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Abstract

This study, based on five years of monthly in situ data collected from 2018 to 2022, examines the seasonal and interannual fluctuations of suspended particulate matter (SPM) concentration in Nokoué Lagoon, Benin. Seasonally, SPM exhibits significant variations primarily influenced by changes in river discharge. During low-flow periods (December to May), SPM concentrations are relatively low (<15 mg L-1) throughout the lagoon. During this time, slight temporal variations are correlated with wind energy and likely associated with wind-induced resuspension of sediments. This is confirmed by slightly higher concentrations of SPM in the bottom layers compared to the surface. Resuspension appears to be lower in the west than in the east, likely due to the increased presence of *acadjas* (brush parks) in the west, reducing fetch and wind intensity, thus decreasing resuspension. At the onset of the river flood period (July-August), associated with the West African monsoon, increased river flow generates a significant turbid plume extending from the northeast of the lagoon to the Cotonou channel, connecting the lagoon to the Atlantic Ocean. SPM levels then increase considerably (>100 mg L^{-1}), with a pronounced SPM gradient from the western to eastern regions of the lagoon. The less dense freshwater laden with sediment from the rivers flows over the denser saline water of the lagoon, leading to slightly higher SPM concentrations in the surface layers. Between September and November, SPM concentration gradually decreases as river flows reach their peak values. Thus, on a seasonal scale, the relationships between SPM and river discharge show a temporal lag, resulting in a clockwise hysteresis cycle. This is explained by the early mobilization of fine sediments during rising river flows, followed by reduced sediment availability and dilution effects as the flood peaks. On an interannual scale, SPM variations are relatively low with slight temporal shifts observed in the formation and expansion of the turbid plume and peak SPM levels. The total SPM mass in the

lagoon ranges from 0.2 to 0.3×10^4 tonnes during low-flow periods to $20\text{-}30\times10^4$ tonnes at the onset of flooding. We also discuss uncertainties associated with SPM determination, estimated at approximately 5-15%. This study leverages a unique database in West Africa and provides valuable insights into the hydro-sedimentary dynamics of Nokoué Lagoon.

Keywords: Suspended particulate matter; seasonal and interannual variability; lagoon; Nokoué; resuspension; sediments.

1. Introduction

Coastal lagoons, encompassing approximately 13% of the world's coastline (Barnes, 1980) are characterized by pronounced variations in their physical, biogeochemical, and biological parameters. Lagoons, acting as transitional zones between the land and the ocean, generally exhibit a dynamic behavior driven by the interplay of freshwater and saltwater exchanges. Being among the most productive ecosystems globally, they provide vital ecosystem services that cater to diverse activities such as aquaculture, fishing, recreation, tourism, sand extraction, and transportation (Macintosh, 1994; Alongi, 1998; Spurgeon, 1999 Pérez-Ruzafa et al., 2012). The effective management of these aquatic systems relies upon an in-depth understanding of their functioning.

The concentration of suspended particulate matter (SPM) in the water column is an important environmental parameter influencing the functioning of coastal lagoons. Spanning a size range from a few µm to several hundred µm, SPM exerts a significant influence on biogeochemical cycles and water quality through various processes. On one hand, both inorganic and organic SPM attenuate light, resulting in reduced photosynthesis and subsequent oxygen production, thereby impacting primary production and biological activity (Davies-Colley and Smith, 2001). On the

other hand, SPM also affects water quality by serving as sites for aggregation and adsorption of pollutants onto their surfaces (Etemad-Shahidi et al., 2010; Hossain et al., 2004). Consequently, these adsorbed pollutants can accumulate within the trophic chain, particularly through filter-feeding organisms, while also being transported and subsequently deposited as sediments in sediment reservoirs.

Transport and deposition of suspended particulate matter (SPM) play a critical role in facilitating sediment redistribution among watersheds, lagoon environments, and the marine ecosystem (Kari et al., 2017; Ouillon, 2018). The inherent variability in SPM inputs contributes to morphodynamic changes observed in diverse environments such as rivers, lagoons, barrier beaches, or deltas, thereby influencing flood control, irrigation, navigation, aquaculture and aquatic habitats (Poff et al., 1997; Barbier et al., 2011; Weston et al., 2014). Monitoring, analyzing, and understanding spatial and temporal variability of SPM is an important step towards a holistic quantification of sediment budgets in order to ensure the sustainable management of coastal and inland water ecosystems.

Variations in suspended particulate matter (SPM) concentrations within a lagoon's water column are influenced by a range of factors, encompassing internal and external forcings. Internally, these variations stem from phenomena such as shoreline runoff caused by rainfall or the resuspension of sediments due to wind-induced currents and waves. External influences are the transportation of particles eroded from the watershed, found in the riverbed and on its banks. Furthermore, oceanic factors, particularly tides, also contribute to SPM variations. Collectively, these diverse forcings contribute to the complex dynamics of SPM concentrations within a lagoon's water column.

Along West Africa, between Ivory Coast and Nigeria, the coastal zone comprises a series of lagoons (Allersma and Tilmans, 1993; Lalèyè et al., 2007; Adite and Winemiller, 1997; Adite et al., 2013). Among these lagoons, Nokoué lagoon, Benin's largest water body (covering ca. 150 km^2), is of significant ecological and socio-economic importance. Designated as a site of international importance under the Ramsar Convention on wetlands, this lagoon is regarded as one of West Africa's most biologically productive ecosystems, supplying 70% of Benin's continental fisheries (Lalèyè et al., 2007). It is flanked by three major urban centers (Cotonou, Abomey-Calavi, and Sémè Podji), with a combined population of over 1.5 million people. Moreover, it is home to West Africa's largest lakeside villages, accommodating 60,000 individuals living in stilt houses (Principaud, 1995), including approximately 15,000 fishermen. The local communities rely on this water body not only for fishing, capturing around 15,000 tonnes of fish annually (Principaud, 1995), but also for domestic water supply, agriculture, market gardening, livestock breeding, etc. However, in addition to its inherent natural variability (e.g., Djihouessi and Aina, 2018; Chaigneau et al., 2022; 2023; Okpeitcha et al., 2022), Nokoué lagoon faces substantial challenges due to extensive anthropogenic pressures, resulting in declining water quality (Adjahouinou et al., 2012; 2014; Aina et al., 2012a; 2012b), increasing eutrophication (Negusse and Bowen, 2010; Mama et al., 2011), and progressive sediment accumulation (Djihouessi et al., 2017).

Over the course of several decades, numerous studies have been conducted to elucidate the general hydro-ecological functioning of Nokoué lagoon (see Djihouessi and Aina, 2018 for a review). However, these investigations primarily rely on sporadic observations. Nevertheless, the global comprehension of sediment dynamics and SPM in the lagoon remains limited. Regarding sediment composition, more than two decades ago, the lagoon was predominantly characterized by silt (composed of very fine particles) in its western and southeastern regions, while its eastern

part consisted of sand (composed of fine and medium grains) (Gadel and Texier, 1986; Adounvo, 2001). In the water column, based on five field campaigns conducted in 2015, Zandagba et al. (2016a) demonstrated that water turbidity and SPM concentrations were elevated in the eastern part of the lagoon, peaking in September during the flood season. Although this work provides preliminary insights into the nature of surface sediments and the variability of SPM in Nokoué lagoon, it is constrained in terms of temporal and spatial coverage, not allowing a full understanding of the underlying physical mechanisms driving the observed variability. Since the end of 2017, a multidisciplinary observational program has been implemented in Nokoué lagoon, enabling systematic and continuous data collection to enhance our understanding of this ecosystem (e.g., Chaigneau et al., 2022; Okpeitcha et al., 2022; Morel et al., 2022; Chaigneau et al., 2023). The objective of our study is to leverage this extensive database, comprising 60 monthly field campaigns, i) to describe the spatial distributions of sediments, SPM, and their organic (Particulate Organic Matter, POM) and inorganic (Particulate Inorganic Matter, PIM) fractions, and ii) to investigate the seasonal and interannual variations of SPM in the lagoon while elucidating the driving factors responsible for these observed fluctuations.

2. Data and methods

2.1. Study area

Nokoué lagoon, situated between 6°21'N and 6°30'N latitude and 2°21'E and 2°33'E longitude, has an average depth of 1.3 m and encompasses an approximate area of 150 km² at low flow (Chaigneau et al., 2022; Fig.1c). It stretches around 20 km from east to west and 11 km from south to north, and it is connected to the Atlantic Ocean through the Cotonou channel in its southern section (4.6 km long and 300 m wide), as well as to the Porto-Novo lagoon in its eastern part via

the Totchè channel (4.5 km long) (Fig. 1c). Along its northern shoreline, the two main rivers flow into the lagoon: the Sô River, with a length of 85 km draining a small watershed of approximately 1000 km², and the 500 km long Ouémé River draining a substantial watershed of roughly 50,000 km² to the north of the lagoon (Le Barbé et al., 1993; Djihouessi et al., 2017).

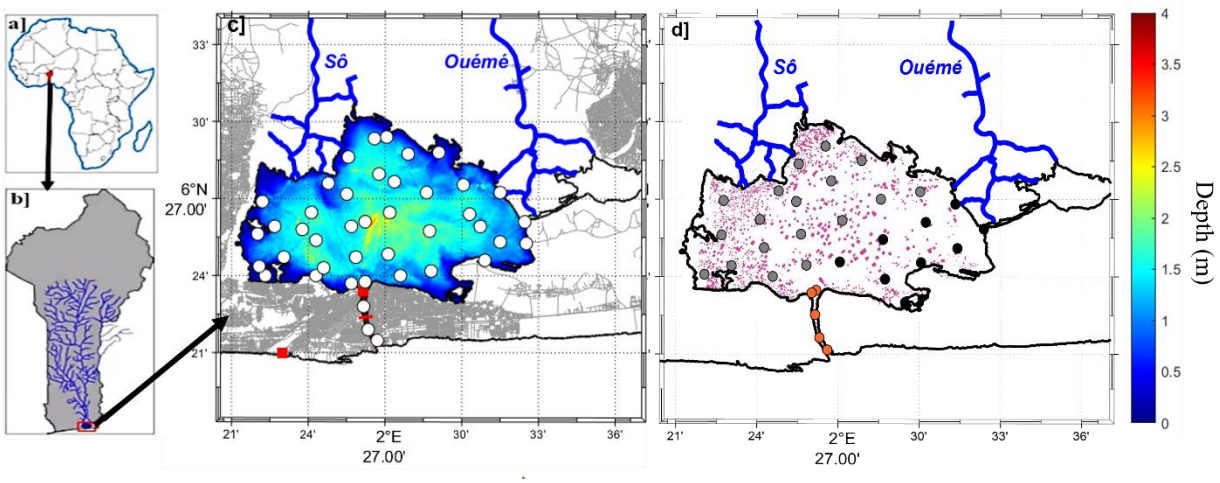

Fig. 1: *Nokoué lagoon (Benin) and hydrographic stations investigated between January 2018 and December 2022. a] Location of Benin in West Africa. b] Hydrographic network of the Sô and Ouémé watersheds. c] Bathymetry of the lagoon during low-flow period (in color) together with the locations of the sediment samples collected to study the grain size and sediment composition and physical forcing stations. The white dots represent the 42 sediment sampling stations. The red squares represent the water level station south of the lagoon and the meteorological station at Cotonou airport. The ADCP section is depicted as a red line at the center of the Cotonou channel. d] Location of the 31 monthly SPM and CTD stations; stations shown in orange, black and gray represent the Cotonou channel, the eastern zone and the central/western zone of the lagoon, respectively (see Section III.3); The pink background map illustrates the distribution of acadjas identified by Chaffra et al. (2020).*

The Ouémé watershed, which represents the primary freshwater and sediment source for Nokoué lagoon lies in two distinct climatic zones. In the northern region, a tropical climate prevails with a rainy season extending from May to October, peaking in August-September (Mama et al.,

2011; Djihouessi et al., 2017; Djihouessi and Aina, 2018). On the other hand, the southern Ouémé delta, where the river enters the lagoon, has a sub-equatorial climate characterized by two rainy seasons: a long rainy season from mid-March to mid-July and a short rainy season in September to October (Mama et al., 2011; Djihouessi et al., 2017; Djihouessi and Aina, 2018).

The average annual rainfall ranges from 960 mm in the northern part of the Ouémé basin to 1340 mm in the southern part (Djihouessi et al., 2017). Under the influence of these hydrological patterns, Nokoué lagoon exhibits three distinct hydrological periods (Chaigneau et al., 2022; Okpeitcha et al., 2022; Morel et al., 2022): a flood period from September to November, characterized by a water level rise of approximately 90 cm and nearly zero salinity; a low-flow period from December to mid-May, during which the lagoon experiences minimal water levels and maximum salinity (S ~ 25); and an intermediate period from June to August, where the water level slightly increases and salinity decreases due to heavy local rainfall in southern Benin (Texier et al., 1979; Le Barbé et al., 1993; Gnohossou, 2006).

The dynamics of Nokoué lagoon is further influenced by the prevailing monsoon winds, which result from the deflection of the equatorial trade winds (Eltahir and Gong, 1996). These dominant warm and humid winds blow consistently from the southwest throughout the year, with an average speed of 3.5 m s^{-1} (Colleuil and Texier, 1987). During December and January, the region experiences episodes of the Harmattan wind, a relatively cold and dry wind originating from the northeast. Both trade winds and Harmattan winds can have, through the generation of wind-induced currents or waves, a notable impact on sediment resuspension, consequently affecting the concentration of SPM in the Nokoué lagoon.

Nokoué lagoon features an abundance of artificial fishing parks called *acadjas*, made up of a substantial quantity of brushwood. *Acadjas* serve as sanctuaries and breeding grounds for aquatic species (Villanueva et al., 2006). According to *Chaffra et al.* (2020), *acadjas* presently cover an area of 16.5 km^2, representing approximately 16% of the lagoon's surface during the dry season, with a higher concentration in the western and northwestern parts of the lagoon (Figure 1d). The decomposition of organic matter from these *acadjas* can lead to oxygen depletion, causing the lagoon's waters to become less oxygenated, altering the composition of suspended solids and sediments, and potentially contributing to the lagoon's silting due to reduction in water flow in and around the *acadjas* (Niyonkuru and Lalèyè, 2010; Mama et al., 2011; Djihouessi et al., 2017).

2.2. Turbidity and suspended particulate matter data

Between January 2018 and December 2022, a total of 60 monthly campaigns, each lasting 2 days, were conducted in the Nokoué lagoon. During each campaign, 31 vertical turbidity profiles were collected (Fig. 1d) using a Valeport MIDAS CTD+ 300 probe equipped with a turbidity sensor, with a vertical resolution of 0.1 dbar (~10 cm).

From April 2019 to December 2021, SPM concentrations were determined at each station following a commonly applied protocol (e.g., Neukermans et al., 2012; Moreina et al., 2013). At each station, a water sample was collected from the surface using a bucket for filtering. The volume of water filtered varied between 20 and 1000 ml depending on the turbidity level. Two types of filters were used for analysis: nuclepore polycarbonate (PC) membranes with a porosity of 0.4 µm for total SPM content, and GF/F glass fiber filters with a porosity of 0.7 µm to estimate the organic (POM) and inorganic (PIM) fractions of SPM. For each monthly campaign, the SPM data obtained from the 31 stations were spatially interpolated onto a regular grid with a resolution of

approximately 100 m × 100 m, using an objective interpolation scheme (Bretherton et al., 1976; McIntosh, 1990; Wong et al., 2003).

2.3. Determination of SPM from turbidity

Fig. 2 illustrates the relationship between surface turbidity and SPM distribution, based on 971 pairs of observations gathered from April 2019 to December 2021. The distribution reveals a significant linear correlation ($p<0.001$) described by the following equation:

$$SPM = 0.86 \times Turbidity + 4.3$$

where Turbidity is measured in FTU (Formazin Turbidity Units) and SPM in mg L^{-1}. This correlation exhibits a strong correlation coefficient ($r = 0.97$) and a root mean square error (RMSE) of 9 mg L^{-1}. Consequently, this relationship enables the reconstruction of SPM levels in the lagoon using turbidity data collected by CTD over an extended period (2018-2022). This reconstruction facilitates the examination of seasonal and interannual variations in SPM within the lagoon.

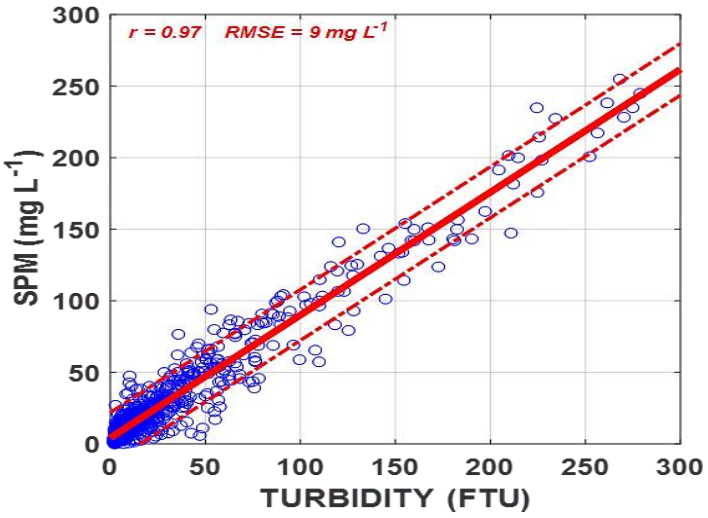

Fig. 2: Relationship between SPM (measured in situ) and turbidity (measured by an optical sensor), obtained from 971 pairs of measurements. The solid red line corresponds to the linear relationship, while the dashed lines delimit

the 95% confidence interval. The correlation coefficient (r) and root mean square error (RMSE) are also provided in red.

2.4. Sedimentological data

In February and April 2019, two campaigns were conducted to specifically determine the composition and grain size of sediment within the lagoon, covering a total of 42 stations (Fig. 1c). At each station, three surface sediment samples were extracted using an Ekman grab sampler. These samples were combined, thoroughly mixed, and a 500 g portion was retained for subsequent laboratory analysis. After drying the sediment at 60°C for 48 hours, the weight of the dry sediment was recorded, and the fine fraction was separated through wet sieving using a 45 µm mesh sieve. The remaining sediment (>45 µm) was then dried and weighed to determine the mass of the finest fraction (<45 µm) by calculating the difference in mass.

The sediment was further sieved using a vibrating column equipped with eight sieves (with mesh sizes of 4 mm, 2 mm, 1 mm, 500 µm, 250 µm, 125 µm, 63 µm, and 45 µm) for a duration of 15 minutes. The sediment retained on each sieve was weighed to determine the dry mass for each of the eight particle size classes. To determine the proportion of sediment in each particle size class at each station, the mass of each class was divided by the total dry mass. According to Wenworth's (1922) classification, three primary particle size classes were defined: very fine clays and silts below 45 µm, fine to coarse silts ranging between 45 µm and 63 µm, and very fine to fine sands ranging from 63 µm to 250 µm. The sediment fraction corresponding to these three classes was assessed at the 42 sampling stations and subsequently spatially interpolated using the same

objective interpolation scheme employed for the SPM and turbidity maps (Bretherton et al., 1976; McIntosh, 1990; Wong et al., 2003).

2.5. River flow and wind speed

To explore the drivers of the observed spatio-temporal variations in SPM concentration within the lagoon (as discussed in Section III), two key parameters were taken into consideration: (1) river flow, responsible for transporting SPM from catchments, and (2) wind, which generates waves and currents that can resuspend surface sediments in the water column through bottom shear stress (Maxam & Webber, 2010; Llebot et al., 2014; Jalil et al., 2019).

To obtain the time series of total river flows discharging into the lagoon for the period 2018-2022, water levels were continuously and frequently measured (every 20 minutes) at the mouth of the Cotonou channel and Nokoué Lagoon (Fig. 1c) using an immersed pressure sensor (Onset HOBO U20L-01; Chaigneau et al., 2022), and converted to water flow using a rating curve obtained from 33 pairs of simultaneous water level and flow measurements taken at different times of the year and covering all hydrological seasons (see Supplementary Material). The net tidally-averaged outflow from the Cotonou channel represent approximately the total river inflow entering the lagoon from the Sô et Ouémé watersheds (Supplementary Material; see also Morel et al. (2022)). It is important to note that rating curves can contain large errors, that can be due to several facts which are well describe in the supplementary material. In order to analyze the relationship between river inflow and SPM concentration, for each month between 2018 and 2022, the reconstructed flow rates are averaged over a 3-day period (prior and during data collection).

A wind time series, including direction and intensity at 10-m height was obtained from the National Meteorological Agency of Benin (METEO-BENIN: https://meteobenin.bj/) at Cotonou airport (red dot in Fig. 1c) at daily frequency for the study period of 2018-2022. Similar to flow

rates, these wind data were averaged over a 3-day period. Sensitivity tests were conducted, indicating that variations of this time window, ranging from 1 to 5 days prior to the campaign, had no significant impact on the obtained results. To investigate the potential influence of wind on sediment resuspension, the relationship between SPM and the square of wind intensity will be examined. This approach is employed because shear stresses at the bottom are directly proportional to wind stress, which in turn is proportional to the square of the wind intensity (Maxam & Webber, 2010; Llebot et al., 2014; Jalil et al., 2018).

3. Results

3.1. Lagoon-scale characterization of sediments and suspended particulate matter (SPM)

3.1.1. Sediment distribution

Fig. 3 shows the spatial distribution of sediments for the 3 particle size classes investigated (Section II.4). As mentioned in Section II.4, these data were collected during the 2019 low-flow period. Clay and very fine silts (<45 µm) are predominantly present in the western and southeastern zones (Fig. 3a); fine to coarse silts (45-63 µm) are mainly found in the northeast and center of the lagoon (Fig. 3b), while fine sands (63-250 µm) are dominant in the east and north, as well as around the Cotonou channel (Fig. 3c).

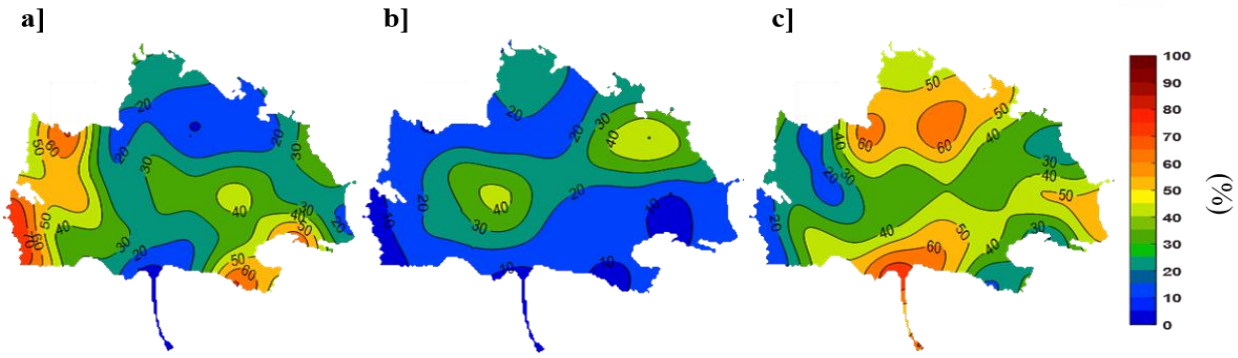

Fig. 3: Spatial distribution of sediment mass fraction (in %) for the 3 main particle size classes. a] clay and very fine silt (<45 µm.) b] fine to coarse silts (45-63 µm). c] very fine to fine sands (63-250 µm).

3.1.2. Average suspended particulate matter distribution

SPM concentrations and the fractions of PIM and POM have notable spatial patterns in their averaged distribution (average from April 2019 to December 2021) (Fig. 4). Surface and bottom SPM concentrations exhibit significant variation, ranging from 12 to 75 mg L^{-1}. The highest values are observed in the eastern region, where a turbid plume extends between the mouth of the Ouémé River and the Cotonou channel. Conversely, the lowest SPM values are found in the central and western parts of the lagoon. The vertical differences in SPM concentration remain relatively small, ranging from 0 to 10 mg L^{-1} (Fig. 4a-b).

The average POM fraction shows strong variability, ranging from 25% to 60% (Fig. 4c). The maximum values are observed in the western and northern areas, while the minimum values are found between the eastern region and the Cotonou channel. Conversely, the PIM fraction exhibits an inverse relationship to that of POM, reaching its maximum (~75%) towards the east, near the mouth of the Ouémé River, and its minimum (<50%) in the western and northern regions (Fig. 4d).

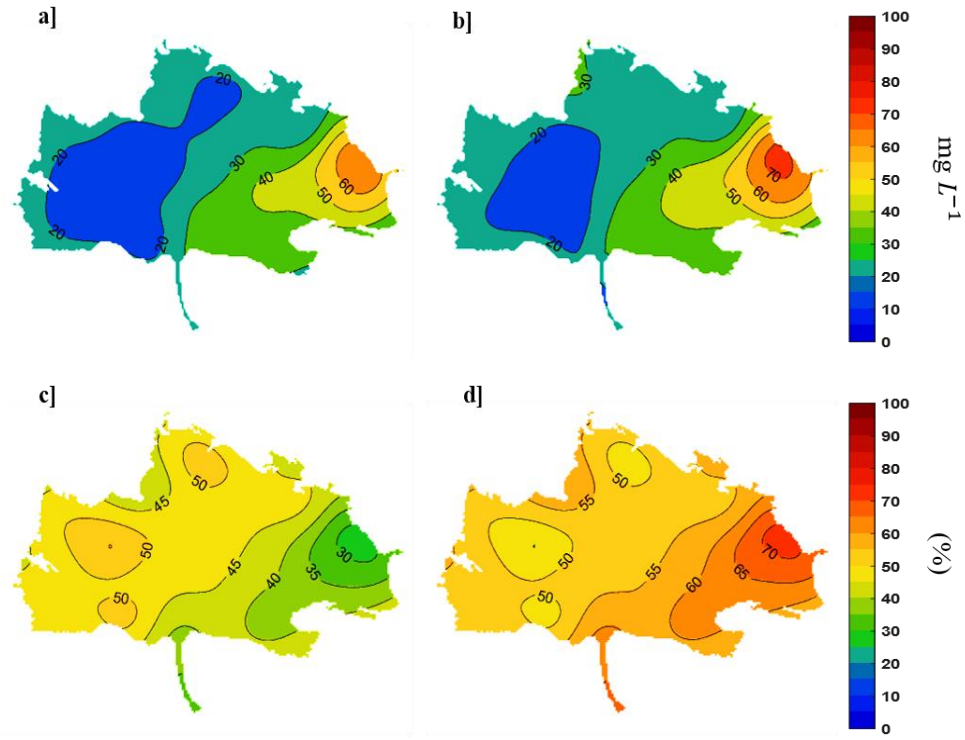

Fig. 4: Average spatial distribution (April 2019-December 2021) of suspended solids (SPM in mg L-1) and organic (POM, in %) and inorganic (PIM, in %) fractions. a] SPM at surface. b] SPM at bottom. c] POM at surface. d] PIM at surface.

3.2. Seasonal and interannual variations in SPM

3.2.1. Seasonal variation

Fig. 5 illustrates the average seasonal variation in SPM concentrations observed between 2018 and 2022 and reconstructed from turbidity measurements. During the low-flow period from January to May (Fig. 5a), the SPM concentration remains relatively low throughout the lagoon, ranging from 5 to 30 mg L^{-1}. In June, SPM concentration starts to increase at the Ouémé mouth, and a turbid plume extending from the Ouémé to the Cotonou channel becomes visible between July and September. During this period, relatively high SPM values (50-90 mg L^{-1}) are also observed around the Sô area in the northwest of the lagoon. The maximum values are reached in

August, with an increasing gradient from west (30 mg L^{-1}) to east (200 mg L^{-1}). From October to December, the SPM concentration significantly decreases (10-60 mg L^{-1}), reaching its minimum in January (Fig. 5a).

Fig.5b depicts the monthly lagoon-averaged SPM concentrations, ranging from 10 mg L^{-1} during low-flow periods to 70 mg L^{-1} in August. The high standard deviations observed between July and September indicate the pronounced spatial contrasts in SPM concentrations observed during this period in Figure 5a. As further discussed in Section 4.1., during low-flow periods, the mean SPM concentration at the bottom slightly exceeds that at the surface. However, in July and August, the SPM concentrations at the surface are slightly higher than those at the bottom.

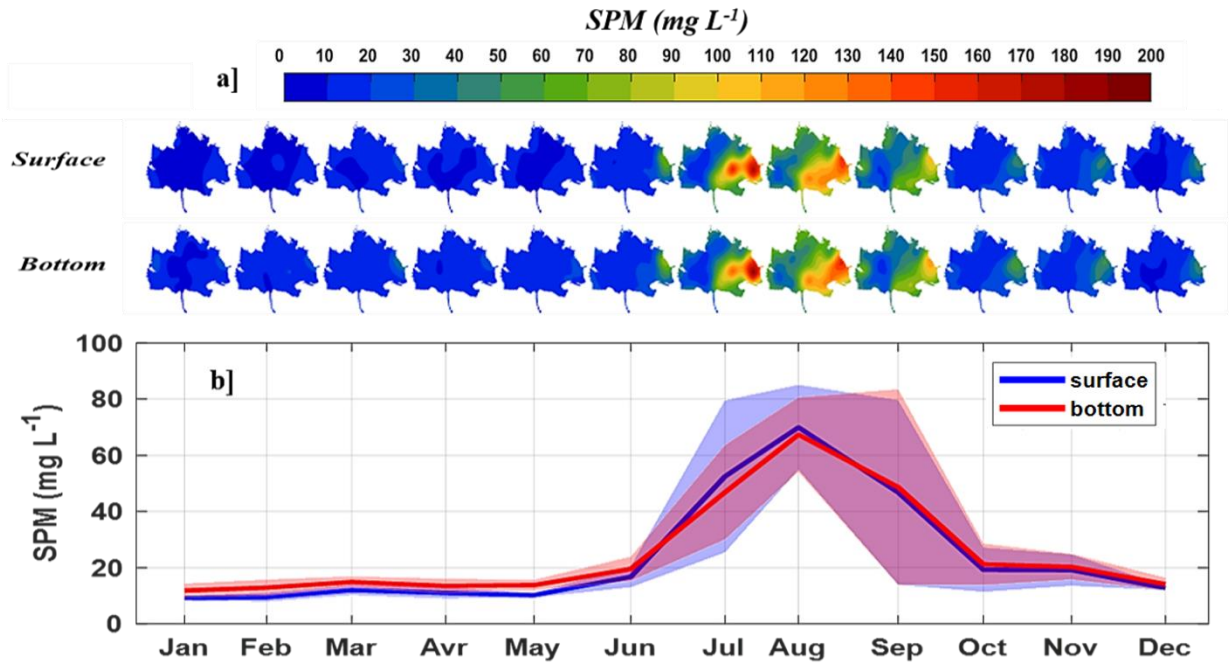

Fig. 5: *Average seasonal cycle (2018-2022) of the SPM. a] Monthly spatial distribution at the surface (upper panel) and at the bottom (lower panel); climatological months are indicated at the bottom of b]. b] Average monthly temporal evolution of the SPM in Nokoué lagoon.*

3.2.2. Interannual variation

Interannual variations in surface SPM are shown on a monthly scale in Fig. 6a. The maximum SPM is systematically observed between July and september with some variability across the years resulting from interannual variations in river inflow. At the end of the flood period, the distribution and intensity of the Ouémé plume to the east differs from year to year: in December 2018 and 2019, SPMs at the mouth of the Ouémé are much lower than in 2020-2022.

Fig. 6b shows that, on average in the lagoon, the SPM peak observed in July-August is higher in 2018 and 2022 (90-110 mg L^{-1}) than in 2019-2021 (60-70 mg L^{-1}). We also note that during the SPM peaks in 2020 and 2021, concentrations were higher at the surface.

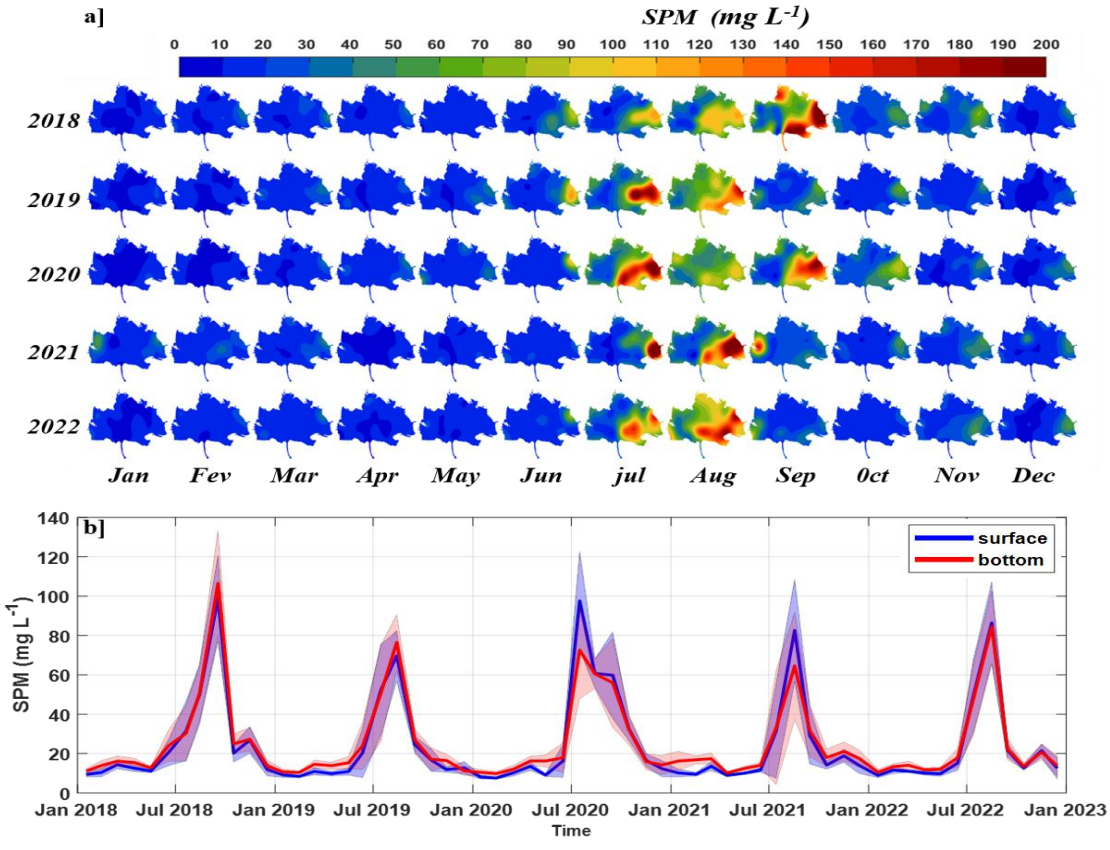

Fig. 6: Monthly interannual variation in SPM. a] Monthly spatial surface distribution. b] Average monthly temporal evolution in Nokoué lagoon.

3.3. Relationship between suspended matter and environmental drivers (river inflow and wind speed)

The spatial distributions of SPM and their temporal variability (Figs. 4 to 6) suggest that the study area can be divided into 3 sub-regions: the turbid plume zone in the east (black dots on Fig. 1d), the zone of relatively low SPM concentration in the center and west (gray dots on Fig. 1d), and the Cotonou channel (red dots on Fig. 1d) corresponding to the lagoon outlet. It is important to note that a clustering analysis, which groups stations with similar SPM variations, was also conducted and yielded the same grouping (not shown). To determine the main drivers of SPM variability in the lagoon, we examined the temporal evolution of SPM in the 3 defined zones and their relationship with two key factors: river discharge and wind.

3.3.1. Impact of river inflow on SPM seasonal variability

Fig. 7a presents the average seasonal cycle of SPM in the 3 predefined regions of the lagoon. In the eastern plume area, SPM concentrations reach an average of 125 mg L^{-1} in August, while in the western part of the lagoon, they are only 50 mg L^{-1} (Fig. 7a). The Cotonou channel exhibits an intermediate peak of 80 mg L^{-1}. From October to December, the eastern part of the lagoon has a higher sediment load (~30 mg L^{-1}) than the western zone or the Cotonou channel (<20 mg L^{-1}). Between January and May, the 3 zones show relatively similar SPM levels, ranging from 10 to 20 mg L^{-1}.

Comparing these variations with the seasonal cycle of river inflow (Fig. 7a) reveals four distinct phases. The first period, from January to May, corresponds to the low-water phase, during which both the SPM concentrations (<20 mg L^{-1}) in the lagoon and the river flow (~50 m^3 s^{-1}) are low. The second phase, from June to August, coincides with the main rainy season in southern Benin

and the onset of the flooding period. During this period, river flows slightly increase (from 50 to 150 $m^3 s^{-1}$), while SPM begin to rise in the east in June and subsequently increase sharply throughout the lagoon in July and August. The third phase, from August to October, represents the peak flooding phase, characterized by an average river flow of 900 $m^3 s^{-1}$, while SPM levels decrease significantly (<40 mg L^{-1}). The last phase, in November and December, corresponds to the recession phase, with considerable reduction in flows and slight decline in SPM levels (around 10 mg L^{-1}). These relationships between SPM and river flow result in a clockwise hysteresis cycle (Fig. 7b), characterized by a SPM peak occurring prior to the peak of maximum flow (Fig. 7a). As further discussed in Section 4.1, the early mobilization of fine sediment during rising river flows, followed by reduced sediment availability and dilution effects as the flood peaks.

Fig. 7c illustrates the interannual variation in SPM in the 3 predefined regions of the lagoon. The eastern zone consistently exhibits higher SPM levels compared to the west and the Cotonou channel. The average maximum SPM values, observed at the head of the flood 1 to 3 months before maximum flows, range between 130 mg L^{-1} and 180 mg L^{-1} in the eastern zone, depending on the year. In the west, the values fluctuate between 40 mg L^{-1} and 80 mg L^{-1}, while in the Cotonou channel, they range between 50 mg L^{-1} and 120 mg L^{-1}. During the low-flow period, SPM concentrations display slight interannual variations of around 10-25 mg L^{-1} in the eastern zone and 5-15 mg L^{-1} in the western zone and the Cotonou channel. Between 2019 and 2021, one-month lag can be observed in SPM peaks between zones, possibly attributed to the propagation time of the turbid plume from the East zone, where it forms, to the Central and Cotonou Channel zones, where it gradually expands (see also Fig. 6). Finally, a noteworthy observation is the occurrence of a double SPM peak exclusively in the east during July and September 2020, which does not coincide

with any distinct river flow pattern. Similarly, it is worth noting that the intensity of SPM peaks does not show a direct temporal coincidence with the maximum intensity of river flows.

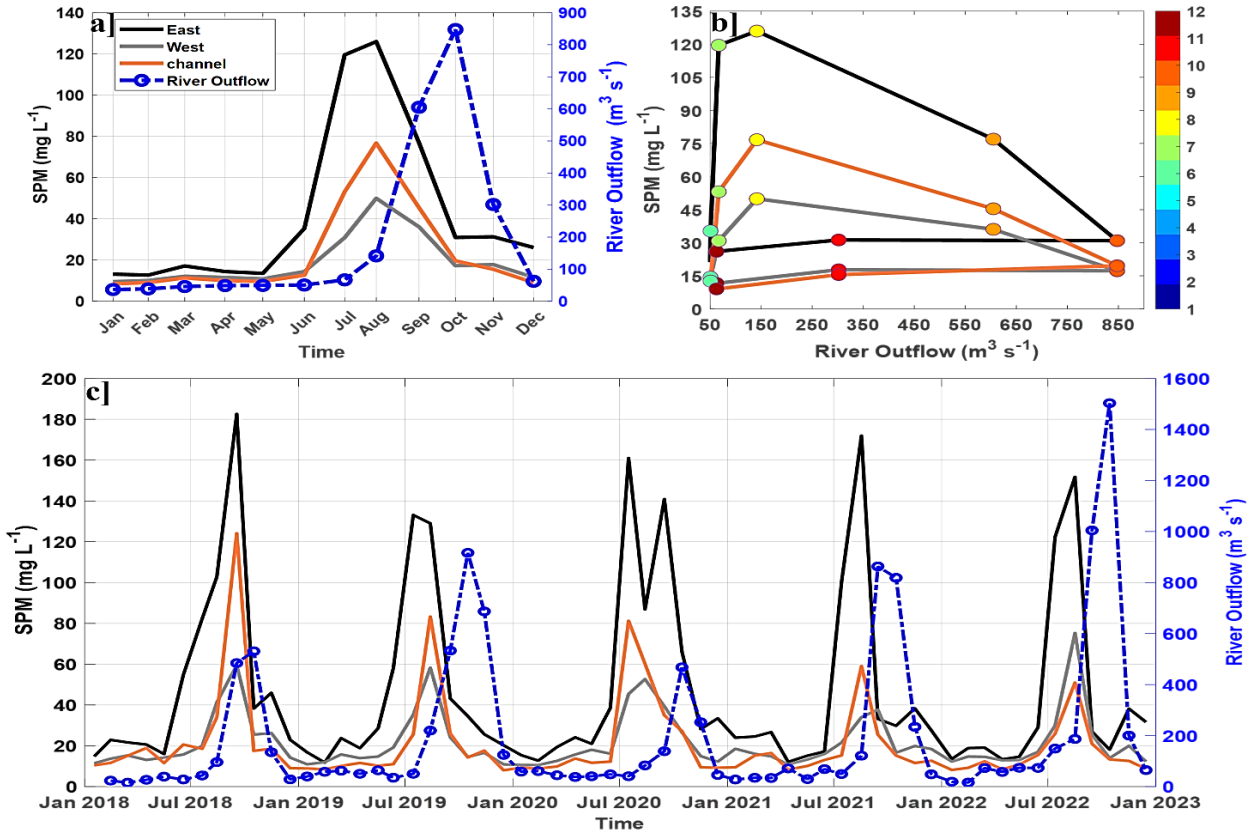

Fig. 7: Seasonal and interannual variations (2018-2022) in SPM and the sum of river discharges from the Sô and Ouémé rivers entering the lagoon. a] Average seasonal cycle (2018-2022) of SPM in the 3 sub-regions and discharges. b] Relationship between SPM and river discharges.

3.3.2. Impact of wind and sediment resuspension

Both wind energy and fetch, representing the uninterrupted distance over water that the wind blows, play a crucial role in determining the size and energy of waves. Additionally, factors such as the depth of water and sediment characteristics further modulate the intensity of sediment resuspension. While the most significant seasonal fluctuations in SPM are primarily driven by river inflow during high-flow periods, the relatively minor variations observed during low-flow

periods do not directly correspond to the hydrological regime of the rivers. We thus hypothesize that during this season (January to May) wind-induced processes may be responsible for the observed SPM variations through sediment resuspension.

The resuspension of sediment in the water column during low-flow period is also likely supported by Figures 5 and 6, showing a higher concentration of SPM in the bottom layer. Unfortunately, we lack current or wave data to thoroughly study the processes involved in the resuspension. However, Figure 8 reveals a notable finding: in all 3 sub-regions, a significant linear correlation can be observed between SPM concentrations during low-flow periods and the square of wind speed. The prevailing southwest winds are moderate, with values between 2.5 and 5.5 m s^{-1}. The variations in wind speed squared and SPM exhibit a correlation of 50-65% during low-flow periods, with the strongest correlation being observed in the Cotonou channel. This suggests that wind-induced waves and currents likely contribute to the resuspension of sediment in the water column, thereby accounting for the observed fluctuations in SPM when river flows and water levels are low. Consequently, wind-driven resuspension emerges as a significant process contributing to SPM variability during this period. It is important to note that the amount of sediment resuspended by the wind is more pronounced but not significantly (greater linear slope in Fig. 8) in the eastern part of the lagoon compared to the western part, despite the sediments being coarser (refer to Fig. 3). As further discussed in Section 4, this is likely due to the higher concentration of *acadjas* in the western part of the lagoon (Figure 1d) that decrease the intensity of the wind-induced processes in the water column.

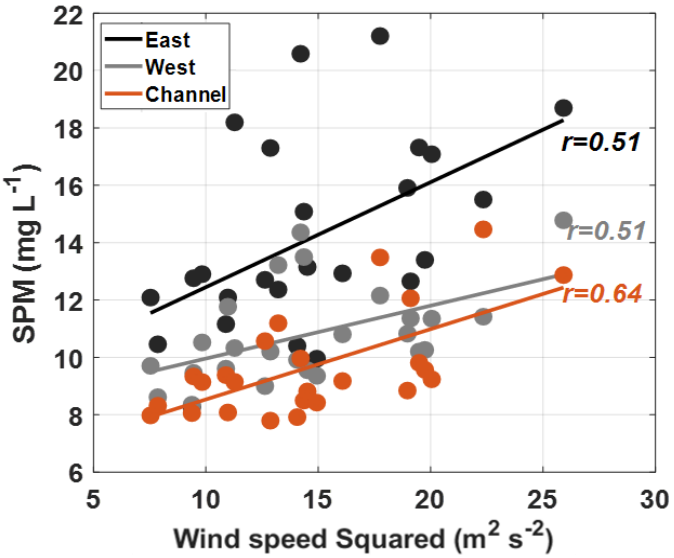

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Fig. 8: Relationship between the mean SPM concentration in each sub-region and the squared wind speed during the low-flow months (January-May) of each year (2018-2022). For each of the 3 sub-regions, a linear fit is presented along with the corresponding correlation coefficient (r). The colors black, gray and red correspond to the East, West and Cotonou Channel regions, respectively.

378 3.4. Uncertainties in SPM measurements

379 In order to quantify the uncertainties in SPM estimations, over 60 duplicate measurements of
380 SPM were conducted during campaigns carried out in different seasons and contrasting locations
381 within the lagoon, characterized by varying levels of turbidity. For each duplicate, the average
382 value of SPM from the 2 replicates ($\overline{SPM}$) is calculated, as well as the absolute difference (ΔSPM,
383 en mg L^{-1}) or relative difference ($\Delta SPM/\overline{SPM}$, en %). Similar analyses are performed for PIM and
384 POM. For all three variables (SPM, PIM et POM), the measurement differences between
385 duplicates do not significantly depend on concentration (Fig. 9a-d). Across all SPM duplicates, the
386 average difference is 1-2 mg L^{-1}, regardless of whether the measurements were obtained from

polycarbonate filters (Fig. 9a) or GF/F filters (Fig. 9b). Similarly, the uncertainties for PIM and POM are 0.7 mg L^{-1} and 1.3 mg L^{-1}, respectively (Fig. 9c-d). The relative uncertainties (in %) decrease as SPM concentrations increase (Fig. 9e-h) because, for a filtered water volume, there is greater variability in the spatial distribution of particles in less turbid sampled waters (Doxaran et al., 2012). On average, the uncertainties are approximately ~10% for SPM (regardless of filter type, Fig. 9e-f) and 15% and 9% for PIM (Fig. 9g) and POM (Fig. 9h), respectively. For SPM ranges of 0-25, 25-50, and >50 mg L^{-1}, the average relative uncertainty is 11%, 6%, and 2%, respectively, for measurements obtained with GF/F filters, and 16%, 8%, and 2%, respectively, for measurements obtained with polycarbonate filters. These values are consistent with the values of 16%, 10%, and 2% obtained by Doxaran et al. (2012) for SPM concentrations ranging from 0.04–1, 1–10, and 10–100 mg L^{-1}, respectively. Likewise, the relative uncertainties of POM and PIM measurements decrease as the concentration increases.

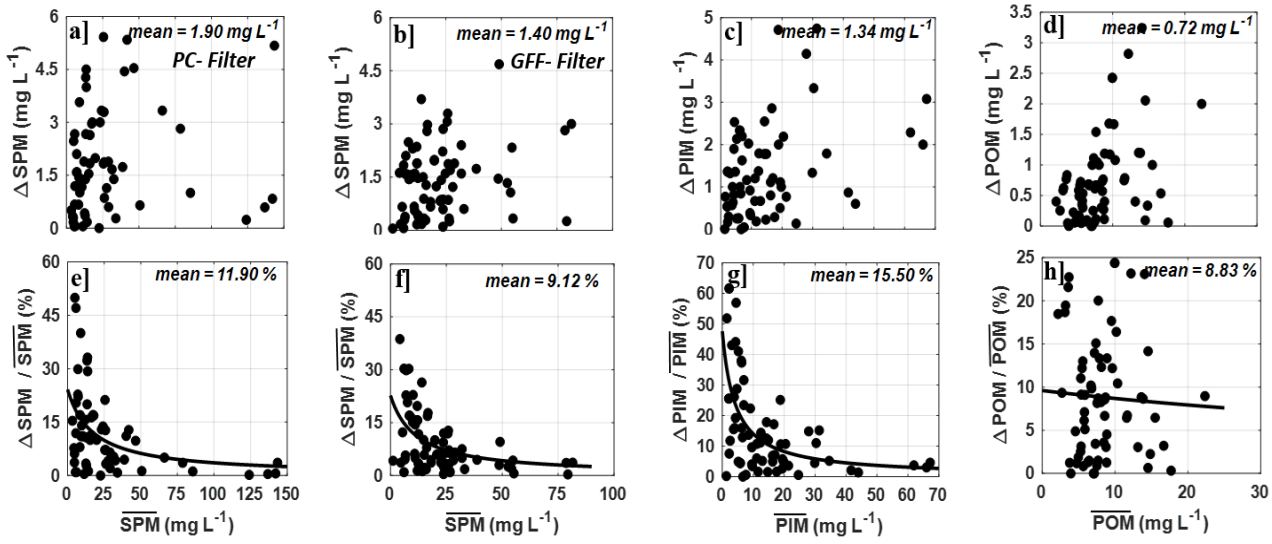

Fig. 9: Distribution of measurement uncertainty as a function of their mean values. a-d] Absolute difference (ΔSPM, ΔPIM, ΔPOM, in mg L-1) of duplicates obtained on polycarbonate filters (a]) and GF/F (b-d]). e-h] Relative

difference (in %) of duplicates obtained on polycarbonate filters (e]) and GF/F (f-h]). Black curves represent best fits to the data.

4. Discussion

4.1. Spatio-temporal variations of sediment and SPM

The surface sediments in Nokoué lagoon are primarily composed of small particles, including clay, silt, and fine sand, as depicted in Figure 3. This spatial distribution closely resembles the findings reported more than three decades ago by Gadel and Texier (1986), suggesting that the hydrodynamic conditions and sediment composition in the lagoon have remained relatively stable over time. The finest particles are predominantly located in the western and southeastern regions of the lagoon, likely a result of reduced water circulation far from river mouths and Cotonou channel as well as the high density of *acadja*s (Niyonkuru and Lalèyè, 2010; Mama et al., 2011; Djihouessi et al., 2017; Chaffra et al., 2020). These *acadjas* impede current velocity and mitigate the resuspension of particles by wind, thereby facilitating their retention and accumulation. In addition, these areas are adjacent to major urban centers and receive a significant inflow of runoff from open storm drains (Afouda et al., 2004; Hountondji et al., 2019), which can transport fine particles into the lagoon. In the western part of the lagoon, an elevated concentration of POM was observed, consistent with Texier et al. (1979). This increase can be attributed to several factors. The greater presence of *acadjas* (Fig. 1d and Chaffra et al. (2020)), along with the decomposition of aquatic vegetation, leads to the production of organic-rich particles and the deposition of peaty sediments (Gadel and Texier, 1986). Indeed, the western zone of the lagoon is known for its significant seasonal influx and rapid proliferation of water hyacinths, which become trapped in the acadjas (Mama, 2010; Mama et al., 2011; Dovonou et al., 2011; Chaffra et al., 2020). As water

levels recede and salinity increases, these hyacinths naturally decay and decompose, resulting in the enrichment of organic matter within the water column. Moreover, recent research by Chaigneau et al. (2023) has emphasized the western zone of the lagoon as a favorable environment for abundant zooplankton, which may also contribute to the observed increase in POM.

In contrast, sediments near the mouths of the rivers Sô and Ouémé and Cotonou channel are dominated by fine sands. This can be attributed to the intensified currents resulting from fluvial and tidal inputs, which effectively transport and disperse the finer particles from the seafloor. Towards the eastern region of the lagoon, the Ouémé River inflow contributes significantly to the generation of a turbid plume, extending as far as the Cotonou channel during flood periods. The sediment input and influence of the Ouémé River on SPM levels exceed that of the Sô River, presumably due to the Ouémé's drainage area being fifty times larger. Consequently, a gradient in average SPM concentration between the western and eastern sections of the lagoon is observed, consistent with previous studies on water transparency in the lagoon (Adite and Winemiller, 1997; Mama, 2010; Zandagba et al., 2016a; Djihouessi and Aina, 2018). Regarding vertical variations, SPM levels exhibit little difference between surface and bottom due to the shallow depth of the lagoon, which justified the use of surface SPM only.

On a seasonal scale, our observations reveal a prominent peak in Suspended Particulate Matter (SPM) concentrations at the onset of the flood (Fig. 7), preceding the maximum discharge. This phenomenon is characterized by a clockwise hysteresis loop in the relationship between SPM and river discharge (Fig. 7b). This pattern has also been documented for decades in other lagoons or aquatic environments (Arnbord et al., 1967; Walling & Webb, 1981; Van Sickle & Beschta, 1983; Williams, 1989; Zăvoianu, 1996; Bhutiyani, 2000; De Sutter & Verhoeven, 2001; Picouet et al., 2001; Kumar et al., 2002; Banasik et al., 2005; Baca, 2008). According to these authors, during

early heavy rainfall events and the onset of river flow, fine particles are mobilized from the riverbanks, leading to the resuspension and transport of fine particles that had settled and accumulated on the watershed bed during the previous low-water and recession season. This fine sediment rests loosely on the riverbed and is easily eroded as flows increase. Consequently, a substantial influx of SPM into the Nokoué lagoon occurs at the onset of the flood, resulting in the formation and propagation of a turbid plume between the Ouémé and Cotonou channel. After the onset of the flood, the riverbed is covered with less easily entrainable sediments before the water discharge reaches its maximum, as observed elsewhere (Arnbord et al., 1967; Walling, 1974; Wood, 1977; VanSichle and Bechta, 1983; Williams, 1989). Indeed, according to Williams (1989), early depletion or flushing of fine sediments can occur due to a limited available supply or a sustained and/or very intense flood. Therefore, as the flood reaches its peak (September-November), the availability of fine sediments decreases in the Sô and Ouémé, leading to a reduction in SPM concentrations. Additionally, a second process can be invoked: during the flood, the lagoon level rises by approximately 0.9 meters (Chaigneau et al., 2022), corresponding to a 70% increase in volume. Thus, assuming a constant sediment load, suspended solids dilute within a larger water volume, resulting in a decrease in their concentration during the flood.

During periods of low river flow, the observed variations in SPM cannot be solely attributed to flow conditions. Instead, wind-induced sediment resuspension emerges as a probable influencing factor (Fig. 8), aligning with findings from other expansive lagoons like Patos (Brazil) and Chilika (India), where wind drives SPM variations during relatively low river flows (Castelao and Moller, 2003; Kumar et al., 2016). In shallow aquatic environments, sediment resuspension is strongly influenced by wind (e.g., Jalil et al., 2019; Maxam and Weber, 2010; Llebot et al., 2014) as it generates currents and waves interacting with the bottom layer. The resuspension of sediments and

nutrients by these mechanisms is well-documented (Luettich et al., 1990; Bengtsson & Hellström, 1992; Arfi et al., 1993; Qin et al., 2000; Zhu et al., 2005). However, due to the absence of wave or current measurement data in Nokoué Lagoon, we are unable to analyze in detail the specific physical mechanisms responsible for the observed SPM variations, despite a relatively strong correlation between SPM concentration and wind energy. Nevertheless, we have noted that larger quantities of SPM are resuspended by the wind in the eastern zone compared to the western zone, where sediment particles are smaller in size and weight. This discrepancy is likely attributed to the prevalence of *acadjas* in the western zone, characterized by dense branches extending from the lagoon bottom up to 1-2 meters above the water surface during low-flow periods. These *acadjas* reduce both wind intensity and fetch at the water surface, thereby diminishing wind-induced currents, waves, and turbulence in that area. While we have emphasized the significant role of wind-induced resuspension in modulating SPM concentration during low-flow periods, future studies should specifically target different processes (currents, waves, turbulence). Achieving this requires deploying dedicated observation platforms (anemometers, wave gauges, current meters, etc.) at various locations within the lagoon, as well as inside and outside the *acadjas*, to assess their specific effects. This approach will contribute to confirming the results and processes discussed herein.

Generally, tidally-driven currents may play a role in the supply and resuspension of SPM, but the tidal amplitude in Nokoué lagoon is less than 5 cm (Chaigneau et al., 2022), and tidal currents are in the order of a few centimeters per second (Zandagba et al., 2016b). Therefore, their impact on SPM is expected to be minor compared to other driving forces, except perhaps in the Cotonou Channel where tidal currents are stronger (approximately 0.5-1.5 m s^{-1}) (Zandagba et al., 2016b).

Based on our dataset, the relationship between tidal coefficients and SPM concentrations did not reveal any significant dependence in either the Nokoué lagoon or the Cotonou Channel.

On the vertical, during periods of low water flow (January-May), the average SPM concentration at the lagoon bottom slightly exceeds that at the surface (Fig. 5 and 6), likely due to sediment resuspension leading to an increase in SPM-laden content in the bottom layer. However, in July and August, when SPM concentrations peak, the surface SPM levels slightly surpass those at the bottom. This can be attributed to the less dense SPM-laden freshwater from rivers, causing a 1-2 PSU increase from surface to bottom and resulting in lagoon stratification (Okpeitcha et al., 2022). As a consequence, a more laden turbid plume is observed at the surface, while the bottom layer is less laden. Such stratification is a characteristic of hypopycnal flow, which is commonly observed in lagoon systems connected to the open sea, as opposed to enclosed lakes where the opposite occurs and it is called hyperpycnal flow (Halfman & Scholz., 1993; Parsons et al., 2001; Mulder et al., 2003; Boggs, 2012; Zavala, 2020).

4.2. Variation in total suspended solids in Nokoué lagoon

Finally, we estimated the total amount of suspended solids (TSS, in tonnes) in the lagoon for each month of the study period (2018-2022). To do this, we used the entire set of turbidity profiles and the linear relationship established between SPM and turbidity (Section II.3) to reconstruct a three-dimensional SPM field. The TSS was then obtained by integrating the SPM field over the varying volume of the lagoon. It is important to note that the surface area of the lagoon during low-flow periods is 150 km^2 (Chaigneau et al., 2022), and its volume varies proportionally with the measured water levels.

The variability of TSS aligns qualitatively with that of the average SPM (Fig. 10). Specifically, there is a tenfold difference between minimum and maximum SPM, whereas the variation in volume is not even twofold. Consequently, when these factors are multiplied, TSS tends to be dominated (and thus exhibits phase coherence) by SPM variations rather than volume variations. However, this relationship is not strictly proportional to SPM due to the significant fluctuations in the lagoon's volume. Peaks in TSS within the lagoon coincide with periods of elevated water volume and high concentrations of suspended particles (SPM), whereas TSS reaches a minimum when both factors are at their lowest.

Large and highly variable quantities of suspended solids transit through the Nokoué lagoon, ranging from approximately 2000 tonnes to 32000 tonnes depending on the hydrological seasons, with an average value of around 6500 tonnes over the study period. Part of this total SPM load is contributed by rivers, while another part is associated with local sediment resuspension. Additionally, a portion is exported to the Atlantic Ocean through the Cotonou channel, while another portion settles and contributes to the infilling of the lagoon. These figures provide an initial estimation of the total SPM load in the Nokoué lagoon, but further measurements and studies are necessary to conduct a comprehensive sediment budget analysis of the lagoon. This budget will involve determining: i) the sediment input into the lagoon from the two main watersheds (Sô and Ouémé), ii) the export of sediments to the ocean through the Cotonou channel, and iii) the amount of sediment deposition in the Nokoué lagoon.

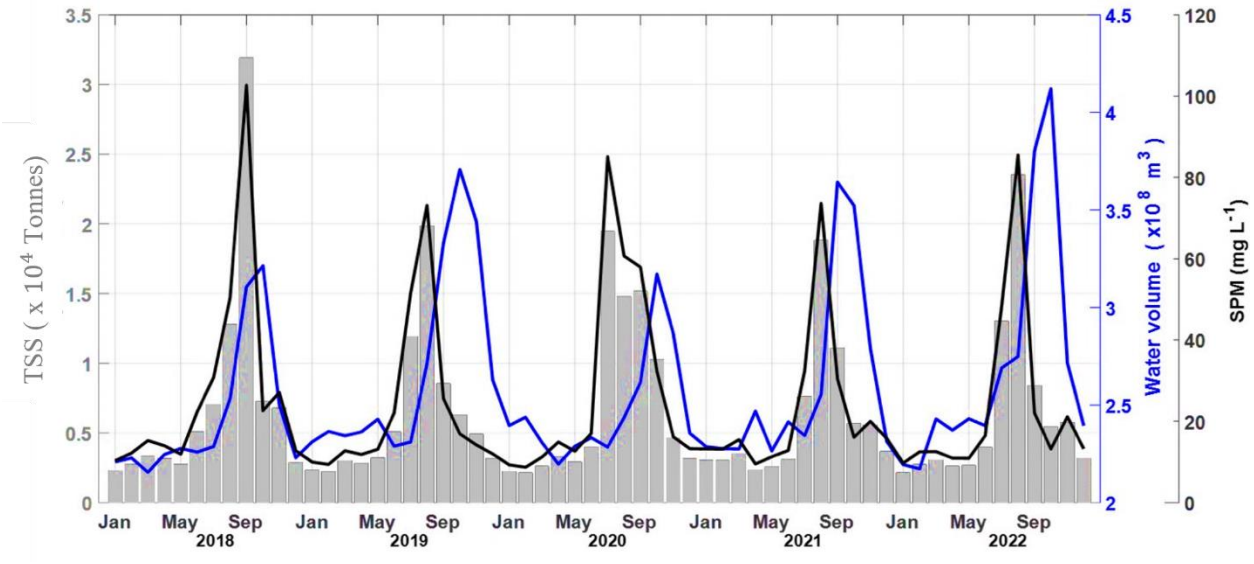

Fig. 10: Monthly variation of the total amount of suspended solids (TSS, gray vertical bars), water volume (blue line), and average concentration of SPM in the Nokoué lagoon from 2018 to 2022.

5. Conclusion

This study provides a thorough analysis of five years (2018-2022) of monthly SPM data in Nokoué lagoon, Benin, aiming to characterize SPM variations and identify driving mechanisms. SPM concentrations consistently remained below 200 mg L^{-1}. The SPM and river flow relationship revealed a pronounced clockwise hysteresis cycle, with maximum SPM during the flood's onset generating a turbid plume in the eastern zone. Low-flow periods (December-May) exhibited minimum SPM levels, influenced by wind-induced resuspension. Interannually, SPM variations were relatively low, with temporal shifts in turbid plume formation and peak SPM levels. The study unveils sediment characteristics, highlighting differences between the western and eastern zones.

These results provide a base for future research on different time scales not covered in this study. For instance, it would be valuable to investigate the impact of flash floods on SPM inputs

to the lagoon at high frequencies, or the influence of African monsoon-induced wind gusts on sediment resuspension. Similarly, conducting a sediment balance in the lagoon at lower frequencies is crucial, which would involve quantifying the material input from the Sô and Ouémé catchments and determining the fraction exported to the Atlantic Ocean through the Cotonou channel. Estimating the rate of sedimentation and infilling of this shallow lagoon will require methods such as dating of sediment cores using natural and artificial radionuclides and numerical modeling. The obtained results offer important metrics and diagnostics for the development and calibration of a hydrosedimentary model, which could be used for scientific and management purposes.

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