

Simultaneous Effects of the Climate Change and the Recent Hydromorphological Modification of Vridi Channel (Côte d'Ivoire) on Some Its Hydrochemical Characteristics

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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. Author NS 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.

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ABSTRACT

This work aims to assess the simultaneous effects of the climate change and the hydromorphological modification of Vridi channel on its hydrochemistry. To best estimate, this fact, the seasonal dynamic of the particle size distribution, pH, redox potential, salinity, conductivity, moisture and organic matter contents of Vridi channel sediments have been followed and compared during two different annual periods, where the climate and the hydromorphology of this estuary have been different. The first annual period, covering the period from April 2014 to March 2015, has been characterized by a climatic regime close to the climatic normal of the study area and, this channel had its former hydromorphology. The second period annual, covering the period from October 2018 to September 2019, has been marked by a disruption of the climatic regime throughout Côte d'Ivoire, and this channel presented its modified hydromorphology. A monthly sampling has been done in this channel during each annual period. All These physical

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and chemical parameters have been determined by the corresponding AFNOR standards. Results have shown that these superficial sediments, with a predominantly sandy texture over the period from April 2014 to March 2015, have presented a texture predominantly of silt and clays over the period from October 2018 to September 2019. The climate change and the recent hydromorphological modification of this ecosystem had simultaneous very few effects on their pH and redox potential over the study period. On the other hand, they have caused an important increase in their salinity, moisture and organic matter contents and, a decrease in their electrical conductivity over the period from October 2018 to September 2019 relative to those determined in these substrates over the period of April 2014 to March 2015. This fact has certainly affected its biodiversity, especially that of its benthic fauna.

Keywords: Atlantic Ocean; climate change; Côte d'Ivoire; hydromorphology; pollution; sustainable development; Vridi channel.

1. INTRODUCTION

The diversity and accessibility of the coastal aquatic ecosystems have always favored the establishment of humans and its activities on their watersheds. However, the strong anthropogenic pressure on these ecosystems, due to the strong demography growth and the development and intensification of anthropogenic activities of all kind, threaten their ecological balance [1,2]. This is especially the case of the major development works (canals, dredging, extraction of sand and gravel, construction of bridges and dikes, etc.), which changing their hydromorphology, are likely to influence their hydrochemistry and hydrodynamic [3,4]. Climate change, increasing in their last decade [5], strongly contributes to this situation. The direct effects of this phenomenon on these ecosystems are their heating and acidification. Its diffuse effects on them are the modification of hydroclimatic conditions, which are essential for their functioning. So, climate change affects their biodiversity and existence [6-8].

The assessment of anthropogenic pressure and its consequences on aquatic ecosystems is global concern. Several approaches were carried out, including monitoring of the dynamic of some physical and chemical characteristics such pH, redox potential, salinity, electrical conductivity, moisture and organic matter contents, etc [8]. These physical and chemical parameters play fundamental roles in the various biogeochemical phenomena. The high variations of these parameters in these ecosystems illustrate the modification of their functioning, because each of its ecosystems has its own characteristics in these parameters. The monitoring of the variation of these parameters in aquatic ecosystems makes it possible to identify origins of their pollution and/or of their water exchange. Sediments are commonly used for characterizing

anthropogenic impacts and/or climate change on aquatic ecosystems, because they are considered as a memory indicator of these ecosystems [9,10].

Vridi Channel is the only pass between Atlantic Ocean and Ebrié system. It is an exceptional, because resulting from the breakthrough of the Jacquville dyke (Côte d'Ivoire) [11]. It has a remarkable biodiversity that simultaneously straddles marine, continental and lagoon environments. Its biodiversity is seriously threatened by strong anthropogenic pressures and climate change. This situation will be more with its recent hydromorphological modification. Given its ecological importance, it is important to carry out studies with a view to understanding its functioning, and this, in order to better assess its health status for its protection and sustainable development. It is within this framework that this present study was led. Its objectives are to assess the effects of the climate change and the recent hydromorphology modification of this estuary on the seasonal dynamics of pH, redox potential, salinity, conductivity, relative humidity, organic matter content and particle size distribution of its superficial sediments.

2. MATERIALS AND METHODS

2.1 Study Area

Located directly above Abidjan district and at the eastern of the Jacquville department, Vridi channel is located in the south of Côte d'Ivoire. It is located precisely at 4°0'50" West longitude at the North latitude of 5°15'23" (DMS) (5.257636 N; 4.011545 W in decimal degrees) (Fig. 1).

In order to avoid its rapid silting up, it was oriented from the southwest to the northeast [11,12]. Its former (from 1951 to 2017) and current (since 2018) hydromorphologies characteristics are given in Table 1.

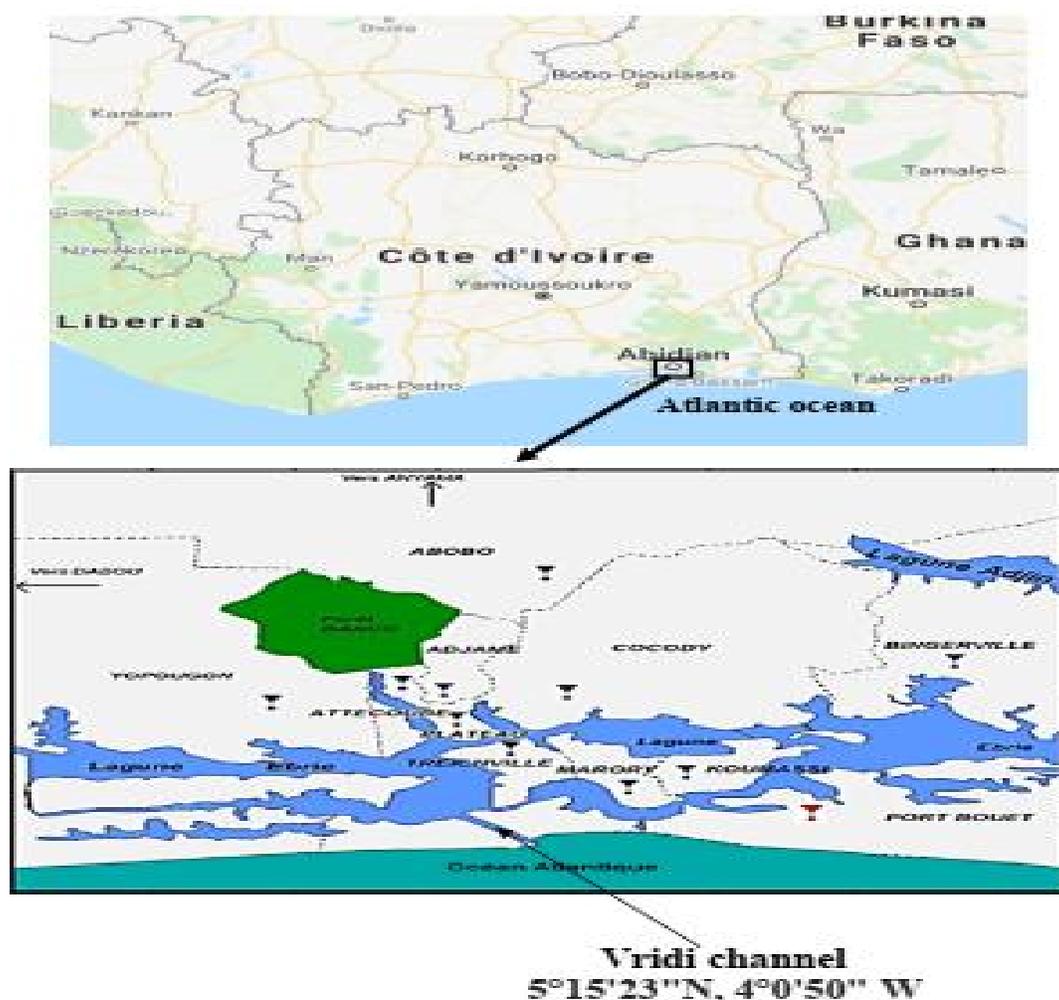


Fig. 1. Geographical location of Vridi channel

Table 1. Former and current Hydromorphologies characteristics of Vridi channel

	Former hydromormology (From 1950 to 2017)	Current hydromorphology (Since 2018)
Mean length (km)	2.70	2.70
Mean wide (km)	0.37	0.37
Mean depth (m)	-14.00	-18.00
Water draft (m)	12.00	16.00
Air draft (m)	11.80	15.00
West jetty	Mean wide (m)	200.00
	Mean depth (m)	-12.00
East jetty	Mean wide (m)	370
	Mean depth(m)	-13.00

Vridi channel is in a subequatorial regime. 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 [13]. The

proximity of this channel to Atlantic Ocean, of which it is an extension, makes it an artificial marine estuary. As a result, it is characterized by a very strong permanent water hydrodynamics [11,12]. Also, by its position, this artificial estuary

has a very impressive hydrographic network, made up of Atlantic Ocean on the one hand, and Ébrié system and its hydrographic network, on the other. The hydrographic network of the Ébrié system is made up of numerous rivers and coastal rivers, the most important of which are the Comoé river (the most important river of Côte d'Ivoire) and the coastal rivers Mé and Agnéby. In their flood seasons, the coastal rivers Mé and Agnéby (June and October-November) and the Comoé river (October-December) pass through Vridi channel to reach Atlantic Ocean. Given its position, the water seasons of this estuary result from those of Atlantic Ocean in front of Abidjan district defined by Durand and Skibich [13] and those of Ébrié system defined by Durand and Guiral [14]. Yao and Trokourey [10,15] and Yao et al. [16] define them as follow:

- A Hot Season (HS) from February to April, the waters of this channel are essentially the warm waters of Atlantic Ocean due to the low inflow of meteorite waters.
- A Rainy Season (RS) from May to July, where the influx of meteorite runoff and the warm Guinean water from Agnéby and Mé are important in this channel. However, the marine influence still remains dominant.
- A Great Cold Season (GCS) from August to September, characterized by the installation in this channel of the cold marine waters from the great marine upwelling season of Atlantic Ocean in Guinea gulf in front of Abidjan district.
- 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 warm Sudanese waters of the Comoé river coexist simultaneously in this channel with the cold marine waters from the small marine upwelling season of Atlantic Ocean in the Guinea gulf in front of Abidjan district.

Vridi channel is fed with solid sediment load by Atlantic Ocean, Ebríé system and river sediment inputs. Atlantic Ocean supplies this channel with coarse to very coarse fraction sands [12,17]. As for Ébrié system, the Comoé river and the coastal rivers Mé and Agnéby, they supply this channel with sands of very variable granulometry

[17]. These surface waters also supply this artificial estuary with silts, clayey silts and silts or clays [18].

Vridi channel is currently the transit point for all the pollutants from the autonomous harbour of Abidjan. This is the case for all pollutants resulting from Human activities in Abidjan district, which have been of considerable importance with the strong demographic growth. This fact is the consequence of the dysfunction and obsolescence of the sanitation system in Abidjan district [19]. Also, this estuary is also the transit point for many pollutants carried by continental waters in Atlantic Ocean in general, and in particular those by the coastal rivers Agnéby and Mé, and from the Comoé river [16,10,15]. This is due to the development and intensification of agriculture with intensive use of phytosanitary products in their watersheds. For illustration, Pottier et al. [20] mentioned that the Comoé River is responsible for two thirds of the metal pollution of Ebríé system. All these pressures ended up degrading this marine estuary and seriously threatening its biodiversity [16,10,15].

2.2 Experimental Techniques

2.2.1 Sample collection

In the implementation of this study, two annual periods were considered. The first annual period, covering the period from April 2014 to March 2015, was characterized by a climatic regime close to the normal climatic in the study area. Also, Vridi channel presented its former hydromorphology over this annual period. The second annual period, covering the period from October 2018 to September 2019, was marked by a disruption of the climatic regime throughout Côte d'Ivoire. During this annual period, Vridi channel presented its current hydromorphology.

For a better estimate of the effects of the climate change and the recent hydromorphological modification of Vridi channel on the seasonal dynamics of pH, redox potential, salinity, conductivity, moisture content, organic matter content and particle size distribution of its superficial sediments, have been investigated in these different annual periods and compared. So, the samples were taken at the same sampling sites over the two annual study periods. Three sampling sites, 900 m apart, were chosen taking into account the spatial heterogeneity of this channel (Fig. 2). The sampling site S1 is located in the center of the west jetty, precisely at

5.250120N, 4.004542W. It had -12.00 m deep over the period from April 2014 to March 2015, and -22.50 m over the period of October 2018 to September 2019. As for the sampling site S2, it is located at the center of this artificial estuary, precisely at 5.256616N, 4.012781W. It had a depth of -15.00 m over the period from April 2014 to March 2015, and of -26.00 m over the period from October 2018 to September 2019. Regarding S3, it is located in the center of the east jetty, precisely at 5.265163N, 4.021021W. S3 had -20.00 m deep over the period from April 2014 to March 2015, and -28.50 m over the period from October 2018 to September 2019.

A monthly sampling has been done at each site; or a collection of 36 samples per annual period and 72 samples in total during the study period. The samplings have been done at 5 cm below the sediment surface using a Van-Veen type bucket according to the AFNOR X 31-100 standard [21]. Once collected, the samples have been collected in dry and very clean polyethylene bottles and stored in a cooler, as recommended by the AFNOR NF ISO 18512 (X31-607) standard [22].

2.2.2 Preliminary treatment of samples and determination of the physical and chemical parameters studied in laboratory

In the laboratory, the superficial sediment samples from this channel have been previously

cleared of coarse elements composed mainly of bone debris, shells, large rocky debris and large plant debris. Some quantity of the raw sample (non-dried sediment samples) has been used for the determination of their moisture content, while the other quantity, in large proportion, has been cold dried by freeze-drying to a constant weight according to the AFNOR NF EN ISO 16720 standard [23]. The quantity of dried sediment samples has been also divided into two sub-quantities: a small quantity has been kept for the determination of the particle size and, the other quantity has been reduced to diameters less than 2 mm after grinding, sieving, separation and pulverization operations according to the AFNOR NF ISO 11464 (X 31-412) standard [24]. All dry sediment samples have been stored in very clean, tightly closed, dry polyethylene bottles. These samples, thus conditioned, have been stored in the dark at about 20°C for future analyzes, as recommended by the AFNOR NF ISO 18512 (X31-607) standard [25]. The moisture content of the superficial sediment samples from Vridi channel was obtained according to the AFNOR NF ISO 11465 standard [26]. Their particle size distribution has been determined in accordance with the AFNOR NF X 31-107 standard [27]. Their pH and U have been determined in accordance with the AFNOR NF ISO 10390 standard [28] and the AFNOR NF ISO 11271 standard [29] respectively. As for their organic matter content, it has been determined according to the modified Walkley-Black method [30] standardized by AFNOR under the number NF ISO 14235 (X31-419) [31].

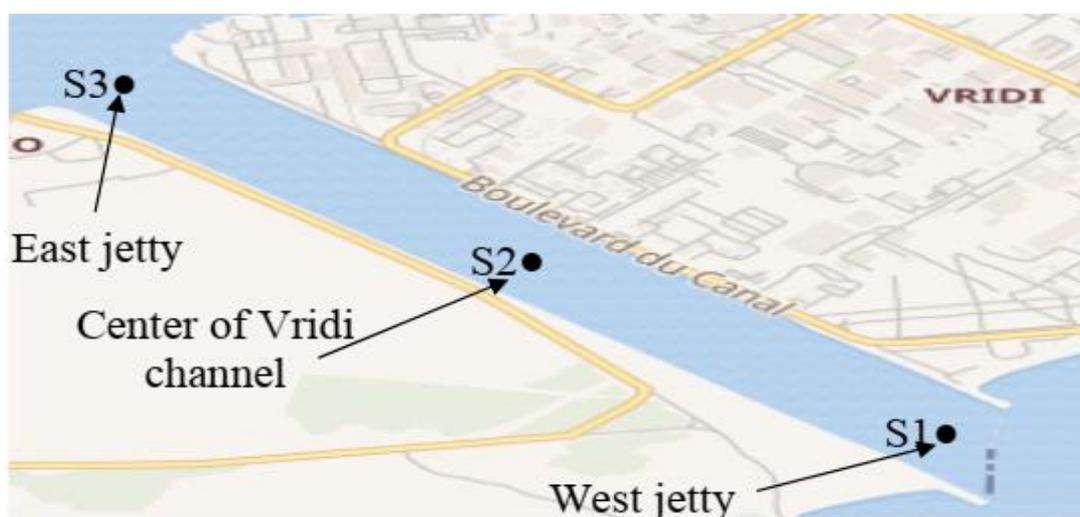


Fig. 2. Geographical location of the three sampling sites in Vridi channel on the study period

2.2.3 Hydroclimatic data sources and statistical techniques used for results treatment

Monthly data on rainfall and ambient air temperature in Abidjan, and tides in the autonomous harbour of Abidjan over the study period have been provided by SODEXAM [32].

The different results obtained in this study have been processed by standard statistical techniques, such as the mean (m), the standard deviation (s) and the variation coefficient (VC).

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Rainfall, ambient air temperature, and tides in the study area over the study period

The annual mean values of ambient air temperature have been of $(27.02 \pm 1.23)^\circ\text{C}$ over the period from April 2014 to March 2015, and of $(28.37 \pm 1.91)^\circ\text{C}$ over the period from October 2018 to September 2019. So, the study period has been relatively warm, particularly that from October 2018 to September 2019.

The annual mean values of cumulative rainfall have been of (1904.7 ± 169.11) mm over the period from April 2014 to March 2015, and of (808.4 ± 60.70) mm over the period from October 2018 to September 2019. The period from October 2018 to September 2019 has been characterized by a break in the rainfall regime in Abidjan, shown by a rainfall deficit.

The annual mean values of the tidal coefficient have been of (71.82 ± 2.68) cm over the period from April 2014 to March 2015, and of (70.82 ± 3.40) cm over the period from October 2018 to September 2019.

3.1.2 Physical and chemical parameters assessed in the superficial sediments of Vridi channel over the study period

3.1.2.1 Seasonal and annual particle size distribution

As shown the Table 2, the superficial sediments of Vridi channel have presented a coarse texture (dominated by sands) over the period from April 2014 to March 2015 and, a fine texture (dominated by silts and clays) over that from October 2018 to September 2019.

The seasonal dynamic of the particle size distribution of these sediments over the period from October 2018 to September 2019, shows that still a high presence of silts and clays in these substrates, followed by that of sands. The values of VC for their sand and rudite contents are relatively very important, but relatively low for those concerning their silt and clay contents (Table 3). This would illustrate contributions of silt and clay almost constant and those variables of sands and rudites by the different waters inputs in this estuary in its different seasons.

3.1.2.2 Seasonal and annual dynamics of pH, conductivity, redox potential, salinity, organic matter and moisture contents

The seasonal and annual mean values of pH, salinity, redox potential, conductivity, moisture and organic matter contents of the superficial sediments of Vridi channel obtained over the study period are given in Table 4.

The analysis of these results reveals that the superficial sediments of Vridi channel were slightly neutral to basic and reducing characters with relatively high salinity, conductivity, moisture and organic matter contents over the study period.

Table 2. Mean \pm standard deviation (variation coefficient VC (%)) of the particle size distribution for the superficial sediments of Vridi channel over the study period

Study period	Minerals			General texture
	Rudites	Sands	Slits and clays	
April 2014 à March 2015	3.06 \pm 1.17 (38.04%)	74.84 \pm 4.07 (5.43%)	22.10 \pm 0.35 (1.55%)	Sands
October 2018 à September 2019	10.23 \pm 3.07 (29.99%)	24.77 \pm 6.86 (27.70%)	70.00 \pm 5.84 (8.99%)	Slits and clays

Table 3. Mean \pm standard deviation (variation coefficient VC (%)) of the Particle size distribution for the superficial sediments of Vridi channel over the period from October 2018 to September 2019

	Water seasons of Vridi channel				
	HS	RS	GCS	FS	SCS
Rudites	6.88 \pm 2.90 (42.23%)	11.13 \pm 5.87 (52.70%)	9.28 \pm 5.14 (55.43%)	14.6 \pm 11.07 (75.83%)	9.27 \pm 7.76 (83.71%)
Sands	21.05 \pm 4.10 (19.50%)	29.44 \pm 17.37 (58.98%)	17.52 \pm 19.32 (110.28%)	31.64 \pm 6.18 (19.52%)	24.21 \pm 15.29 (63.16%)
Slits and clays	72.07 \pm 6.20 (9.18%)	59.43 \pm 14.74 (24.80%)	73.21 \pm 15.67 (21.00%)	53.76 \pm 2.63 (4.90%)	66.52 \pm 14.81 (22.27%)

These sediments have been permanently slightly neutral to the basic character in all the water seasons of this channel over the study period. This has been again shown by the values of seasonal VC, which were very low over the study period. Also, the low difference between their higher pH over the study period, obtained in GCS over the period from April 2014 to March 2015, and their lower pH over the study period, obtained in FS over the period from April 2014 to March 2015, illustrated this fact. Over the period from October 2018 to September 2019, their highest pH has been obtained in HS, and their lowest pH in FS.

The superficial sediments of Vridi channel presented a permanent reducing character in all the water seasons of this artificial estuary over the study period. This has been also shown by their low values of seasonal VC. The low difference between their most significant reducing character, obtained in FS over the period from October 2018 to September 2019, and the lowest one, determined again in FS over the period from April 2014 to March 2015, confirms this fact. The lowest seasonal mean of their reduction character over the period from October 2018 to September 2019 has been obtained in FS, and that the most significant over the period from April 2014 to March 2015 has been also determined in FS.

All the seasonal mean values of their salinity obtained over the period from October 2018 to September 2019 have been all very important relative to those determined over the period from April 2014 to March 2015. The seasonal values of VC for their salinity have been relatively considerable in all seasons, except in GCS and FS, over the period from April 2014 to March 2015; but, they have been very low, except relatively in FS, over the period from October 2018 to September 2019. Their most important seasonal salinity has been obtained in HS, and

the lowest in SCS over the period from April 2014 to March 2015. Over the period from October 2018 to September 2019, their highest seasonal salinity has been determined in SCS, and the lowest in FS.

In contrast to the seasonal mean values of their salinity, the seasonal mean values of their conductivity obtained over the period from April 2014 to March 2015 have been all higher than those determined over the period from October 2018 to September 2019, except in RS. The seasonal values of VC for their conductivity have been relatively important in all the seasons, except in RS, over the period from April 2014 to March 2015. That has been the opposite over the period from October 2018 to September 2019, where the seasonal values of VC for this parameter have been very low, with the exception of FS. Over the period from April 2014 to March 2015, their highest seasonal conductivity has been obtained in SCS, and the lowest in RS. For the period from October 2018 to September 2019, their highest seasonal conductivity has been determined in SCS, and the lowest in GCS.

These superficial sediments have presented very high seasonal mean values of organic matter content over the period from October 2018 to September 2019 compared to those obtained over the period from April 2014 to March 2015, as illustrated again by their annual mean values of organic matter content on these two annual periods. The seasonal values of VC of their organic matter content have been very considerable over the period from April 2014 to March 2015, but low over the period from October 2018 to September 2019. The seasonal mean values of their organic matter content obtained over the period from April 2014 to March 2015 have been very slightly higher than those determined for the period from October 2018 to September 2019 in HS and SCS. In the

Table 4. Mean \pm standard deviation (variation coefficient VC (%)) of pH, conductivity, redox potential, salinity, organic matter and moisture contents for the superficial sediments of Vridi channel over the study period

	Annual period	HS	RS	GCS	FS	SCS	Annual mean
pH	April 2014-March 2015	7.64 \pm 0.18 (2.40%)	7.79 \pm 0.31 (3.97%)	8.07 \pm 0.61 (7.60%)	7.51 \pm 0.09 (1.20%)	7.80 \pm 0.21 (2.71%)	7.76 \pm 0.20 (2.60%)
	October 2018-September 2019	7.95 \pm 0.22 (2.77%)	7.70 \pm 0.18 (2.27%)	7.68 \pm 0.05 (0.69%)	7.55 \pm 0.16 (2.15%)	7.89 \pm 0.06 (0.70%)	7.75 \pm 0.04 (0.49%)
Conductivity (mS.cm ⁻¹)	April 2014-March 2015	5.02 \pm 1.70 (33.84%)	1.59 \pm 0.28 (17.42%)	2.55 \pm 2.14 (83.64%)	5.23 \pm 2.06 (39.30%)	5.72 \pm 3.69 (64.56%)	4.02 \pm 1.22 (30.29%)
	October 2018-September 2019	2.91 \pm 0.22 (7.43%)	1.97 \pm 0.10 (5.09%)	1.39 \pm 0.20 (14.06%)	3.04 \pm 1.23 (40.64%)	3.69 \pm 0.13 (3.42%)	2.59 \pm 0.33 (12.76%)
Redox potential (mV)	April 2014-March 2015	-29.72 \pm 3.51 (11.82%)	-31.82 \pm 1.38 (4.35%)	-32.43 \pm 0.55 (1.71%)	-25.70 \pm 4.64 (18.05%)	-29.76 \pm 2.53 (8.52%)	-29.88 \pm 1.73 (5.80%)
	October 2018-September 2019	-36.74 \pm 6.55 (17.82%)	-28.05 \pm 8.30 (29.57%)	-27.72 \pm 0.33 (1.18%)	-38.05 \pm 7.13 (18.74%)	-28.25 \pm 5.84 (20.67%)	-31.34 \pm 2.17 (6.92%)
Salinity (‰)	April 2014-March 2015	1.69 \pm 0.78 (45.95%)	0.74 \pm 0.50 (67.82%)	1.25 \pm 0.13 (10.48%)	0.90 \pm 0.19 (21.29%)	0.62 \pm 0.24 (38.02%)	1.04 \pm 0.27 (25.88%)
	October 2018-September 2019	5.02 \pm 0.63 (12.62%)	3.78 \pm 0.30 (7.97%)	2.35 \pm 0.27 (11.52%)	5.95 \pm 2.16 (36.34%)	7.28 \pm 0.12 (1.66%)	4.88 \pm 0.56 (11.50%)
Matter organic content (% dry weight)	April 2014-March 2015	14.09 \pm 12.44 (88.30%)	11.28 \pm 11.73 (103.95%)	18.74 \pm 21.74 (115.99%)	15.18 \pm 21.74 (115.99%)	15.18 \pm 9.82 (64.71%)	15.38 \pm 5.32 (34.61%)
	October 2018-September 2019	12.63 \pm 1.21 (9.59%)	26.55 \pm 4.00 (15.07%)	43.59 \pm 0.58 (1.33%)	27.06 \pm 5.40 (19.97%)	14.18 \pm 1.83 (12.95%)	21.91 \pm 0.44 (1.99%)
Moisture content (% dry weight)	April 2014-March 2015	1.16 \pm 0.83 (71.60%)	0.63 \pm 0.55 (87.46%)	0.73 \pm 0.54 (73.55%)	0.61 \pm 0.35 (56.95%)	0.70 \pm 2.27 (322.59%)	0.77 \pm 0.78 (102.00%)
	October 2018-September 2019	6.71 \pm 2.70 (40.19%)	4.90 \pm 4.08 (83.25%)	2.56 \pm 0.55 (21.56%)	12.26 \pm 7.41 (60.38%)	26.34 \pm 9.85 (37.55%)	10.54 \pm 3.87 (36.74%)

other three seasons, namely RS, GCS and FS, the opposite has been observed, and that with a significant difference. Their highest organic matter content has been obtained simultaneously in FS and SCS, and the lowest in RS over the period from April 2014 to March 2015. Over the period from October 2018 to September 2019, the most important of their seasonal content has been obtained in GCS, and the lowest in HS.

Similar to their seasonal mean values in organic matter content, their seasonal mean values of moisture content obtained over the period from October 2018 to September 2019 have been very important to those determined over the period from April 2014 to March 2015, such as also showed their annual mean values in this parameter over the two annual periods. The seasonal values of VC of their moisture content have been very marked over the period from April 2014 to March 2015, but have been very low over that from October 2018 to September 2019. Their highest seasonal moisture content has been obtained in HS, and the lowest in FS over the period from April 2014 to March 2015. Over the period from October 2018 to September 2019, their highest seasonal moisture content has been obtained in SCS, and the lowest in GCS.

3.2 Discussion

As illustrated by these different results, the hydrochemistry of Vridi channel has been considerably impacted both by its recent hydromorphology modification and the climate change over the study period.

The two annual mean values of ambient air temperature, higher than the annual normal of ambient air temperature in Abidjan (of 26.6°C obtained over the period from 1941 to 2000 [33]), illustrate the climate change on the study area. This is also the case for rainfall, which has been so close to the annual normal of rainfall in Abidjan (of 1922 mm obtained over the period from 1961 to 2014 [12,34]) over the period from April 2015 to March 2015, but in deficit over the period from October 2018 to September 2019. This resulted in a different influence of meteorite inputs on this channel in these two annual study periods. Indeed, the effects of the climate change on the second annual study period have been illustrated by a drop in rainfall in the south of Côte d'Ivoire during its rainy season on land, where is located this channel. These effects have been again shown by relatively abundant rainfall

with its onset earlier than expected in other regions of this country, particularly in the Comoé river watershed. This resulted in a drop in meteorite runoff and river water inputs from Agnéby and Mé in Vridi channel in RS over the period from October 2018 to September 2019 relative to those over the period from April 2014 to March 2015. This variability in rainfall over the period from October 2018 to September 2019 also led to an important water supply from the Comoé River and its installation very early and over a long period (from August to December) in this ecosystem over this annual period, unlike its relatively lower contribution and its installation over a short period in this channel (from October to December) over the period from April 2014 to March 2015. The climate change has also materialized over the study period by the very early influence and over a long period of the great upwelling season of Atlantic Ocean on this channel (from June to October); and this, with a strong intensity over the period from October 2018 to September 2019. Under normal climatic conditions, as over the period from April 2014 to March 2015, the influence of this upwelling on this channel was carried out over a shorter period (from August to September).

The different annual mean values of tidal coefficient, very close to one another, testify to the strong permanent water hydrodynamics of this estuary. Thus, its recent hydromorphological modification would have had very few effects on its water hydrodynamics. However, it has an very important effects on particle size distribution of its superficial sediments, which has been different from one annual study period to another. Over the period from April 2014 to March 2015, the water circulation and its strong hydrodynamics in the former hydromorphology of this channel would lead to sedimentary inputs with a high dominance of marine rudites up to a third of the estuary from its west jetty and sediment inputs with a high sand content from lagoon up to two-thirds from its east jetty [16]. Over the period from October 2018 to September 2019, these waters and their strong hydrodynamics in its new hydromorphological configuration would lead to significant sedimentary deposits with very high silt and clays content throughout its length. These minerals have been essentially from continental environment.

Like all of southern Côte d'Ivoire, rainfall is very low in the study area during the hot land season. It follows the weak influence of meteorite inputs on Ebrié system and Atlantic Ocean, therefore on

Vridi channel. Thus, the entire area, from Vridi channel to the area of Ebrié lagoon in Abidjan district, is subjected to the very strong influences of the warm marine waters of Atlantic Ocean [35,36]. So, the waters of Vridi channel are essentially those of Atlantic Ocean in HS [15]. That would generally explain the neutral to slightly basic and reducing characters of their superficial sediments, with their relative high conductivity, salinity, organic matter and moisture contents in this season over the study period. In this season, the very high presence of silts and clays in these sediments over the period from October 2018 to September 2019 would have resulted in the formation of large mud plugs in this aquatic ecosystem relative to that over the period from April 2014 to March 2015, where these shallow sediments have been dominated by sands and rudites [37,38]. That would be justified by their very high moisture content over the period from October 2018 to September 2019 compared to that over the period from April 2014 to March 2015. The high presence of silts and clays in these sediments would also explain their high pH over the period from October 2018 to September 2019 relative to that obtained over the period from April 2014 to March 2015. This can be explained by their carbonates content, because carbonates present high affinities with fine particles [39]. This would also be the case for their more pronounced reducing character over the period from October 2018 to September 2019. It would be further favored by their moisture content on the one hand, and their intense anoxia linked to the significant degradation and mineralization of organic matter [40], on the other hand. This could also explain their organic matter content obtained over the period from October 2018 to September 2019 which is slightly lower than that determined over the period from April 2014 to March 2015. In this season, the presence of this significant organic matter would be favored by its strong water hydrodynamics. Nevertheless, its strong water hydrodynamics would partially inhibit their reducing character, especially over the period from October 2018 to November 2019 due to their texture dominated by silts and clays [37-38]. Their different particle size distribution would also be explained an evolution of their salinity contrary to that of their conductivity over each of these years. Indeed, silts and clays would have a tendency to accumulate more sodium chloride (NaCl) compared to sands and rudites [41,42]. As for sands and rudites, they would promote good thermal conductivity and high electrical resistivity compared to clays and silts [43]. This

would be shown by the simultaneous observation of their relative high salinity with their relatively low conductivity over the period from October 2018 to September 2019 and, the reverse over the period from April 2014 to March 2015.

In RS, meteorite inputs modify the hydrochemistry of Vridi channel. These inputs are essentially characterized by the waters of Agnéby and Mé rivers, which are slightly acidic to neutral, desalinated, oxidizing and weakly mineralized [44] and by meteorite runoff, slightly acidic to neutral, weakly mineralized and oxidizing due to atmospheric pollution by fine particles [45] and urban and industry discharges [46]. The same is true for the waters and sediments of Ebrié lagoon, far from this channel. Thus, these water inflows lead in this season to the marine influence decrease on the waters of this channel by dilution effect [15]. This would have caused the drop in their salinity and conductivity from HS to RS over the entire study period, especially their conductivity over the period from April 2014 to March 2015. These meteorite inputs would also lead to a modification of the particle size distribution of these sediments, by the inputs of relatively important lagoon sands compared to those achieved by the warm marine waters in HS over the period from October 2018 to September 2019 and, by simultaneous inputs of lagoon sands and marine rudites greater than those produced by these marine waters in RS over the period from April 2014 to March 2015. Thus, these sedimentary inputs, with the water circulation induced by meteorite waters, would have favored muddy plugs decrease in this artificial estuary [37,38]. This would be shown by the drop in moisture content of these superficial sediments in this season relative to that determined in HS over the study period. This would also result in a drop in their pH over the period from October 2018 to September 2019 due to their granulometric texture. However, the addition of more marine rudites over the period from April 2014 to March 2015 in this season would have favored more the growth of their pH [47] in this season relative to that obtained in HS. These meteoric inputs would again lead to an important enrichment in organic matter these superficial sediments in this season relative to HS, especially over the period from October 2018 to September 2019. This would result in their organic matter content in this season greater than that determined in HS over the study period. The significant degradation and mineralization phenomena of this organic matter, accompanied by anoxia phenomena [40], will

have take place in this season over the period from April 2014 to March 2015 than over the period from October 2019 to September 2019, due to the highly evolved nature of this organic matter over the last annual period of study. This would be shown by the decrease of their reducing character in this season relative to that of HS over the period from October 2018 to September 2019 and, its growth in this season relative to that of SC over the period from April 2014 to March 2015.

In GCS, the phenomenon of the great upwelling of Atlantic Ocean affects the entire area from Vridi channel to Ebrié lagoon waters in Abidjan district [15]. This would have been more so over the period from October 2018 to September 2019, when the intensity of this phenomenon has been exceptionally very intense. In this season, the Comoé River would have affected the hydrochemistry of this estuary differently, due to the variability of rainfall in its watershed over the study period. Over the period from April 2014 to March 2015, the rainfall regime has been normal and the Comoé River would have by flushing effect drained the lagoon waters (from its mouth to Abidjan district) to Vridi channel in this season. Over the period from October 2018 to September 2019, the disturbance in the rainfall regime observed in watershed of this river would have led it to settle earlier than expected in this artificial estuary. These water inputs, with of the hydromorphological modification of this channel, would therefore have modified the particle size distribution of these superficial sediments over the two annual study periods. Therefore, over the period from April 2014 to March 2015, the cold marine waters of Atlantic Ocean would have resulted in a high presence of marine rudites while the flushing effects of lagoon waters by the Comoé River would cause a high presence of lagoon sands. Over the period from October 2018 to September 2019, the Comoé river would have led to enrichment of these sediments in silts and clays, from river and lagoon origins. With the exception of the conductivity and salinity of these superficial sediments, these water inputs in this season would have had the same effects on the other physical and chemical parameters evaluated as the meteorite inputs of RS over the study period. This would be justified by the dynamic profile of these parameters identical over these two seasons, but with an more important amplitude in GCS. The simultaneous presence of the Comoé River with that of the cold marine waters would favor the high growth of their organic matter

content in this season. It is the same case with the strong water hydrodynamics of this estuary with the drop in the temperature of these waters in this season, particularly over the period from April 2014 to March 2015. The water supplies of Ebrié lagoon would favor the growth of their pH in this season over the period from April 2014 to March 2015 on one hand, and the high presence of silts and clays in these sediments would contribute to the drop in their pH over the period from October 2018 to September 2019, on the other. Regarding the dynamics of their salinity and conductivity, it would be identical to their dynamics in HS, also with an important amplitude. This would be explained by a relatively high presence of all minerals (clays, silts, rudites and sands) in these sediments in this season relative to HS.

In FS, the Comoé river settles completely in the Vridi canal [15]. The meteorite runoff from the small rainy season on land contributes to the meteorite inputs in this channel. Due to its acidic, anoxic and oxidizing characteristics [15,39], this river would modify the hydrochemistry of this channel in this season. This would also be the case for meteorite runoff of slightly acidic to neutral, weakly mineralized and oxidizing characters [45]. As a result, the marine influence on the superficial sediments of this artificial estuary would have been strongly attenuated by the presence of this river and these meteorite contributions. The drop in pH of these sediments in this season, exhibiting practically the same seasonal value over the two annual study periods and which has been the lowest for each corresponding annual study period, would perfectly illustrate this fact. Also, this river would drain there a significant amount of particulate matter in clays and silts forms [15] and sediments from lagoon areas. This river would transport these sediments in a more decalcifying form, due to its characters [15,48,49]. To these contributions, would be added alluvium dominated by rudites and sands brought by the meteorite runoff. This fact would be especially in this season over the period from October 2018 to September 2019. As in GCS, their high sandy texture would have further inhibited the formation of mud plugs in this season over the period from April 2014 to March 2015. This would result in the continuous of their moisture content decrease from GCS to FS, which has been also the lowest both over this annual period and over the study period. On the other hand, the water circulation induced by this river would have contributed more to the formation of mud plugs in

this estuary, although the silts and clays content has been less important than that of GCS [37,38]; consequently to the growth of their moisture content in this season relative to that in GCS over the period from October 2018 to September 2019. The significant presence of decalcified clays and silts in these sediments during this season over the period from October 2018 to September 2019 and the significant mud plugs has been also responsible for their very high salinity [50], one of the most important during the study period. Also, the relative high presence of decalcified sand in the superficial sediments would promote the increase of their conductivity in this season over this annual period, which has been more important than in GCS. The decrease in mud plugs, linked to the relative high presence of sand in these superficial sediments in this season over the period from April 2018 to March 2019, would explain the decrease of their salinity from GCS to FS [41,42]. Also, the predominance of decalcified sand in these sediments would lead to their high conductivity in this season over this annual period, one of the most important over the study period. The Comoé river transport organic matter in highly evolved and/or mineralized forms [15]. Also, the relatively high waters temperature of this channel, due to the presence of this river, would favor the degradation and mineralization of organic matter in these superficial sediments in this season over the study period [51,52]. This would explain the drop in their organic matter content in this season relative to that of GCS over the study period. However, the high sediment input in clays and silts forms by this river [15] would lead to a relatively high presence of organic matter in these sediments over the period from October 2018 to September 2019 compared to that observed in these substrates over the period from April 2014 to March 2015. The significant anoxia phenomena linked to the strong degradation and mineralization of these organic matter [40], the anoxic nature of this river [15,39] and the dominance of these superficial sediments by the fine fraction would cause its strong reducing character over the period from October 2018 to September 2019, which has been the most important over this annual period and over the study period. These anoxia phenomena would have been less intense in this season over the period from April 2014 to March 2015 due to the relatively low organic matter content of these sediments compared to that of GCS over this annual period and in this season over the period from October 2018 to September 2019 on the one hand, and their dominance by

sands and rudites, on the other. This would be shown by the decrease in their reducing character from GCS to FS over the period from April 2014 to March 2015, and low compared to that determined in this season over the period from October 2018 to September 2019.

In SCS, the Comoé River, at the start of the low-water season, would have its influence which would diminish considerably on this estuary. Also, the cold marine waters, resulting from the small upwelling of Atlantic Ocean in Guinea Gulf in front of Abidjan district, would influence the hydrochemistry of this channel in this season, but with low amplitude compared to that of the cold marine waters resulting from the great upwelling of this ocean in GCS. The simultaneous presence of these waters would confer a brackish character to the waters of this estuary in this season [15]. The simultaneous effects of these waters in this aquatic ecosystem would result in pH increase of these sediments in this season relative to that obtained in GCS over each annual study period. Their pH, obtained in this season, have been among the highest determined, over the study period. The circulation of water induced by these waters would also have favored the formation of muddy plugs, especially over the period from October 2018 to September 2019 when they would have been the most important over this annual period and over the study period. This fact would be illustrated by the growth of the moisture content of these surface sediments in this season relative to that of GCS over each annual period and, in particular their very high moisture content over the period from October 2018 to September 2019. As in previous seasons, this could be explained by the dominance of these sediments by silts and clays [37,38], brought simultaneously by these waters in this estuary in this season over the period from October 2018 to September 2019. As in FS, the Comoé river would enrich these superficial sediments few in organic matter. This would also be the case for these cold marine waters in this season over the study period. This would be shown by the drop in their organic matter content, which presenting practically the same value in this season over each annual period relative to that determined in FS. Their organic matter contents have been among the lowest over the study period. The degradation of this organic matter, with the anoxia phenomena [40], would be reduced by the drop in temperature induced by the presence of the cold marine waters [51,52]. These processes would result in a decrease in their

reducing character, also presenting approximately the same value over each annual period, in this season compared to that determined in FS. The very high presence of silts and clays in these superficial sediments in this season over the period from October 2018 to September 2019 would also be responsible for their very high salinity, which has been also the most important over this annual period and over the study period. The opposite effect was observed with these entities over the period from April 2014 to March 2015, which having their particle size distribution highly dominated by sands and rudites, presented the lowest salinity in this season over this annual period, and also over the study period [41,42]. The relatively high presence of sands in these superficial sediments in this season over these two annual study periods would have resulted in their high conductivity [43], the highest in each of these annual periods. This would have been especially so for these sediments in this season over the period from April 2014 to March 2015.

4. CONCLUSION

This present study has shown that the climate change combined with the recent hydromorphological modification of this estuary has led to a modification of its hydrochemistry. This is reflected in part by the modification of some physical and chemical characteristics of its surface sediments, in particular their particle size distribution, salinity, conductivity, organic matter and moisture contents. This would have an impact on its biodiversity, particularly on its benthic fauna. As a result, this study therefore deserves to be deepened by extending it to the effects of these phenomena on some forms of chemical pollution of this estuary, and the likely ecological risks which result.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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