ébrié system, Comoé river, Mé river and Agnéby river with very variable grain size sands, but also by silts, clays and clay silts.

This estuary is currently the preferred transit point to Atlantic Ocean for almost all waste of all kinds from Abidjan district; but also pollutants carried by continental inputs, particularly Comoé river which, is responsible for two thirds of metal pollution in Ébrié system [30-32].

2.2 Experimental Techniques

2.2.1 Samples collection, their treatment and conservation

Sampling was carried out at the same sampling sites over the two annual study periods. For this purpose, three sampling sites, 900 m apart from each other, were chosen taking into account the spatial heterogeneity of this channel (Fig. 2). The characteristics of these sampling sites are given in Table 1.

In the first annual period of this study, this channel was presented its former hydromorphological characteristics of its creation in 1951. In the second annual period, this channel presented its current hydromorphological characteristics.

2.2.2 Assessment of some trace metals content and of P forms content

2.2.2.1 Carbonates, Al, Ca, Fe, Mg and Mn contents

The carbonates content of the superficial sediments samples was determined by using AFNOR NF EN ISO 10693 (X31-105) standard [41].

Regarding to their Al, Ca, Fe, Mg and Mn contents, they were determined in the sediment samples following two steps:

- the first step consisted to the digestion of these trace metals by acid attack according to AFNOR NF X 31-150 standard [42];

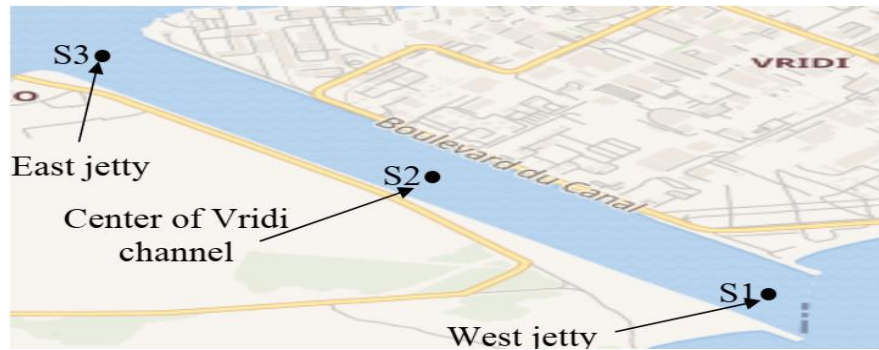


Fig. 2. Geographical localization of sampling sites in Vridi channel for this study

- the second step concerned their assays in the solution obtained in the first step. The Ca and Mg contents of the samples were obtained in accordance with AFNOR NF EN ISO 7980 (T 90-005) standard [43], that of their Al content according to AFNOR NF A08-556 (A08-556) standard [44] and, those of their Fe and Mn contents according to AFNOR FD T90-112 (T90-112) standard [45].

These different assays were carried out by the atomic absorption spectrophotometer method. The spectrophotometer Varian type model SpectrAA510 was used for this purpose.

2.2.2.2. P fractions contents

2.2.2.2.1 Analytical method used for the assay of the samples after their different pretreatments

All P fractions contents, obtained after their pretreatment according to the standard used in the different cases, were obtained by UV/visible spectrophotometry method according AFNOR T90 -023 standard [46]. The Jenway 7315 brand UV/Visible spectrophotometer was used for this purpose.

2.2.2.2.2 P total

P total (TP (AM)) was obtained in this study by the acid digestion method as recommended AFNOR NF X31-147 standard [47].

2.2.2.2.3 Sequential extraction protocols of P used in this study

Two protocols were used for the sequential extraction of P in this study: the modified Van

Eck method [4,5] and that of the modified Olsen method [6,7].

The sequential extraction protocol of the modified Van Eck method [4,5] is describes below by the Fig. 3.

The total mineral P (TMP), the total organic P (TOP) and Total phosphorus obtained according this method (TP(VE)) have been deduced as follow:

$$TP(VE) = PL + PE + PO + PR + P - CO_3 + P - Ca + POR \quad (1)$$

$$TMP = PL + PE + PO + PR + P - CO_3 \quad (2)$$

$$TOP = P - Ca + POR \quad (3)$$

As concerned to the modified Olsen method [6,7], its sequential extraction protocol extraction is given by the Fig. 4.

2.2.3 Statistical techniques, sources of hydroclimatic data and some physical and chemical parameters used in this study

Only the simple standard techniques, such as mean (m), standard deviation ($\pm s$) and variation coefficient (VC (%), were used in this study.

The annual rainfall data and the annual ambient air data for each annual study period were provided by SODEXAM [37]. Those relating to P form contents in the superficial sediments of Vridi channel over the period from April 2014 to March 2015 were taken from the studies of N'Da et al. [3]. The annual mean values ($m \pm s$ (VC (%)) of pH, redox potential, salinity, conductivity, organic matter and moisture contents of these surface sediments over these two annual periods come from the recent studies of N'Da et al. [34] (Table 2).

Table 1. Sampling sites characteristics used in this study

Sampling sites	GPS coordinates	Position in Vridi channel	Depth (m) from the surface water	
			Over the period from April 2014 to March 2015	Over the period from October 2018 to November 2019
S1	5.250120N 4.004542W	In West jetty	-12.00	-22.50
S2	5.256616N 4.012781W	In the center of the channel	-15.00	-26.00
S3	5.265163N 4.021021W	In East jetty	-20.00	-28.50

Table 2. Annual mean values (\pm s (VC (%)) of some physical and chemical parameters of the superficial sediments of Vridi channel over the study period (Source: N'Da et al. [34])

	Over the period from April 2014 to March 2015	Over the period from October 2018 to September 2019
pH	7.76 \pm 0.20(2.60%)	7.75 \pm 0.04(0.49%)
Conductivity (mS/cm)	4.02 \pm 1.22(30.29%)	2.59 \pm 0.33(12.76%)
Redox potential (mV)	-29.88 \pm 1.73(5.80%)	-31.34 \pm 2.17(6.92%)
Salinity (‰)	1.04 \pm 0.27(25.88%)	4.88 \pm 0.56(11.50%)
Matter organic content (% per weight of dry sediment)	15.38 \pm 5.32(34.61%)	21.91 \pm 0.44(1.99%)
Moisture content (% per weight of dry sediment)	0.77 \pm 0.78(102.00%)	10.54 \pm 3.87(36.74%)

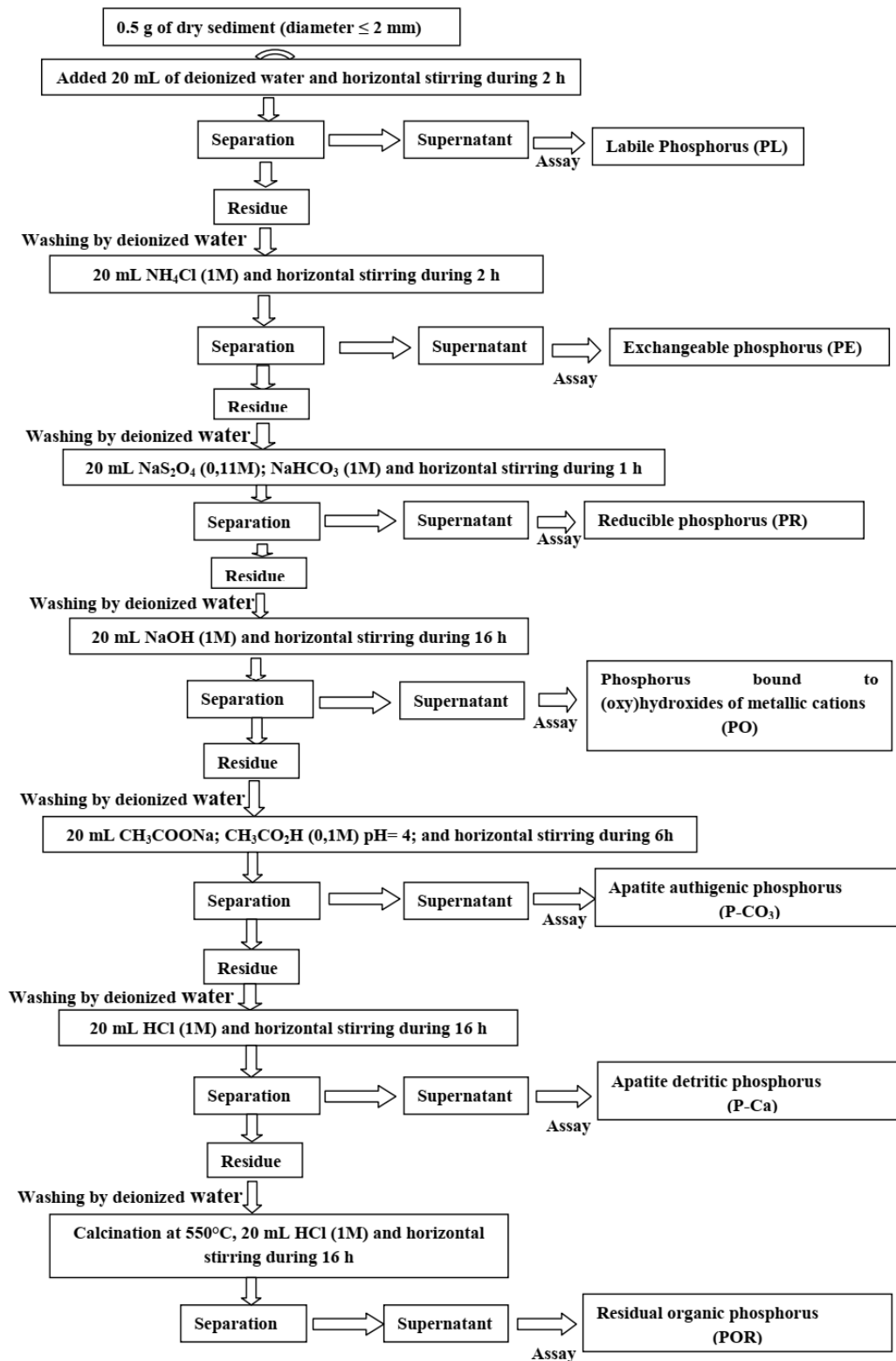


Fig. 3. Sequential extraction protocol of the modified Van Eck method [4,5]

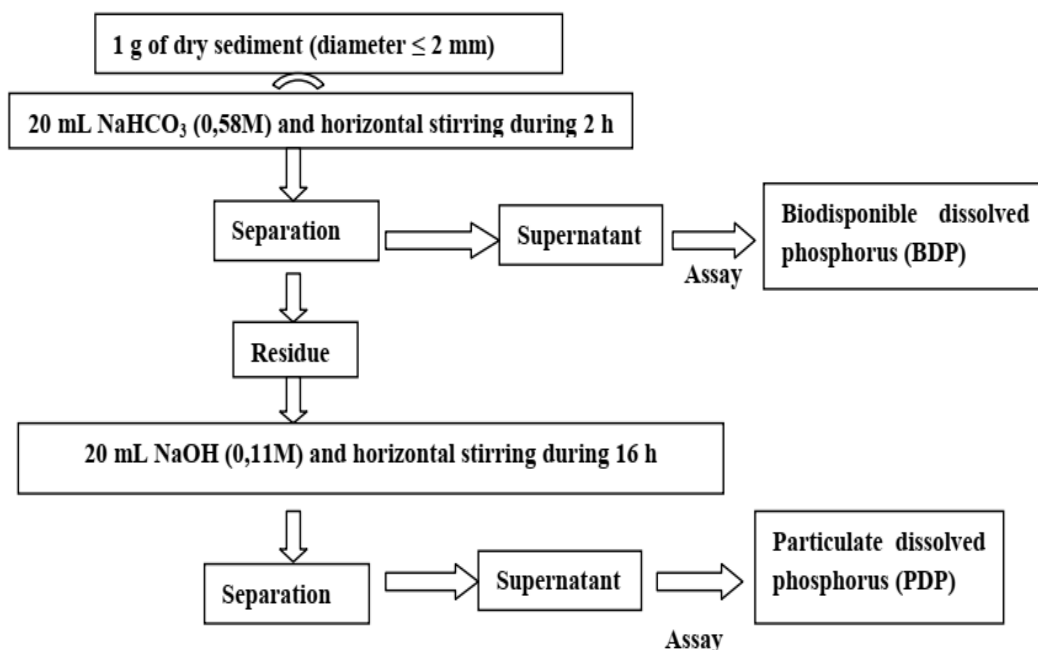


Fig. 4. Extraction sequential protocol of the modified Olsen method [6,7]

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Carbonates, Al, Ca, Fe, Mg and Mn contents

The table 3 give the annual mean values (\pm VC(%)) of carbonates, Al, Ca, Fe, Mg and Mn contents of the superficial sediments of Vridi channel over the study period.

These results show that these sediments were presented the relatively high Al and Ca contents over the period from October 2019 to September 2019. This is also the case for their carbonates, Fe, Mg and Mn contents over all the study period. Their annual mean value of their carbonates content obtained over the period from April 2014 to March 2015 has been very slightly higher than that determined over the period from October 2018 to September 2019. Their Fe, Mg and Mn contents obtained over the period from October 2018 to September 2019 have been very important relative to those determined over the period from April 2014 to March 2015. The

annual variation in their Al and Ca contents over the period from October 2018 to September 2019 and that of carbonates and Fe over all the study period have been low. This was not the case for the annual variation of their Mg and Mn contents, which have been fairly important over all study period.

3.1.2 P fractions contents

All the annual mean values of P fractions contents obtained over the period from April 2014 to March 2015 have been significant to those determined over the period from October 2019 to September 2019, except that of P-Ca. Over the period from April 2014 to March 2015, all the annual variations of PL, PO, P-CO₃ and DBP contents of these sediments have been significant, especially that of POR which has been extremely significant. Over this same period, the annual variations in their PE, PR, P-Ca, TMP, TOP, TP(AM), TP (VE) and PBP contents have been low. Over the period from October 2018 to September 2019, all the annual variations of these P fractions contents have been relatively less important (Table 4).

Table 3. Annual mean values (\pm (VC(%)) (per weight of dry sediments) of carbonates, Al, Ca, Fe, Mg and Mn contents of the superficial sediments of Vridi channel over the study period

	Over the period from April 2014 to March 2015	Over the period from October 2018 to September 2019
Carbonates	0.379 \pm 0.016 (4.133%)	0.341 \pm 0.012 (3.496%)
Al	-	2409.467 \pm 195.345 (7.547%)
Ca	-	876.421 \pm 116.975 (13.347%)
Fe	31760.46 \pm 5652.69 (17.80%)	13028.415 \pm 1432.538 (11.571%)
Mg	981.14 \pm 377.48 (38.47%)	240.970 \pm 64.536 (26.935%)
Mn	981.14 \pm 377.48 (38.47%)	246.938 \pm 70.271 (30.459%)

Table 4. Annual mean values (\pm s (VC(%)) (mg/kg per weight of dry sediments) of P fractions contents of the superficial sediments of Vridi channel over the study period

Analytical method used	P fraction	Over the period from April 2014 to March 2015 (Source: N'Da et al., [3])	Over the period from October 2018 to September 2019
Acid digestion method	TP(AM)	47.28 \pm 4.95 (10.48%)	32.12 \pm 7.38 (19.36%)
	PL	10.66 \pm 5.15 (48.29%)	4.57 \pm 1.69 (37.09%)
Modified Van Eck method [4,5]	PE	19.75 \pm 5.91 (29.93%)	5.13 \pm 0.73 (14.24%)
	PO	8.05 \pm 5.29 (65.79%)	5.21 \pm 0.87 (16.68%)
	PR	9.93 \pm 3.61 (36.31%)	4.48 \pm 1.49 (33.34%)
	P-CO ₃	26.89 \pm 12.24 (45.50%)	12.09 \pm 0.78 (6.43%)
	P-Ca	7.45 \pm 1.48 (19.88%)	7.60 \pm 1.73 (22.74%)
	POR	14.68 \pm 15.38 (104.76%)	4.30 \pm 0.28 (6.55%)
	TMP	75.23 \pm 8.06 (10.72%)	31.48 \pm 3.25 (10.34%)
	TOP	22.14 \pm 5.11 (23.09%)	11.90 \pm 2.33 (19.62%)
	TP(VE)	97.37 \pm 7.17 (7.37%)	43.38 \pm 2.83 (6.52%)
	Modified Olsen method [6, 7]	DBP	7.14 \pm 5.89 (82.53%)
PBP		45.43 \pm 9.49 (20.89%)	43.00 \pm 4.35 (10.11%)

3.2 Discussion

As in the case of the physical and chemical parameters assessed by N'Da et al. [34], the climate change and the recent development of Vridi channel led to a general decrease in the carbonates and ETM contents, as well as the different P fractions considered in this study. So, the present hydromorphological configuration of this artificial estuary, with the support of the climate change, is similar to a purifier of pollutants from Ebrié system towards Atlantic Ocean in front of Abidjan district.

The significant carbonates contents of the superficial sediments of Vridi channel over the study period would come more from lagoon, meteorite and marine sediment inputs [31,32] than from atmospheric deposits [48]. Also, it should be noted the important contribution of urban discharges [49,50] in general, and in particular that from the harbour industrial zone near this channel [30]. The important degradation and mineralization of organic matter in the surface sediments of this artificial estuary would also lead to a relatively high presence of carbonates within it. However, the strong water hydrodynamics of this estuary [30-32] would dissolve partially carbonates drained in this estuary by these inputs, in addition to that which would sediment by early diagenesis [51,52]. Also, a loss of these carbonates in these sediments would be linked to the phenomena of decalcification of these substrates, due to the acidification of this ecosystem [52]. This phenomenon mainly takes place in RS with meteorite inputs and in FS with the presence of Comoé river in this estuary. All these processes would explain carbonates contents of these superficial sediments relatively lower than those of Comoé estuary (on average of 0.6 mg/kg per weight of dry sediments in the fine fraction) [53], but also less important than that of modern marine sediments where carbonates formation is estimated at $1.35 \pm 0.5 \times 10^{11}$ C/year [54]. The recent development of this estuary and the climate change would have very slightly affected the annual dynamic of carbonates content of its superficial sediments, despite the decrease in salinity, the increase in moisture content, and above all the change of the nature and the particle size distribution of these substrates. In reality, this fact would highlight a change of the different carbonates species contents in these entities, due to the change of their nature and particle size distribution [55] with that of these other physical and chemical characteristics. For

illustration, the stability of some carbonates species, such as calcite, depends both on redox potential and pH of sediments [56].

The relative high presence of Ca in these superficial sediments testifies to their limestone character, like the whole of the ivoirien coast [40]. The presence of this oligo-element in these substrates would have been impacted by several hydrochemical phenomena, particularly by the temperature of this channel over the period from October 2018 to September 2019. Indeed, the relatively hot temperatures of this channel would favor Ca precipitation in the superficial sediments of this aquatic ecosystem, particularly in calcites, dolomites and gypsum [57,58], in addition to its presence in its oxidized forms. This would happen more in HS, RS and FS. On the other hand, the relatively cold temperatures of this channel during the upwelling seasons of Atlantic Ocean in front of Abidjan district (GCS and SCS) would lead to the solubilization of Ca precipitates, in particular those of calcites and gypsum [58]. Also, the intense decalcification phenomena that take place in this channel due to the acidic nature of some seasonal water inputs (meteorite inputs in RS [59,60] and Comoé River in FS and SCS [32, 53]) would contribute to reducing their presence in these sediments [52].

As concerned to their relatively high Al content over the period from October 2018 to September 2019, it would mainly be due to continental and lagoon sediment inputs, which also constitute the vectors of Al from urban discharges and industrial effluents, particularly those from Abidjan district [50]; as well as agricultural effluents and residues drained into this estuary by meteorite inputs [25,53]. Also, it is worth mentioning its important contribution in this ecosystem linked to atmospheric deposits [50], particularly that from the harbor industrial zone near this channel [30]. The annual mean value of Al content of these superficial sediments is much lower than that of Aghien lagoon, of $(24,182.05 \pm 10,868.73)$ mg/kg per weight of dry sediments [25]. However, it is very much higher than the mean values of Al contents of Biétry bay, between 141 and 154 µg/kg per weight of dry sediments [50]. The Al high presence in these superficial sediments dominated by silts and clays, particularly by kaolinites, would be due to smectites [25]. However, this trace metal would seem to be drained in this estuary mainly in sands and rutiles forms over this annual period. Indeed, pH and reducing nature of these sediments will favor its presence in its particulate

forms than in its soluble forms [61]. The acidic and oxidizing characteristics of meteorite runoff waters [59,60] would further enrich these sediments in Al particulates form in RS and FS. These meteorite inputs would contribute to this enrichment by leaching soil polluted, but also by that of the geological base. This would be favored by the sandy nature of the soils of lower Côte d'Ivoire, which is therefore poor in humus and clay [25]. Also, Comoé River, also exhibiting acidic and oxidizing characteristics [32,53], would enrich these sediments in Al in FS. However, Atlantic Ocean, due basic and reducing characteristics, would attenuate this enrichment of these sediments, by partially promoting its solubilization [61]. This would happen more in GCS and SCS.

The relatively high Fe and Mn contents of these superficial sediments illustrate once again the high presence of these trace metals in the geological basement of Côte d'Ivoire [62]. The recent development of Vridi channel would also have greatly affected Fe, Mg and Mn contents of these superficial sediments over the study period. This would be particularly due to the change of their nature and particle size distribution. Indeed, the high presence of rudites and sands in these superficial sediments over the period from April 2014 to March 2015 contributed highly to their relatively very high contents of these trace metals [30] compared to those of these entities over the period from October 2018 to September 2019, whose particle size distribution was dominated by silts and clays. The great difference between their annual mean values of Fe, Mg and Mn contents over the two different annual study periods would highlight their contribution mainly in sands and rudites forms in this channel. Generally, these three trace metals would be drained in this aquatic ecosystem simultaneously by marine, continental and lagoon sediment inputs over the period from April 2014 to March 2015 and, simultaneously by continental and lagoon sediment inputs over the period of October 2018 to September 2019. This fact would result from their contributions through urban releases [49], especially from in Abidjan district, which, given the obsolete and dysfunctional nature of its sanitation system, are directly discharged into the Ébrié lagoon in front of this district [50]. This would also be the case for industrial effluents [49,50] and atmospheric deposits [50], due to the location of this artificial estuary in the greatest industrial zone of Côte d'Ivoire [30]. The same would be true of their inputs from agricultural effluents and residues

drained into this estuary by lagoon and meteoric inputs [25,53]. The high relative moisture content of these superficial sediments over the period from October 2018 to September 2019 would further promote the resuspension and the solubilization of these trace metals, compared to the period from April 2014 to March 2015. This process would be more so for Fe, which for pH close to neutrality would dissolve [32]. This could be one of the reasons for its relatively low presence in the superficial sediments of this artificial estuary over the period from October 2018 to September 2019, where pH of these entities was very close to neutrality. Also, the presence of these trace metal in these superficial sediments would be importantly influenced by decalcification phenomena [51,52], especially in RS and FS by the acid and oxidizing characteristics of meteorite runoff waters [59,60] and in FS by those of Comoé river [32,53].

All the annual mean values of their P fractions contents studied over the period from April 2014 to March 2015 have been greater than those determined over the period from October 2018 to September 2019.

The important difference between the annual mean values of TP(AM) and TP(VE) contents of these superficial sediments would show a priori that P was mainly associated with the coarse fractions than with its fine fractions in these sediments on the study period. The similar results were obtained by El Jakani et al. [14] in a same study carried out in the sediments of OumEr-Biâa river mouth (Morocco-Atlantic). Also, the results obtained in this study contradict the remarks generally made about TP in surface sediments, as many studies admit that P is generally associated with the fine fraction of sediments, rich in organic matter [11,23]. These results would also show that P was present mainly in mineral form in these sediments over the study period. This would have been illustrated by the high proportion of the different mean annual values of their TMP contents representing more than 70% of the different annual mean values of their TP(VE) contents respectively over the study period. All these remarks could be explained by a relative high presence of heavy titanium-type minerals in these sediments [14,15], especially over the period from April 2014 to March 2015. Indeed, these minerals are predominant in the sedimentary basins of ivorian onshores, dominated by feldspars (arkosic arenites with ferruginous cement) and formed of continental

origin sand and resulting from short-term river-lagoon transport. These minerals are also found in the ivorian offshore sedimentary basin, made up of quartz (quartz sandstone with ferruginous cement sometimes carbonated) and resulting from terrigenous materials carried by rivers during a long transport [40].

TP(VE), TMP, TOP and TP(AM) contents of these superficial sediments would have been of particular importance with their relatively high content of heavy titaniferous minerals [14,15] and the increase in their carbonate [28], Ca [26,27], Fe, Mn [21], Mg [19,29] and probably Al [24,25] contents determined over the period from April 2014 to March 2015 compared to those obtained on the period from October 2018 to September 2019. This would have been the case for their DBP and PBP contents, to which the strong water hydrodynamics of this estuary would have contributed [9,10] to that.

The hydrochemistry change of this estuary following its recent development with the climate change would have significantly impacted P fractions dynamic obtained according to the modified Van Eck method [4,5] in these sediments over the study period. As a result, their relative high content of heavy titanium-type minerals over the period from April 2014 to March 2015 relative to that over the period from October 2018 to September 2019 would have contributed to the great difference observed between the annual mean values of these P fractions contents. Also, the strong water hydrodynamics of this channel [9,10] with the high dominance of these superficial sediments by silts and clays [11,12] and their relatively high moisture content [10,13] would have favored the strong remobilization and solubilization of these P fractions on the period from October 2018 to September 2019. This would also have favored obtaining the mean annual values of these P fractions contents over the period from April 2014 to March 2015 which are greater than those determined over the period from October 2018 to September 2019.

Their significant reducing character would have partially inhibited the growth of their PL content [21,22], while their pH, close to neutrality, would have been favorable to this process [19,20] over all the study period. Also, their relatively high salinity over the period from October 2018 to September 2019 would have further contributed to their PL content drop over all this annual period [14,15]. This would justify the low annual

mean value of their PL content obtained over the period from October 2018 to September 2019 relative to that determined over the period from April 2014 to March 2015.

Their significant reducing nature would have been very conducive to the growth of their PE content [21,22] over all the study period. This would also have been the case for their high conductivity [3, 18] and high Ca [26,27], Mn and Fe [21] contents over the period from April 2014 to March 2015, which would have contributed to obtaining the annual mean value of their PE content over this annual period higher to that determined over the period from October 2018 to September 2019.

In contrast to their significant reducing nature [21,22], their pH close to neutrality [32], their relative low salinity [14,15] and their relatively important organic matter content [11,23] simultaneously with their high Fe, Mn [21] and carbonates [28] contents over the period from April 2014 to March 2015 would also have contributed to obtaining the annual mean value of their PR content higher than that determined over the period from October 2018 to September 2019.

Their pH, close to neutrality, would also have contributed to the growth of the annual mean value of their PO content [19,20], while their significant reducing character would have partially inhibited it [21,22] over the study period. The decrease in their organic matter content [11, 23] with their high Fe and Mn contents [21], unlike the decrease in their Mg content [19,29], over the period from April 2014 to March 2015 would have favored obtaining the annual mean value of their PO content greater than that determined over the period from October 2018 to September 2019. Also, the relatively high salinity of these sediments over the period from October 2018 to September 2019 would have further favored P-Mn conversion into PO [14,15], thereby helping to reduce the difference between their PO contents obtained over these two annual study period.

pH of these sediments, close to neutrality, would be unfavorable to the growth of their P-Ca content over the study period. Over the period from April 2014 to March 2015, the high presence of P-Ca in its occluded form in these superficial sediments [14], dominated by sand and rudites, with their high Ca content [26,27] and the relative decrease in their organic matter

content would have resulted in their high P-Ca content. This process was partially attenuated by their relatively high Mg content [19,29]. Over the period from October 2018 to September 2019, their Mg content drop with their high Ca content would have further favored P co-precipitation with Ca; and this, despite their relatively high organic content [11,23]. These processes, leading to P-Ca formation over the period from October 2018 to September 2019, would have been more prevalent than those of the period from April 2014 to March 2015. However, this fact would be highly impacted by their important moisture content [10,13] and the very strong waters hydrodynamics of this channel [9,10]. This could explain the importance of their P-Ca content obtained over the period from October 2018 to September 2019 compared to that determined over the period from April 2014 to March 2015.

Over the period from April 2014 to March 2015, the relative high presence of heavy titanium-type minerals in these substrates with their high carbonates content [28] would also have favored their high P-CO₃ content, despite their high conductivity [3,18] and Fe, Mn [21] and Mg [19,29] contents. On the other hand, over the period from October 2018 to September 2019, their low Fe, Mn and Mg contents would, on the contrary, have favored P co-precipitation with carbonates. However, as in the case of P-Ca over the period from October 2018 to September 2019, their important moisture content [10,13] simultaneously with the strong waters hydrodynamics of this artificial estuary [9,10] would have led to the important remobilization and solubilization of this P fraction over this annual period. This would justify the low annual mean value of their P-CO₃ content obtained over the period from October 2018 to September 2019 relative to that determined over the period from October 2018 to September 2019.

The important reducing nature of these superficial sediments would have contributed to reducing their POR content over the study period [21,22]. The relatively high presence of titaniferous-type heavy minerals in these superficial sediments would have resulted in their very high POR content. This is due to "organic matter-Fe-phosphate oxide" complexes [14,15]. However, this process was partially reduced by their relatively low organic matter content [11,12] over the period from April 2014 to March 2015. Over the period from October 2018 to September 2019, their high organic matter content would

have been very conducive to the growth of their POR content. However, this process would have been very significantly affected by their high moisture content [10,13] and the strong water hydrodynamics of this artificial estuary [9,10]. This fact would justify the annual mean value of their POR content obtained over the period from April 2014 to March 2015 greater than that determined over the period from October 2018 to September 2019.

4. CONCLUSION

This study once again illustrates the effect of the recent development of this estuary and the climate change on its hydrochemistry functioning. This fact, with as a corollary the modification of the physical and chemical characteristics of its superficial sediments, would have had the effect of clearing P towards the Atlantic Ocean and/or accelerating its sedimentation; hence the reduction of eutrophication risk of this aquatic ecosystem. The results obtained in this study could serve as a basis for further possible decisions and actions aimed at its protection for its sustainable development.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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