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1 **From seasonal flood pulse to seiche: Multi-frequency water-**
2 **level fluctuations in a large shallow tropical lagoon (Nokoué**
3 **Lagoon, Benin).**

4
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31

32 **Abstract**

33 This study investigated the main water-level (WL) variability modes of Nokoué
34 Lagoon in Benin (West-Africa). The average WL ranges between 1.3 and 2.3 m between
35 the low- and high-water seasons. Seasonal as well as weak interannual variations
36 between 2018 and 2019 are driven by rainfall regime over the catchment and associated
37 river inflow. At sub-monthly scales, the lagoon is tidally choked: ocean tides can reach
38 90 cm, whereas in the lagoon semi-diurnal and diurnal tides hardly reach few
39 centimeters. Choking conditions vary with river inflow and ocean tide amplitude,
40 correctly represented by a simple tidal choking model. Diurnal modulation and
41 asymmetry of the tide are stronger (weaker) during high (low) water period. We also
42 observed WL variations of ± 5 -10 cm at a fortnightly frequency, stronger during wet
43 (high-water) season. Superimposed on the seasonal, fortnightly and tidal WL variations,
44 we further observed short-term high-frequency seiche events. Mostly observed during
45 dry (low-water) conditions, they are characterized by typical standing-wave oscillations
46 of 5-10 cm amplitudes and 3 h periods. They are forced by the passage of fast-moving
47 squall-lines that induce strong wind variations, heavy rainfalls and rapid drop-off of the
48 air temperature. Results obtained in this study provide useful metrics for the validation
49 of flood forecasting models to be implemented in Benin, and elsewhere on the West
50 African coastline.

51

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53 **Keywords:** Water-levels; Lagoons; Tides; Seiches; Nokoué; Wavelet analysis.

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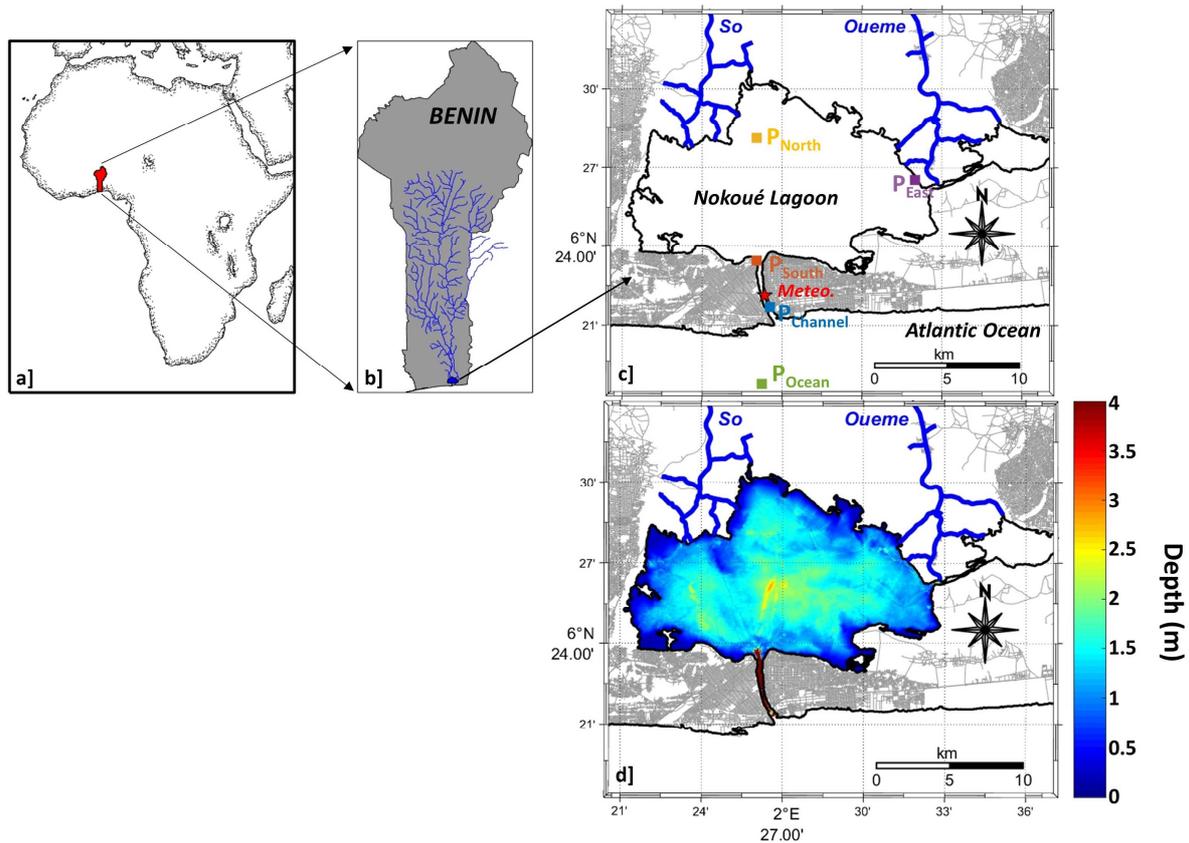
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57 **1. Introduction**

58 In the eastern tropical Atlantic Ocean, the coastal zone bordering the Gulf of
59 Guinea include a series of coastal lagoons of varying sizes (Allersma and Tilmans, 1993;
60 Lalèyè et al., 2007; Adite and Winemiller, 1997; Adite et al., 2013). These lagoons are
61 often the main mixing zone of continental freshwater and coastal seawater, supporting
62 some of the most productive aquatic ecosystems in the world (Knoppers, 1994; Valiela,
63 1995; Duck and da Silva, 2012). These coastal systems support important ecosystem
64 services for the local populations who benefit from these natural or semi-natural areas
65 through different activities (fishing, tourism, sand and/or salt extraction, etc.)
66 (Djihouessi et al., 2017; Newton et al., 2018).

67 Among the various Beninese coastal lagoons, Nokoué Lagoon (Figure 1) is the
68 largest and most exploited of the country's water bodies (Lalèyè et al., 1995; 2003). This
69 lagoon, which is also one of the most productive in West Africa (Lalèyè et al., 2007), is at
70 the heart of important ecological and socio-economic issues. It is part of the RAMSAR
71 site #1018, recognized to be of international importance for its various ecosystems that
72 include flood plains, mangroves, floating vegetation, and diverse fauna. This lagoon also
73 hosts several lacustrine villages inhabited by more than 60000 people living in stilt
74 dwellings (Principaud, 1995). These local populations depend on this water body not
75 only for fishing, which provides ~15000 tons of fish per year (Principaud, 1995), but
76 also for domestic water supply, agriculture, market gardening, animal husbandry, etc.
77 But the Nokoué Lagoon, also bordered by 3 major urban centers (Cotonou, Abomey-
78 Calavi, and Sémè Podji) totalizing more than 1.5 million inhabitants, is strongly impacted
79 by various anthropogenic pollution sources. For instance, the lagoon is the receptacle of
80 numerous urban drains and direct discharge by the surrounding populations of various
81 wastes which has led to a deterioration of the water quality (Adjahouinou et al., 2012;
82 2014; Aina et al., 2012a; 2012b). In addition, Nokoué Lagoon is also embedded within
83 the 500 km long West African coastal water corridor that stretches from Lagos (Nigeria)
84 to Accra (Ghana). This coastal corridor is projected to become the largest African
85 urbanized area (Choplin, 2019), a development that will threaten the lagoons'
86 ecosystems and their service function. The planning and implementation of coastal
87 management strategies requires a comprehensive knowledge of processes involved in
88 the physical, chemical and ecological dynamics of the Nokoué Lagoon.

89



90

91 *Figure 1. Geographical location of the Nokoué Lagoon in Benin. b) Hydrological network of the Sô and Ouémé river*
 92 *catchment basins. c) Position of the water-level stations (colored squares) and the weather station (red star). d)*
 93 *Bathymetry in low water season obtained from a spatial interpolation of ~123000 depth soundings.*

94 One of the key parameters of coastal lagoon dynamics is the water level (WL)
 95 whose variations are mainly subject to the triple influence of (i) ocean tides, (ii) the
 96 hydrological variability of the catchment and (iii) direct rainfall contributions. Generally,
 97 high WL is associated with strong freshwater river discharge and low WL with time
 98 periods when salty oceanic water penetrates into the lagoon. First, WL fluctuations
 99 impact the lagoon circulation and consequently the turnover, residence or flushing times
 100 and therefore the dispersion or retention of pollutants. Second, the lagoon WL
 101 determines the exchange of properties between the continent and the ocean and
 102 controls the ecosystems by various direct or indirect processes. In a direct way, WL
 103 fluctuations control the salinity of the lagoon (e.g. Djihouessi and Aina, 2018), which
 104 directly impacts the ecosystem composition from plankton to fish (Le Barbé et al., 1993;
 105 Gnohossou, 2006; Adandedjan et al., 2017; Odountan et al., 2019; Laléyé et al., 2003;
 106 2005). In an indirect way, WL variations impact lagoon and sediment dynamics by
 107 modifying erosion and sedimentation zones and the rate of sediment resuspension.
 108 Thus, turbidity and the availability of light on the vertical can vary according to the WL,
 109 which can modify the structure of biological communities, particularly phytoplankton

110 (Evtimova and Donohue, 2016). Similarly, WL fluctuations are correlated with
111 modifications of nutrient concentrations, mixing and vertical stratification in the water
112 column, eventually affecting the development, distribution and dilution of organisms as
113 observed in other water bodies (e.g. Lobo et al., 2018; Stević et al., 2013).

114 Third, in addition to having direct or indirect effects on the ecosystem, variations
115 in the WL of Nokoué Lagoon can have dramatic repercussions on local populations.
116 Indeed, lacustrine villages and urbanized areas adjacent to the lagoon episodically
117 experience flooding linked to major watershed floods and the regular overflow of the
118 lagoon. For instance, in 2010, flooding killed tens of people and affected 360 000, leaving
119 100 000 homeless (World Bank, 2011; Ahouangan et al., 2014; Biao, 2017). More
120 recently, in October-November 2019, the floods, less intense but spread over several
121 weeks, also caused extensive damage and affected tens of thousands of households.

122 Finally, variations in the WL may also impact the quality of the groundwater that
123 is exploited by residents bordering the lagoon, who use this unregulated shallow
124 groundwater resource for domestic purposes, including drinking water supplies
125 (Houéménou et al., 2020).

126 Despite the importance of monitoring and understanding WL fluctuations in
127 particular to implement appropriate water resource and flood management measures,
128 very few studies have described their variations in Nokoué Lagoon. On seasonal scales,
129 Le Barbé et al. (1993) observed an increase of ~50-70 cm during the 1980 flood season.
130 Similarly, using monthly observations acquired from 2001 to 2010, Djihouessi and Aina
131 (2018) described an average seasonal WL variation of 55 cm. On (semi)diurnal scales, a
132 hydrodynamic model calibrated with high-frequency WL measurements acquired over
133 two 5-day periods, elucidated the tidal characteristics in the lagoon (Zandagba et al.
134 2016). Their simulation suggested a 2-4h phase shift between tidal fluctuations in the
135 ocean and lagoon, and semi-diurnal tidal amplitudes of few centimeters in the lagoon.
136 These 3 studies were based on limited observations obtained either over isolated and
137 short time periods (Le Barbé et al., 1983; Zandagba et al., 2016), or at low temporal
138 resolution (Djihouessi and Aina, 2018). Our study aims to fill this gap and to investigate
139 WL variations in Nokoué lagoon at a wide range of time scales from a 2-year in-situ
140 dataset at high temporal resolution (20 min sample intervals), and to determine the
141 main physical mechanisms governing the observed fluctuations. Thanks to these
142 intensive measurements, unique in West Africa, we complement past studies by

143 highlighting the different modes of WL variability to which Nokoué lagoon is subjected,
144 from hourly to seasonal scales. We further aim at better characterizing the lagoon's tide,
145 not only at the semi-diurnal scale as in Zandagba et al. (2016) but also at the diurnal
146 scale and, in particular, investigating its asymmetry. Finally, various lagoons around the
147 world are subject to wind-forced seiche phenomena (e.g. Chapman and Giese, 2001).
148 Given the significant changes in the wind regime in Cotonou, especially during the
149 passage of squall lines frequently observed in West Africa (Omotosho, 1984; 1985), it is
150 likely that these seiche phenomena are also observed in the lagoon. In this study, we will
151 therefore perform a wavelet analysis of the WL variations to highlight the different
152 modes of variability, and will specifically describe the processes in the most energetic
153 spectral bands.

154

155 **2. Material and methods**

156 **2.1. Study area and hydrology**

157 Nokoué is a coastal lagoon that extends about 20 km from east to west along the
158 coast and 11 km from south to north (Figure 1), covering an average area of $\sim 170 \text{ km}^2$
159 (Texier et al., 1980; Le Barbé et al., 1993; Mama et al., 2011; Djihouessi et al., 2019). Two
160 main rivers flow into the lagoon on its northern shore, the Sô river, draining a relatively
161 small catchment area of $\sim 1000 \text{ km}^2$, and the Ouémé river, the largest Beninese river,
162 which drains a catchment area of $\sim 50000 \text{ km}^2$ (Le Barbé et al., 1993; Djihouessi et al.,
163 2017). The Sô and the lower Ouémé valley flow into the Nokoué Lagoon forming a large
164 flooded deltaic plain (e.g. Le Barbé et al., 1993). A third river, the Djonou, whose
165 extension and flow are much smaller, also contributes to the freshwater inflow in the
166 lagoon's southwestern part (Djihouessi and Aina, 2018).

167 On its southern part, Nokoué Lagoon is connected with the Atlantic Ocean by the
168 $\sim 280 \text{ m}$ wide and $\sim 4 \text{ km}$ long Cotonou channel (Texier et al., 1980; Le Barbé et al.,
169 1993). Through this relatively narrow channel, exchanges of fresh and salt water take
170 place at the rhythm of the tides and the hydrological regime. Since the channel's
171 construction in 1885, the previously unconnected 'Lake' Nokoué (as it is still known in
172 colloquial language) is today an extensive lagoon that exhibits important salinity
173 variations (e.g. Okpeitcha et al., 2022).

174 On the eastern side, Nokoué Lagoon is connected to the Porto-Novo lagoon (35
175 km^2) via the $\sim 4 \text{ km}$ long Totchè channel. Porto-Novo lagoon extends eastward into a

176 narrow coastal channel that discharges in the Atlantic Ocean at Lagos (Nigeria) at a
177 distance of ~100 km from Nokoué Lagoon, with little effect on the dynamics and WL of
178 Nokoué Lagoon (Texier et al., 1980; Le Barbé et al., 1993).

179 On seasonal scales, the lagoon's hydrological regime is driven by the West African
180 summer monsoon related to the meridional shift of the intertropical convergence zone
181 (ITCZ) and the associated intense tropical rain belt (Sultan and Janicot, 2000; Gu and
182 Adler, 2004), resulting in two rainy and two dry seasons. The main rainy season extends
183 from April-May to late July when the ITCZ moves northward from its near-equatorial
184 southernmost position, while the second shorter and less intense rainy period extends
185 from late September to November when the ITCZ migrates southward from its
186 northernmost position (e.g. N'Tcha M'Po et al., 2017; Ahokpossi, 2018). However, this
187 double rainy season and associated local rainfalls only slightly influence the WL of the
188 Nokoué Lagoon that is more subject to the hydrology of the central part of Benin, where
189 the main area of the Ouémé catchment takes place (e.g. Colleuil, 1987; see also Figure
190 1b). This latter region is characterized by a single rainy season, with maximum
191 precipitation between July and October (Biao, 2017; Ahokpossi, 2018; Lawin et al., 2019,
192 Colleuil, 1987). The maximum discharge into the lagoon between September and
193 November is unknown (rivers ungauged in the coastal region) and varies, depending on
194 authors, from ~400 m³ s⁻¹ (Le Barbé et al., 1993; Djihouessi and Aina, 2018) to more
195 than 1000 m³ s⁻¹ (Lawin et al., 2019). This river discharge produces a complete
196 desalinization of the Nokoué Lagoon and a strong increase of its volume (Texier et al.,
197 1980; Colleuil, 1987; Djihouessi and Aina, 2018).

198 Figure 1d shows the bathymetry of the Nokoué Lagoon corresponding to the
199 mean WL observed during low-water season in March-April. It was constructed using
200 ~123000 depth soundings recorded with a Garmin GPSmap 421S echosounder and
201 corrected for tidal and seasonal fluctuations. The mean and maximum depth is 1.3 m
202 and 2.9 m, respectively. The lagoon deepens towards the Cotonou channel where the
203 mean and maximum depths increase to ~3 m and ~8 m, respectively (Figure 1d).

204

205 **2.2. Water level and atmospheric data**

206 WL data was acquired by 4 pressure sensors deployed in the Cotonou channel
207 and Nokoué Lagoon for a 2-year period (Figure 1c). Three of them (P_{Channel} , P_{South} , P_{North})
208 were located along a South-North axis whereas the 4th sensor (P_{East}) was deployed East

209 of the lagoon. More precisely, P_{Channel} is located at 1.5 km from the coastal ocean; P_{South} is
210 located at the lagoon entrance; P_{North} is located 8.5 km North of P_{South} and at ~ 2 km from
211 the Sô river; finally, P_{East} is located 11.3 km southeast of P_{North} and 12.3 km northeast of
212 P_{South} .

213 Each of the 4 stations consisted of an Onset HOBO U20L-01 WL logger anchored
214 at 20-30 cm from the bottom in a perforated PVC tube of 7-cm outside diameter. Data
215 were recorded continuously at 20-min interval between February 2018 and January
216 2020, with a typical accuracy of ± 1 cm and a maximum error of 2 cm
217 (https://www.onsetcomp.com/files/manual_pdfs/17153-G%20U20L%20Manual.pdf)
218 (Wilson et al., 2016; Guragai et al., 2018).

219 From 30 August 2018, a Davis Vantage Pro2 weather station was installed on the
220 roof of the Benin Institute of Fisheries and Oceanographic Research (IRHOB; Figure 1c)
221 also recording at 20-min interval. Some of the atmospheric parameters (air temperature
222 and humidity, precipitation rates, and winds) are used to explore the forcing
223 mechanisms involved in high frequency WL variations (Section 3.4). However,
224 atmospheric pressure data were overall used to correct the WL between September
225 2018 and January 2020. Before September 2018, WL was not corrected for barometric
226 fluctuations, but this does not significantly alter the results and main conclusions drawn
227 in this study. Indeed, atmospheric pressure, that varied between 1004 mbar and 1019
228 mbar over the available time period, exhibits two main modes of variability. First, at
229 seasonal scale, atmospheric pressure varies by ~ 4 mbar, being minimum in April and
230 maximum in August. This corresponds to a WL correction of ~ 4 cm which is weak
231 compared with the seasonal WL variations of ~ 90 cm observed in this study (Section
232 3.1). Second, the stronger atmospheric pressure variability is observed at diurnal and
233 semi-diurnal periodicities, with mean and maximum variations of ~ 3 and 6 mbar,
234 respectively. This corresponds to WL variations of ~ 3 -6 cm, of the same order than the
235 tidal amplitudes observed in the lagoon. Thus, the tide characteristics in the lagoon
236 (Section 3.3), are investigated using only WL data corrected from inverse barometer
237 effects from September 2018 to December 2019.

238 Raw pressure data are converted to relative WLs corresponding to the height
239 above the instrument. For each station, as no absolute vertical datum exists, the relative
240 WLs are expressed in terms of anomalies, computed by subtracting the 20-min
241 measurements from the seasonal mean calculated over low-water period of 2018.

242 No continuous in-situ ocean tide data is available. We therefore used the tidal
243 heights computed from the last Finite Elements Solution for ocean tide (FES2014) on a
244 $1/16^\circ \times 1/16^\circ$ grid ([http://www.aviso.altimetry.fr/en/data/products/auxiliary-](http://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html)
245 [products/global-tide-fes.html](http://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html)) (Carrere et al. 2016; Lyard et al. 2020). Thus, WL
246 anomaly timeseries at P_{Ocean} (Figure 1c) was reconstructed using the 34 tidal
247 constituents (amplitudes and phases) computed from FES2014. P_{Ocean} is located ~ 5.5 km
248 to the southeast of P_{Channel} (Figure 1c). FES WL at P_{Ocean} compared well with independent
249 but irregular in-situ WL data acquired at the autonomous port of Cotonou in 2018-2019
250 by its hydrographic service. The correlation coefficient, mean difference, normalized
251 root-mean-square error, and ratio of standard deviations between both datasets are
252 0.99, 0.02 cm, 2.7%, and 0.99, respectively.

253

254 **2.3. Rainfall and river discharge data**

255 Rainfall over the catchment was obtained from a Global Precipitation
256 Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG) product
257 (Huffman et al., 2014). We use the final Level 3 product developed for research
258 applications, which is available daily on a $0.1^\circ \times 0.1^\circ$ longitude/latitude grid
259 (<https://gpm.nasa.gov/>). Rainfall was extracted over the study period (2018-2019) and
260 averaged in the river catchment area shown in Figure 1b. In order to filter out high
261 frequency variability irrelevant to our study, we used monthly cumulative rainfall.

262 Historical estimates of the Ouémé River discharge at Bonou (~ 70 km upstream
263 from the Nokoué Lagoon) and the Sô river discharge at Sô-Awa (~ 3 km upstream from
264 the lagoon) are available. These daily data, available from the 1950's to the 1990's, were
265 collected by the general Benin Directorate of water and made available by the Système
266 d'Informations Environnementales sur les Ressources en Eau et Modélisation (SIEREM:
267 <http://www.hydrosciences.org/spip.php?article1236>). A daily climatology was
268 constructed from this multi-year dataset and the Sô and Ouémé discharges were
269 summed to provide an estimate of the total fresh water discharge into the lagoon.

270

271 **2.4. Time series analyses**

272 The variability of the WL across temporal scales was investigated using a wavelet-
273 based analysis (Torrence and Compo, 1998; Guo et al., 2015). The wavelet power
274 spectrum, that estimates the spectral characteristics of the WL signal as a function of

275 time, is computed here using the Morlet wavelet transform. In order to compare spectral
276 peaks across different scales, the obtained wavelet power spectra, that are slightly
277 biased, are rectified normalizing them by the local scale (Liu et al., 2007; Veleda et al.,
278 2012). Wavelet decomposition can also be used for signal reconstruction and filtering
279 (Torrence and Compo, 1998). By summing over a subset of scales, we here construct WL
280 wavelet-filtered time series in several spectral bands, from high-frequency (periods <
281 5h) to subtidal and low-frequency (periods > 20 days) variability.

282 Global power spectra obtained from wavelet analyses provide consistent estimation
283 of the true power spectra computed from Fourier analyses (Percival, 1995). However,
284 due to the width of the wavelet filter in Fourier space, any close peaks in Fourier spectra
285 could be smoothed out by the wavelet analysis, particularly at small (high-frequency)
286 wavelet scales (Hudgins et al., 1993; Torrence and Compo, 1998). Thus, in order to
287 resolve close principal tidal constituents, their mean amplitudes and phases (e.g. Table
288 1) are obtained from harmonic analyses using T_TIDE package in MATLAB for each time
289 series (Pawlowicz et al., 2002). The temporal evolution of tidal amplitudes is
290 subsequently investigated in the diurnal (D1), semi-diurnal (D2), and quarter-diurnal
291 (D4) spectral bands by integrating wavelet power in these specific frequency/period
292 bands and converting them into wavelet amplitudes as in Guo et al. (2015). The D1, D2
293 and D4 amplitudes are computed for periods of 15-36h, 7.5-15h and 5-7.5h,
294 respectively.

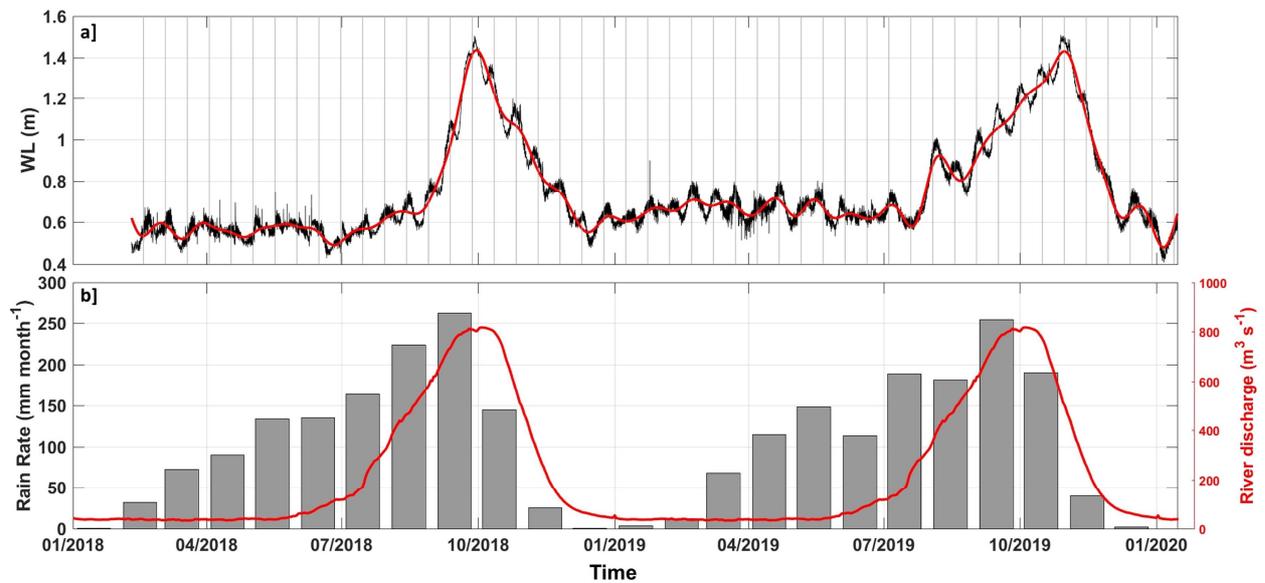
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296 **3. Results**

297 **3.1. Low-frequency variations**

298 At the entrance of the Nokoué Lagoon at P_{South}, in the periods from February to
299 August 2018 and from December 2018 to July 2019, the lagoon WL was low at mean WL
300 of 0.5-0.6 m in 2018 and 0.6-0.7 m in 2019 (Figure 2a). These periods coincide with
301 climatological periods when rivers are at baseflow and have discharges of less than ~50
302 m³/s (Figure 2b). From 20 August 2018 to 30 September 2018, the mean WL increased
303 to reach a maximum value of ~1.4 m (Figure 2a). The peak observed in 2018 coincides
304 with the maximum climatological river discharges of ~800 m³/s at the beginning of
305 October. The decrease of the lagoon WL from 1.4 m to less than 0.6 m was observed
306 between early October and early December 2018. The duration of the decrease was
307 comparable to that of the WL rise. In contrast, the duration of increasing/decreasing WL

308 were strongly asymmetric in 2019. The flooding phase began in late July 2019 and took
 309 3 months to reach the maximum of ~ 1.4 m on 31 October 2019. Although the beginning
 310 of the flooding phase in 2019 approximately follows the climatological river discharge,
 311 the maximum WL was observed 1 month later than the average peak of the hydrograph.
 312 In 2019, the decrease of the lagoon WL took only 1 month, and the low-WL was reached
 313 at the beginning of December, as in 2018.



314
 315 *Figure 2. Water-level and hydrological variations. a) Temporal variations of the water-level (WL) at P_{South}; red line shows*
 316 *the low-frequency component (periods > 20 days) whereas grey vertical lines correspond to the time of oceanic spring*
 317 *tides. b) Monthly cumulative rainfall over the Ouémé river catchment basin (grey bars) and estimated climatological*
 318 *river discharge (red line).*

319
 320 The monthly cumulative rainfall inferred from satellite data in the Sô and Ouémé
 321 catchment basins do not show strong differences between the time periods of the rainy
 322 season of 2018 and 2019 (Figure 2b). In both 2018 and 2019, the maximum rainfalls
 323 occurred in September. However, October 2019 was 35% rainier (~ 190 mm) than
 324 October 2018 (~ 140 mm), which explains the 1-month delay observed in 2019 on the
 325 maximum WL (Figure 2a). Similarly, heavy rainfalls (~ 190 mm) observed in July
 326 2019, are responsible for the earlier rise in WL in 2019, as well as for the local maximum
 327 elevation of ~ 0.95 m observed at the beginning of August 2019. Heavy rainfalls in July-
 328 August 2019 also contributed to spread out the flooding phase and delay the flood peak
 329 in the lagoon.

330 Low-frequency WL variations of the Nokoué Lagoon are related to the rainfall in
 331 the catchment basin and the river flows that discharge fresh water into the lagoon.
 332 However, superimposed on these low-frequency fluctuations, Figure 2a shows that the

333 unfiltered WL signal exhibits high-frequency variability patterns. The main goal of the
334 following Sections is thus to investigate these distinct modes of variability.

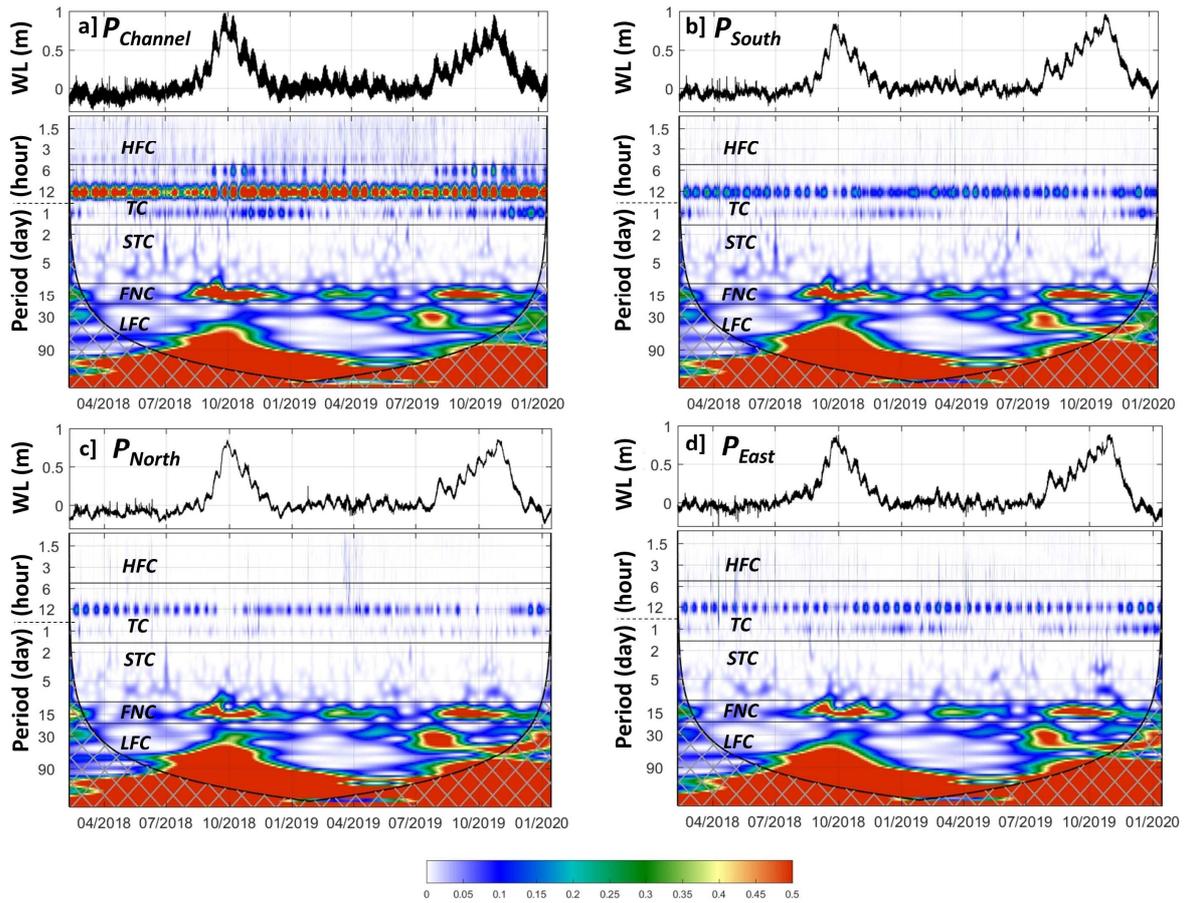
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336 **3.2. WL Wavelet analysis**

337 During the 2-year period, the 4 WL timeseries show similar patterns, not only at
338 low-frequency (Figure 3). Superimposed on the already described low frequency WL
339 variations, higher frequency WL variations with typical ranges of $\sim\pm 20$ cm that decrease
340 from the Cotonou channel to the Nokoué Lagoon are evident (Figure 3). In order to
341 better identify the dominant frequencies, we performed a wavelet analysis (Figures 3
342 and 4). WL timeseries show time-dependent variability with contributions from distinct
343 frequency bands at certain times. Spectra can be divided into 5 main period bands, from
344 high to low frequencies: i) high-frequency component with periods shorter than 5
345 hours; ii) tidal component with periods ranging between 5 hours and 1.5 days; iii)
346 subtidal component with periods of 1.5-10 days; iv) fortnightly component with periods
347 of 10–20 days; and v) low-frequency component with periods longer than 20 days.

348 The low-frequency component has been described in Section 3.1 and
349 corresponds to large WL variations mainly due to rainfall in the catchment basins that
350 drives the seasonal change in river discharge into the lagoon. In contrast, the subtidal
351 component does not present significant spectral energy (Figures 3 and 4) and is thus not
352 further investigated. Fortnightly, tidal and high-frequency components are described in
353 more detail.

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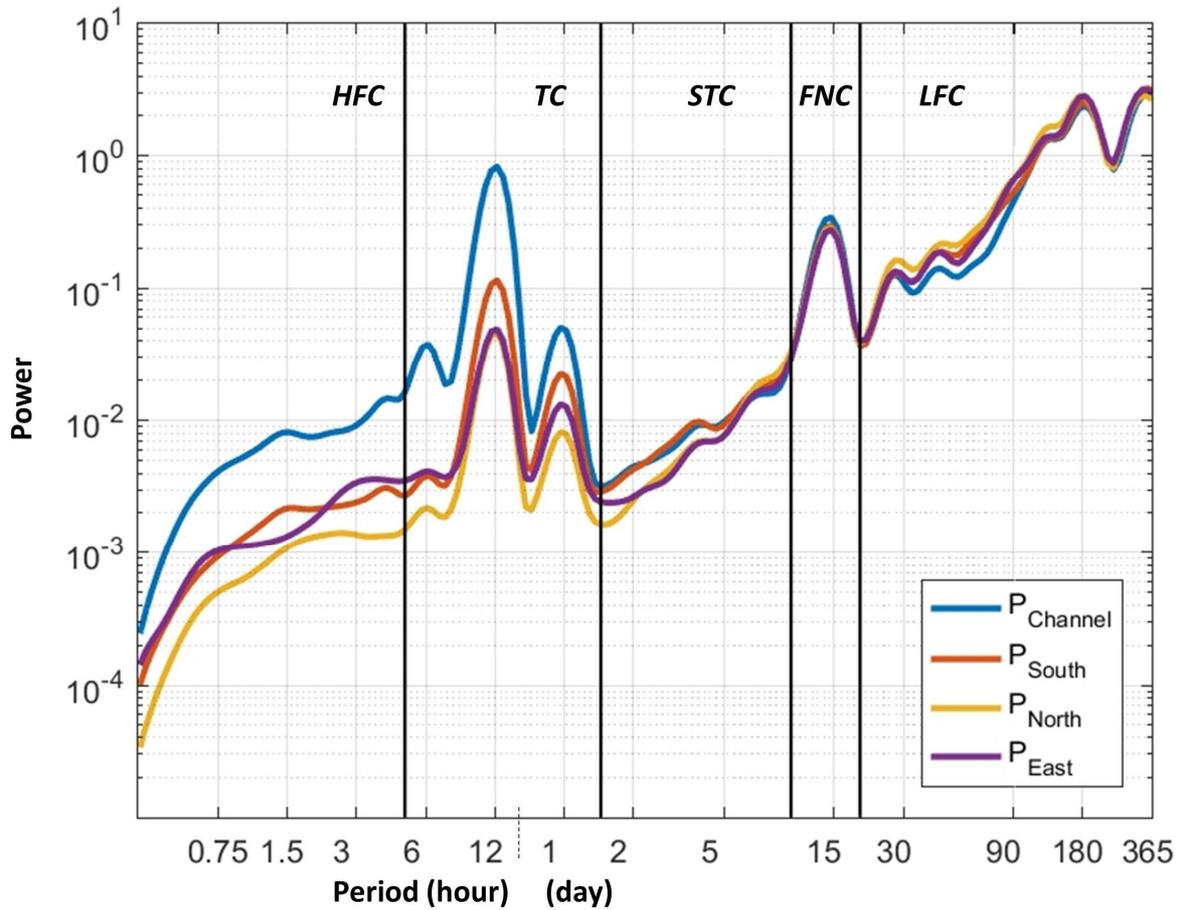
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Figure 3. Water-level (WL) timeseries and corresponding rectified wavelet power spectra, at a) $P_{Channel}$, b) P_{South} , c) P_{North} , and d) P_{East} . The y axis is in day (hour, respectively) for periods higher (lower) than 1 day. The cone of influence is indicated by hatched area. Horizontal black lines on the wavelet spectra delimit 5 frequency bands: High-frequency component (HFC) (periods < 5 hours); Tidal component (TC) (5-36 hours); Subtidal component (STC) (1.5-10 days); Fortnightly component (FNC) (10-20 days); Low-frequency component (LFC) (> 20 days).



361

362 *Figure 4. Global wavelet power spectra obtained by averaging over time the wavelet power spectrum at a) $P_{Channel}$, b)*
 363 *P_{South} , c) P_{North} , and d) P_{East} . Vertical black lines delimit the 5 frequency bands detailed in Figure 4.*

364

365 3.3. Fortnightly and tidal components

366 a) Harmonic Analysis and main tidal constituents

367 Figures 3 and 4 show relatively strong spectral energy in the fortnightly (MSf)
 368 component. These oscillations of a period of ~ 14.8 days on the mean WL are associated
 369 with neap and spring tides. Indeed, the combination of the principal lunar (M2) and
 370 solar (S2) semidiurnal tidal constituents, characterized by very close periods (Table 1),
 371 induces a compound tide (MSf) and fortnightly variation of the oceanic semi-diurnal tide
 372 amplitude (e.g. LeBlond, 1979; Pugh, 1987). In the open-ocean, where the mean WL
 373 variations are weak compared to the tidal range, both the highest and lowest sea-levels
 374 are observed during spring tides, and the mean WL is not significantly modulated at MSf
 375 frequencies (Table 1). In contrast, in shallow lagoons or estuaries, complex non-linear
 376 interactions between oceanic semi-diurnal tides, river fluxes, bottom friction and
 377 morphology of the channel, result in MSf variations of the WL (LeBlond, 1979; Gallo and
 378 Vinzon, 2005; Guo et al., 2015). These MSf variations are observed in the Cotonou

379 channel and Nokoué Lagoon (Table 1), where the highest high-waters are observed
380 during spring tides whereas the lowest low-waters are observed during neap tides
381 (Figures 2a and 3). This is due to the fact that the tidal amplitude is generally weaker
382 than the fortnightly variations of the mean WL (Figures 2a and 3; Table 1) induced by
383 tidal-river interaction processes (e.g. LeBlond, 1979; Guo et al., 2015). Harmonic
384 analyses indicate a mean MSf amplitude of ~4 cm (Table 1), which strongly increases to
385 10-15 cm during the wet season (not shown but see the evolution of the fortnightly
386 component in Figure 3).

387 In the open-ocean off Cotonou, tides are semi-diurnal with a relatively important
388 diurnal component (Table 1). Semi-diurnal tide constituents ($A_{M2}+A_{S2}$) are typically of
389 ~70 cm amplitude whereas diurnal constituents ($A_{O1}+A_{K1}$) are of ~15 cm. As a result,
390 the tidal form factor, $F = \frac{A_{O1}+A_{K1}}{A_{M2}+A_{S2}}$, which is the amplitude ratio of the diurnal to semi-
391 diurnal tide constituents, is of 0.22, close to the mixed-tide threshold of 0.25 (Courtier,
392 1938). Off Cotonou, the tide is thus of semi-diurnal-dominant type, but characterized by
393 two slightly unequal high and low tides per day. In the Cotonou channel and Nokoué
394 Lagoon, tidal ranges are strongly dampened and the tidal form factor increases to 0.41
395 (Table 1). This suggests a stronger modulation of the tides at diurnal scale in the lagoon
396 and a stronger attenuation of the semi-diurnal constituents compared to the diurnal
397 constituents.

398 In shallow water, the progression of a tidal wave is modified by bottom friction
399 and other physical processes that lead to the distortion and asymmetry of the tidal wave
400 (Pugh et al., 1987). These non-linear effects are associated with the generation of higher
401 harmonics such as the main M4 constituent, which is the second harmonic (or overtide)
402 of the principal lunar tide M2, that causes disparities in the rising and falling times (e.g.
403 Pugh et al., 1987; Gallo and Vinzon, 2005; Ray, 2007). Thus, tidal wave deformation and
404 asymmetry are mainly due to M2-M4 interactions (e.g. Friedrichs and Aubrey, 1988;
405 Speer and Aubrey, 1985). The general flood-dominated character of the lagoon system is
406 highlighted by the phase difference of $2\varphi_{M2} - \varphi_{M4}$ in the range of 0-90° that leads to a
407 longer falling tide than rising tide (Friedrichs and Aubrey, 1988; Guo et al., 2015). The
408 magnitude of the amplitude ratio of the M4 and M2 components ($\frac{A_{M4}}{A_{M2}}$) is an indicator of
409 the strength of the tidal asymmetry. This factor is of 0.02 at P_{Ocean} where the tide is

410 symmetric, but increases to 0.11-0.15 in the lagoon system indicating a stronger
 411 asymmetry and, on average, a deformation of the tidal wave (Table 1).

412

413 *Table 1. Average tidal properties: Tidal amplitudes (A) and phases (φ) of major diurnal (D1), semi-diurnal (D2),
 414 quarter-diurnal tides (D4) and fortnightly (FNC) components' frequencies at P_{Ocean}, P_{Channel}, P_{South}, P_{North} and P_{East}.
 415 These average tidal constituent properties were determined by harmonic analyses of 2-year WL timeseries using
 416 T_TIDE (Pawlowicz et al., 2002). Periods are in hours, except for FNC frequencies where they are in days.*

		Period	P _{Ocean}		P _{Channel}		P _{South}		P _{North}		P _{East}	
			A (cm)	φ (°)	A (cm)	φ (°)	A (cm)	φ (°)	A (cm)	φ (°)	A (cm)	φ (°)
FNC	MSf	14.77	0.0	125	4.2	60	3.9	66	4.0	70	3.9	69
	Mf	13.66	0.0	96	1.6	55	1.3	63	1.4	60	1.3	60
D1	O1	25.82	2.6	318	0.3	119	0.2	159	0.2	177	0.2	181
	P1	24.07	3.8	346	0.4	45	0.2	78	0.1	81	0.1	60
	S1	24.00	0.1	91	1.0	110	1.0	115	0.2	186	0.4	144
	K1	23.93	12.5	1	1.4	35	0.6	89	0.5	115	0.7	112
D2	N2	12.66	10.8	101	1.5	130	0.5	153	0.3	217	0.3	222
	M2	12.42	50.8	105	7.5	134	2.7	156	1.5	221	1.6	232
	S2	12.00	17.8	130	1.8	167	0.6	241	0.7	299	0.6	306
	K2	11.97	4.3	144	0.8	184	0.3	196	0.2	253	0.2	265
D4	M4	6.21	1.3	319	1.1	266	0.3	280	0.2	16	0.2	18
	MS4	6.10	0.0	104	0.7	288	0.2	299	0.1	53	0.1	48

417

418

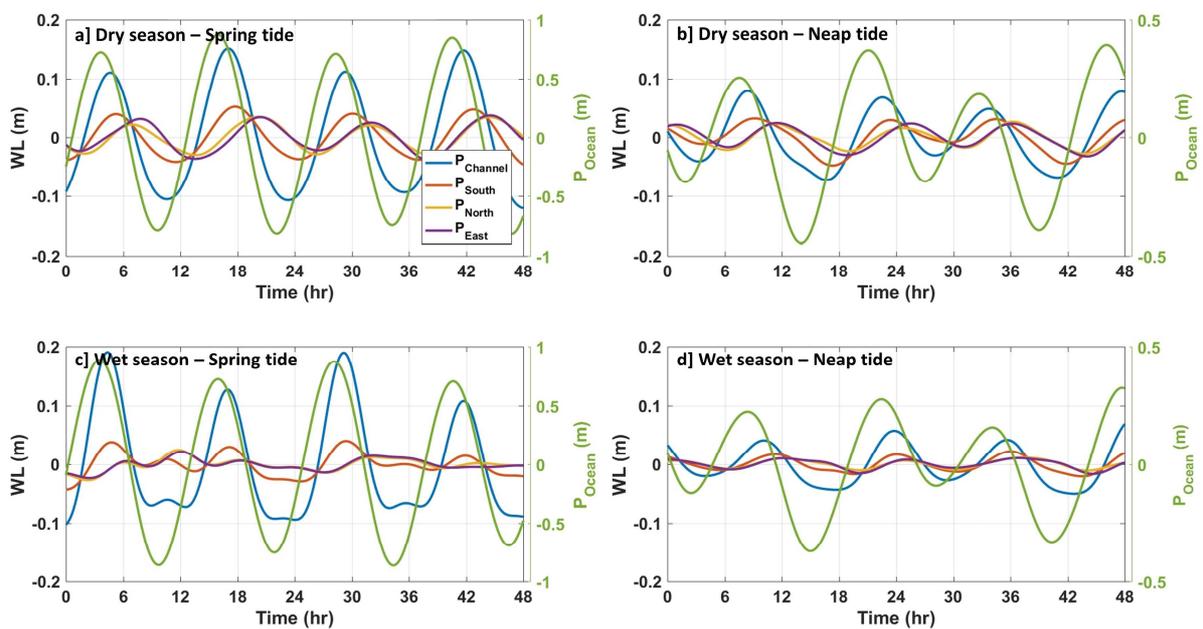
419 **b) Tidal WL fluctuations during dry/wet seasons and spring/neap tides**

420 Figure 5 shows two-day snippets of WL fluctuations during the dry and wet
 421 seasons (April and October, respectively) and for different phases of spring-neap tidal
 422 cycles. During dry season spring tides (Figure 5a), the maximum tidal amplitude is of
 423 ~80-90 cm in the ocean. It decreases to ~10-15 cm in the Cotonou channel and ~3-5 cm
 424 in the lagoon. During this period, the average diurnal tidal amplitude (AD1) is of ~15 cm
 425 in the offshore ocean and of 1-2.5 cm in the lagoon (Table 2). Similarly, the average
 426 semi-diurnal tidal amplitude (AD2) varies from ~90 cm at P_{Ocean} to ~3-15 cm at the
 427 other stations (Table 2). The AD1/AD2 ratio is 0.1-0.3, suggesting that the tide is mainly
 428 semidiurnal without strong diurnal modulation, as seen in Figure 5a. Both the quarter-
 429 diurnal amplitude (AD4) and the AD4/AD2 ratio are weak and the tide appears mostly
 430 symmetric, without strong deformation.

431 During dry season neap tides (Figure 5b), the minimum tidal amplitude is of ~20
 432 cm at P_{Ocean} but is strongly modulated at diurnal scale. The AD1 amplitude is ~18 cm and

433 AD2 decreased to ~ 36 cm leading to a relatively strong AD1/AD2 ratio of 0.5 (Table 2).
 434 In the lagoon, tidal amplitudes decrease to ~ 1 -2 cm for AD1 and to 2-7 cm for AD2.
 435 These values are weaker but the associated AD1/AD2 ratios (0.3-0.7) are slightly higher
 436 to what was observed during spring tides (Figure 5a-b and Table 2). In the Cotonou
 437 channel and Nokoué Lagoon during dry season, the rising and falling tidal durations are
 438 slightly unequal and the tide is only very slightly asymmetric, as indicated by weak AD4
 439 values of 0.1-0.2. Indeed, the ebb-tide lasts ~ 30 -45 min longer than the flood-tide, hence
 440 the lagoon system tends to be flood-dominated (e.g. Speer et al., 1991).

441



442

443 *Figure 5. Examples of water-level (WL) evolution in the tidal frequency band (periods of 5-36 hr) during a) a dry season*
 444 *spring tide, b) a dry season neap tide, c) a wet season spring tide, d) a wet season neap tide. WL at $P_{Channel}$, P_{South} , P_{North} ,*
 445 *and P_{East} correspond to left axes whereas WL at P_{Ocean} correspond to right axes.*

446

447 During the wet season, the tide characteristics in the open ocean are similar to
 448 the dry season, with AD1 of ~ 15 cm and AD2 varying from ~ 95 cm for spring tides to
 449 ~ 30 cm for neap tides (Figure 5c-d and Table 2). In contrast, tide characteristics are
 450 significantly modified in the channel and the lagoon, and more particularly during wet
 451 season spring tides (Figure 5c). AD2 decreases during wet season and AD1 tends to
 452 increase (see also wavelet power spectra in Figure 3). The tidal form factor AD1/AD2
 453 increases from ~ 0.1 -0.7 during the dry season, to 0.5-2.2 during the wet season (Table
 454 2), as a result of a stronger modulation of the tides at diurnal scale during high water
 455 periods. During spring tides (Figure 5c), the flood duration is 4-5 h, whereas the ebb-

456 tide lasts 7-8 h. Notably the wave shape of the tides tends to be positively skewed with a
 457 slack-tide asymmetry, in particular at P_{Channel} (blue line in Figure 5c). This slack-tide
 458 asymmetry is due to a phase difference between M2 and M4 ($2\varphi_{\text{M2}} - \varphi_{\text{M4}}$) that is, on
 459 average, close to 0° (Table 1) (e.g. Guo et al., 2019).

460 Finally, high and low tides are systematically observed 1 hour later at P_{Channel} than
 461 at P_{Ocean} (Figure 5). In contrast, the high or low tide phase shift between P_{South} and P_{North}
 462 or P_{East} , varies from 1h-3h during dry season (Figure 5a,b) and is strongly uncertain
 463 during wet season when the tide is much more asymmetric and deformed (Figure 5c,d).
 464 Note also that winds can impact WL in shallow lagoons, in particular by pushing and
 465 piling up water in the downwind direction (e.g. Stieglitz et al., 2013; Colvin et al., 2018).
 466 However, data from the weather station reveals that the dominant southwest wind is
 467 weak and varies from 2.2 m s^{-1} in December to 4.5 m s^{-1} in August. Similarly, at diurnal
 468 scale, the wind only varies by 2 m s^{-1} , being minimum at 6-7 am and maximum at 3-4
 469 pm. Considering a steady state balance between the wind-stress and the barotropic
 470 pressure gradient generated by the slope of the free surface, these typical winds would
 471 result on wind setups of $\sim 1\text{-}3 \text{ cm}$ in the northeastward direction (see equations in e.g.
 472 Colvin et al., 2018). This weak signal could not be evidenced in the WL dataset, and no
 473 significant WL slope was observed between $P_{\text{North}}/P_{\text{East}}$ and P_{South} , neither at seasonal
 474 nor diurnal scales. However, as described in the following Section, high-frequency
 475 fluctuations of the wind field generate high-frequency variations of the WL slope in
 476 Nokoué Lagoon.

477
 478 *Table 2. Average tidal amplitudes of diurnal (AD1), semi-diurnal (AD2), and quarter-diurnal tides (AD4) at P_{Ocean} , P_{Channel} ,
 479 P_{South} , P_{North} and P_{East} and for 4 selected 48-hour periods. Amplitude ratios (AD1/AD2 and AD2/AD4) are also indicated.
 480 These average tidal constituent properties were determined by integrating wavelet powers in specific frequency/period
 481 bands (15-36h for D1, 7.5-15h for D2, and 5-7.5h for D4). Amplitudes are in cm.*

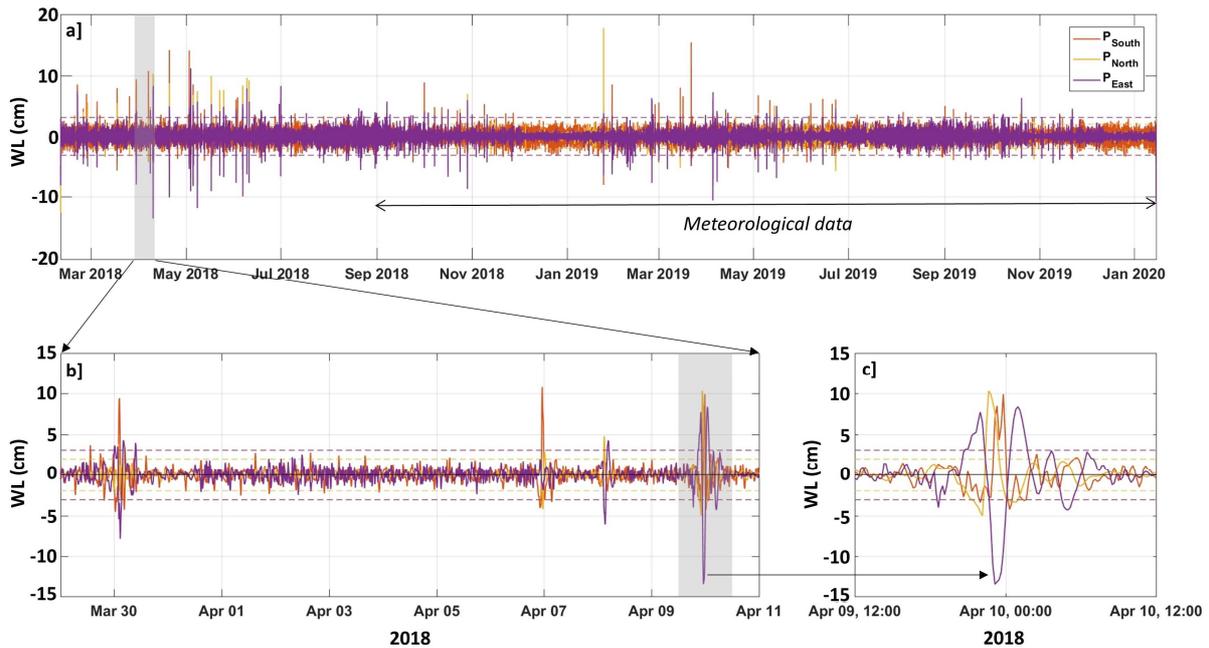
482

	P_{Ocean}	P_{Channel}	P_{South}	P_{North}	P_{East}
<i>Dry Season – Spring Tide</i>					
AD1	13.3	2.6	0.9	1.0	1.0
AD2	94.2	14.2	5.1	3.4	3.5
AD4	3.8	2.0	0.6	0.3	0.4
AD1/AD2	0.14	0.18	0.17	0.30	0.29
AD4/AD2	0.04	0.14	0.12	0.10	0.11
<i>Dry Season – Neap Tide</i>					
AD1	17.6	3.1	2.2	0.6	1.1
AD2	36.0	6.7	3.2	2.4	2.7

483	AD4	1.9	1.2	0.5	0.4	0.3
484	AD1/AD2	0.49	0.47	0.70	0.26	0.42
	AD4/AD2	0.05	0.18	0.15	0.18	0.13
485						
486			<i>Wet Season – Spring Tide</i>			
487	AD1	14.9	3.3	1.8	1.5	1.5
	AD2	95.3	14.0	2.7	0.7	0.7
	AD4	3.8	5.7	1.5	0.8	0.7
	AD1/AD2	0.16	0.24	0.68	2.06	2.24
	AD4/AD2	0.04	0.41	0.57	1.02	1.01
			<i>Wet Season – Neap Tide</i>			
	AD1	16.6	2.1	0.6	0.5	0.6
	AD2	28.0	5.1	1.9	1.0	1.1
	AD4	1.7	1.0	0.5	0.2	0.3
	AD1/AD2	0.59	0.41	0.34	0.54	0.53
	AD4/AD2	0.06	0.21	0.24	0.21	0.28

488 **3.4. High-frequency component (periods < 5 hours)**

489 Relatively strong HF variability was observed between February and June 2018,
490 October-November 2018, and February to June 2019 (Figure 6a). For example, during a
491 2-week period in 2018, 4 individual HF events were observed (Figure 6b). These high-
492 frequency fluctuations can be either in phase or in opposition between the different
493 stations. Typical oscillations of ± 5 -10 cm are observed.
494



495
496 *Figure 6. High-frequency component (HFC) of the water level evolution in the Nokoué Lagoon. a) HFC (periods < 5 hours)*
497 *for the 2-year study period (2018-2019), showing strong HF events. b) HFC for a 12-day period. c) A particular HF event*
498 *observed in April 10, 2018. In these figures, horizontal dashed lines correspond to ± 4 standard deviations around the*
499 *mean and are used to automatically detect HF events associated with seiches.*

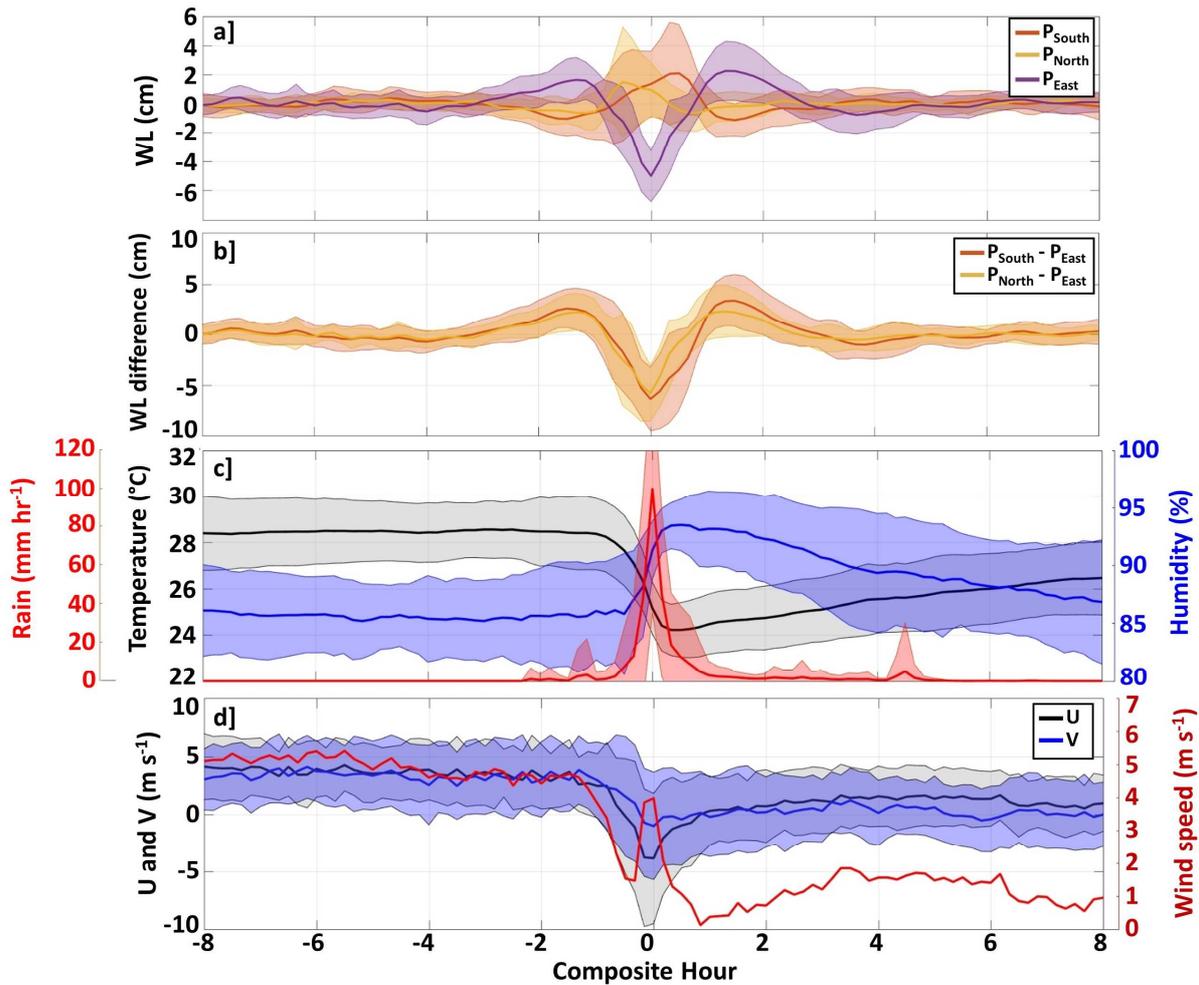
500
501 As an example, Figure 6c shows the HF WL variations for the particular event that
502 occurred during the night 09-10 April 2018. Between 08:00 and 10:00 pm, the WL
503 increased by ~ 7 -8 cm in the eastern part of the lagoon (P_{East}) at a simultaneous decrease
504 of 4-5 cm at P_{South} and P_{North} . Thus, this rapid evolution generated a WL difference of 12-
505 13 cm between the East and the central line of the lagoon joining P_{South} and P_{North} . After
506 10:00 pm, the WL rapidly decreased (increased, respectively) at P_{East} (P_{South} and P_{North})
507 to reach a maximum negative (positive) anomaly of -13.5 cm (+10 cm) between 11:00
508 pm and midnight (Figure 6c). This led to a maximum WL difference of ~ 23 cm between
509 the eastern and central parts of the lagoon. Subsequently, the WL began to oscillate
510 around its equilibrium value with amplitudes of a few cm. These oscillations,

511 characterized by a period of ~2h45min, were rapidly dissipated on 10 April after 08:00
512 am. This ~12-hour duration event, characterized by regular WL free standing-wave
513 oscillations that are progressively dampened, is typical of a seiche event as frequently
514 observed in other lakes, lagoons or coastal embayments (e.g. Chapman and Giese, 2001).
515 For this particular event, the observed standing-wave oscillation period of 2h45min is in
516 close agreement with the Merian's theoretical period of a seiche oscillation in a
517 rectangular flat-bottom basin (Chapman and Giese, 2001): considering the larger
518 dimension of the Lagoon ($L = 20$ km) and a mean depth (H) of 1.3 m, the Merian's
519 theoretical period value ($T = \frac{2L}{\sqrt{gH}}$) is of ~3h.

520 In order to better characterize such HF events, and to provide a more robust
521 description of their main characteristics, a composite analysis was performed. First,
522 individual HF events were filtered as any event associated with a strong WL increase at
523 a given lagoon station (P_{South} , P_{North} , and P_{East}) and a simultaneous strong WL decrease in
524 another gauged station. In order to ensure a high confidence level and exclude any
525 potential false detection, a strong increase/decrease is defined as higher than +/- 4
526 standard deviations from the mean (Figure 6). Peaks with such high variations occur
527 less than 0.1% of the time. A total of 44 HF events, significantly impacting at least 2 WL
528 stations, were detected. Interestingly, more than 75% (34 on 44) of these events were
529 associated with a strong WL minimum in the eastern part of the lagoon at P_{East} , as also
530 observed in Figure 6c. In terms of seasonality, about 85% of the 44 HF events took place
531 during the dry season between February and June and none of them between August
532 and September.

533 Second, since the lagoon is elongated in East-West direction and seiche
534 phenomena are expected to more likely develop along the elongated direction, we
535 selected only HF events characterized by a significant WL minimum at P_{East} .
536 Furthermore, after visual inspections, we retained 32 events characterized by similar
537 evolutions in meteorological parameters. Figure 7a displays the composite analysis of
538 the WL evolution for these 32 events, obtained by centering each event at the time the
539 WL minimum at P_{East} was observed ($t=0$ h in Figure 7). On average, about 3 hours before
540 the start of the seiche, the WL gently rises by 2 cm to the East and decreases by ~1 cm at
541 P_{South} and P_{North} . Note that the seiche is triggered at time $t=-1.5$ h, when the WL starts to
542 decrease (increase respectively) at P_{East} (P_{South} and P_{North}). The WL anomaly reaches its
543 minimum value (-5 cm) at P_{East} at $t=0$ h, while maximum WL anomalies (~2 cm) are

544 observed at P_{North} and P_{South} at $t=-0.5\text{h}$ and $t=+0.5\text{h}$ respectively. Then, as observed for
 545 the individual event shown in Figure 6, the WL oscillates with inverse anomalies
 546 between P_{East} and $P_{\text{North}}/P_{\text{South}}$ (Figure 7a), with an oscillation period of $\sim 3\text{h}-3\text{h}30$. The
 547 dissipation is much faster than the single event analyzed in Figure 6, due to the averaging
 548 of 32 events that can be characterized by slightly different periods and amplitudes.
 549



550
 551 *Figure 7. Composite analysis of seiche events and associated atmospheric parameters. a) Averages of water-level (WL)*
 552 *evolution at P_{South} , P_{North} and P_{East} for the 32 HF events associated with a maximum negative WL anomaly at P_{East} at $t = 0$.*
 553 *b) Mean WL differences between P_{South} and P_{East} and between P_{North} and P_{East} . c) Mean air-temperature, air-humidity and*
 554 *rain. d) Mean wind velocity components (left axis) and wind speed (right axis). Color shading correspond to ± 1 standard*
 555 *deviation around the means. In order not to overload the figure, standard deviations are not shown for wind speed in c).*

556
 557 Finally, in order to better understand the forcing mechanisms involved in the
 558 seiche generation, a composite analysis of some key meteorological parameters was
 559 performed (Figure 7c-d). Leading up to the seiche triggering, atmospheric conditions are
 560 relatively stable with on average an air temperature of $\sim 28.5^\circ\text{C}$, a humidity of $\sim 85\%$,

561 and no rain (Figure 7c). The wind is also regular, blowing towards the Northeast (zonal
562 and meridional components are equal and positive) with a mean speed of 4-5 m s⁻¹
563 (Figure 7d). This wind regime tends to accumulate water in the Northeast/East of the
564 lagoon as observed in Figure 7a. At the start of the seiche (t=-1.5h) the wind suddenly
565 decreases and progressively reverses (Figure 7d). At t=0, when the WL is minimum at
566 P_{East}, the wind blows towards the West-Southwest with a mean speed of ~4 m s⁻¹ (Figure
567 7d). This strong and rapid wind inversion is thus the main forcing mechanism of the
568 seiche, causing the displacement of the water from the East to the West and initiating
569 the WL oscillations. After this maximum wind inversion, the wind progressively blows
570 again towards the Northeast but with a very weak intensity (< 2 m s⁻¹). Interestingly,
571 during the seiche event the air temperature suddenly drops by 4-5°C, the humidity
572 increases to reach an average value of 93% and very strong rain events are observed
573 (Figure 7c). These showers of up ~100 mm/h rainfall have a duration of 30-60 min.
574 These patterns are likely related to the passage of fast-moving squall-lines,
575 characterized by strong pressure jumps and downdraft winds, with short but intense
576 rainfalls (e.g. Omotosho, 1984; 1985; Schrage and Fink, 2007). Interestingly, the
577 seasonal variation of the number of squall-lines in West African coastal regions, shows a
578 bi-modal distribution with a strong maximum in March-June and almost no squall-line in
579 July-September (Omotosho, 1984; 1985). Both the number of squall-lines and the
580 number of seiche events show similar seasonal variations (85% of the seiche events
581 were observed in February and June and none in August-September), which strongly
582 suggests that the passage of these atmospheric disturbances (squall-lines) are likely
583 responsible of the observed seiche phenomena.

584

585 **4. Discussion**

586

587 **4.1. Subtidal WL variations**

588 This study complemented previous limited studies (Le Barbé et al., 1983; Djihouessi
589 and Aina, 2018), highlighting the main roles of river runoffs, tides and winds in the WL
590 variations of Nokoué Lagoon. Observed low-frequency subtidal WL variations of ~0.8-0.9 m
591 are the result of the importance of continental water inflow and the lagoon's evacuation
592 capacities, which depend on the ocean level. At regional scale, the WL has only been
593 measured in the Ebrié Lagoon (Ivory Coast) for 1-year in 1952. This lagoon also showed an

594 increase of 50 cm during watershed flooding in October-November (Varlet, 1978; Durand and
 595 Guiral, 1994). In Nokoué Lagoon, our results suggested a 1-month delay between maximum
 596 rainfall in the catchment basin and the maximum WL in the lagoon, which is encouraging to
 597 elaborate an operational seasonal flood forecasting system in the lagoon from rainfall
 598 observations.

599 Our study also suggests that such forecasting system has to take into account tide
 600 forcing. The interaction of M2 and S2 tidal constituents through non-linear bottom friction
 601 and river interaction resulted in a pronounced fortnightly-period oscillation of lagoon WL, as
 602 expected from one-dimensional simplified models (e.g. Hill, 1994; MacMahan et al., 2014).

603

604 4.2. Tidal WL variations

605 Tides are strongly attenuated, with a main semidiurnal (M2+S2) tidal amplitude
 606 decreasing from 30-90 cm in the ocean to ~1-3 cm in the Nokoué Lagoon (see Table 2 and
 607 also Zandagba et al., 2016). The tidal signal is thus altered by the frictional channel that acts
 608 as a dynamic low-pass filter (Kjerfve and Magill, 1989) and the Nokoué Lagoon can be
 609 classified as a choked coastal lagoon (Kjerfve, 1986) with a choking coefficient varying with
 610 the season and ocean tide amplitude (Table 3).

611 Based on Stigebrandt (1980), many studies have explained choking conditions using a
 612 simple one-dimensional model (e.g. Rydberg and Wickbom, 1996), where the response of the
 613 WL within the lagoon (η_{lagoon}) to the ocean sea-level forcing (η_{ocean} and M2 tide) and a
 614 variable freshwater supply (Q_{river}) is given by:

615

$$616 \quad \frac{d\eta_{lagoon}}{dt} = P \frac{\eta_{ocean} - \eta_{lagoon}}{\sqrt{|\eta_{ocean} - \eta_{lagoon}|}} + S \quad (1)$$

617 where the parameters characterizing the choking conditions are (Stigebrandt, 1980):

$$618 \quad P = \frac{hl}{A\sqrt{1+\lambda}} \sqrt{\frac{2gT^2}{a_{ocean}}} \quad \lambda = 2\kappa \frac{L}{h} \quad \text{and} \quad S = \frac{Q_{river}T}{Aa_{ocean}}$$

619

620 with $g = 9.81 \text{ m/s}^2$ is the gravitational acceleration; $T = 12.42$ hours and $a_{ocean} = 0.5$ m, are the
 621 M2 tidal period and amplitude in the ocean, respectively; $\kappa \sim 0.003$ is a friction coefficient
 622 used in quadratic friction laws (e.g. Robinson et al., 1983; Stigebrandt and Molvær, 1988;
 623 Sternberg, 1968; Rydberg and Wickbom, 1996); $A = 170 \text{ km}^2$ is the lagoon area, $L = 4000$ m
 624 the length of the Cotonou channel, $l = 280$ m its breadth, and $h = 3$ m its depth. The river

625 discharge, Q_{river} , is poorly known but estimated climatologies show it varies from $\sim 50 \text{ m}^3 \text{ s}^{-1}$
 626 in low-water season to $\sim 800 \text{ m}^3 \text{ s}^{-1}$ during flood period (Figure 2).

627

628 *Table 3. Tidal choking coefficients (in bold) obtained from average semidiurnal tidal amplitudes observed in the ocean*
 629 *(a_{ocean}) and Nokoué Lagoon (a_{lagoon}), and from theoretical results from Equation 1 (Stigebrandt, 1980) for different*
 630 *hydrological periods (dry and wet seasons) and tidal characteristics (spring and neap tides). a_{lagoon} was obtained from*
 631 *Table 2, averaging semidiurnal tidal amplitudes (AD2) at the 3 stations located in Nokoué Lagoon (P_{South} , P_{North} , P_{East}).*

	Observations			Theoretical (Stigebrandt, 1980)		
	a_{ocean} (cm)	a_{lagoon} (cm)	$C_c = \frac{a_{lagoon}}{a_{ocean}}$	C_c	P	S
	<i>Dry Season ($Q_{river} = 50 \text{ m}^3 \text{ s}^{-1}$)</i>					
<i>Spring Tide</i>	94.2	4.0	0.04	0.06	0.34	0.01
<i>Neap Tide</i>	36.0	2.8	0.08	0.09	0.54	0.04
	<i>Wet Season ($Q_{river} = 800 \text{ m}^3 \text{ s}^{-1}$)</i>					
<i>Spring Tide</i>	95.3	1.4	0.01	0.02	0.33	0.22
<i>Neap Tide</i>	28.0	1.3	0.05	0.06	0.62	0.75

632

633 In this model, tidal choking depends at first order upon the geometrical characteristics
 634 of the lagoon and channel including friction effects (e.g. Stigebrandt, 1980; Hill, 1994;
 635 MacMahan et al., 2014). River outflows plays an additional role in modifying both the mean
 636 lagoon WL and the tidal amplitude and phase (Stigebrandt, 1980). Given the lagoon and river
 637 discharge characteristics, we obtain $\lambda \sim 8$ indicating a strong control of tidal choking by
 638 bottom friction. P varies from 0.3 for spring semidiurnal tides to 0.6 for neap tides (Table 3).
 639 Interestingly, because of extreme hydrological variability, S varies from 0.01 in dry season to
 640 0.8 in wet season (Table 3), implying a strong influence of river discharge for the choking
 641 process. Following Stigebrandt (1980; see his Table 1), the predicted choking coefficient
 642 varies from 0.02 to 0.09 (Table 3). These results only slightly differ from our estimates (Table
 643 3), in particular because river inflow is poorly known. This good agreement shows that this
 644 simple model is able to explain the observed choking conditions and its strong seasonal and
 645 fortnightly variability.

646 Also, for the considered river outflows (50 and $800 \text{ m}^3 \text{ s}^{-1}$) the Stigebrandt's (1980)
 647 theory predicts a similar tidal asymmetry in the lagoon, with an ebb duration ~ 35 min longer
 648 than the flood. This is in agreement with what we observed during dry season (30-45 min),
 649 but the observed ebb-flood asymmetry was stronger during flood period. The expected phase
 650 delay between high water in the ocean and in the lagoon is predicted to be of 1.5-3 hours
 651 (longer phase shifts for stronger river outflows), in agreement with the values observed in
 652 Section 3.3b. Furthermore, Stigebrandt (1980) suggested from his theory that the mean WL in

653 the lagoon would increase by 5 cm in low-water period and ~80 cm during flood season,
654 which is very close to our observations (Figure 2). These comparisons between observed and
655 predicted values from the Stigebrandt's (1980) theory at different timescales are very
656 promising for using this simplified one-dimensional models to predict WL in Nokoué Lagoon
657 from river discharge data and tidal constituents. Implementing a forecasting system was
658 beyond the scope of the present study, but this problem and approach will deserve future
659 studies.

660

661 **4.3. High-frequency WL variations**

662 Finally, as shown in Section 3.4, the HF WL acquisition rates allowed us to highlight
663 the occurrence of seiches in Nokoué Lagoon and to provide their main characteristics. These
664 HF events, forced by the passage of fast-moving squall lines, are characterized by typical WL
665 oscillations of ± 5 -10 cm. Seiches are commonly observed in large lakes or lagoon in the
666 World (e.g. Chapman and Giese, 2001). However, due to the lack of continuous WL
667 monitoring, these HF events have been only marginally documented in some lakes of Central
668 and East Africa (e.g. Beauchamp, 1939; 1953; Jollyman, 1955; Fish, 1957; Ward, 1959). In
669 West-Africa, only Varlet (1978) mentioned the occasional existence of damped oscillations in
670 the Ebrié Lagoon whose amplitude could reach 10 cm and whose period was about thirty
671 minutes. He also noted that in 1952, a tornado produced a momentary rise of 5-15 cm in the
672 Ebrié lagoon. Our study, based on a robust statistical analysis, provides an unprecedented
673 description of the seiche phenomenon in an African coastal lagoon. These results provide
674 useful metrics to validate barotropic shallow-water models, that in turn could be used to better
675 understand seiche dynamics in Nokoué Lagoon. They also suggest that, to be exhaustive,
676 flood forecasting system should incorporate or parameterize seiche oscillations in Nokoué
677 Lagoon.

678

679 **5. Conclusion**

680 **5.1. Summary of the results**

681 In this study we analyzed new WL data of a poorly observed West African lagoon.
682 High frequency (20 min) and long term (2 years) observation of the Nokoué lagoon WL
683 were analyzed and revealed a strong variability in 4 main frequency bands.

684 First, the known seasonal variability, associated with the West-African Monsoon,
685 causes the WL in the lagoon to increase by ~0.9 m between low and high water periods.

686 We observed interannual variability, and related them to variations of rainfall over the
687 watershed and associated river discharge, but the lack of available contemporary
688 hydrological and meteorological data prevents any further diagnostics.

689 Second, for the first time in this lagoon, we revealed strong fortnightly frequency
690 variations of the mean WL in the lagoon, with the highest high-waters observed during
691 spring tides and the lowest low-waters during neap tides. Amplitudes of the fortnightly
692 variations are much higher (10-15 cm) during the wet season. This process has to be
693 associated to nonlinear interactions of oceanic tidal constituents (Hill, 1994) but the
694 details of the mechanism has to be investigated using a model.

695 Third we showed that, at (semi)diurnal scale, there is a strong attenuation of the
696 tidal range within the Cotonou channel and the Nokoué lagoon is flood-dominated. On
697 average, semi-diurnal (diurnal, respectively) tidal amplitudes decreases from ~70 cm
698 (15 cm) in the ocean to ~2-3 cm (<2 cm) within the lagoon. We showed that the
699 Stiegebrandt (1980) tidal choking model explains this phenomenon: the long Cotonou
700 channel connecting the Lagoon to the ocean, acts as a natural low-pass filter that
701 reduces tidal effect in the lagoon but increase the fortnightly component, and more
702 particularly during wet season when river discharge is high.

703 Fourth, we observed higher frequency WL variability, characterized by periods
704 shorter than 5 h. Most of these energetic events are observed during the dry season, and
705 are associated with typical WL variations of 5-10 cm. We showed that these HF patterns
706 correspond to wind-forced seiches associated with the passage of fast-moving squall-
707 lines. The perturbation of the persistent southwest winds by the passage of these
708 atmospheric disturbances leads to the development of seiches with a period of ~3 h.
709 During these events, that are rapidly dissipated, heavy rainfalls are observed and the air
710 temperature drops on average by 5°C.

711

712 **5.2. Perspectives: towards the development of a flood forecasting model**

713 Floods are one of the most devastating natural hazards in West Africa, increasing in
714 frequency, magnitude and impact in recent decades (Aerts et al., 2014; Di Baldassarre et al.,
715 2010; Ekeu-Wei, 2018). Various west-African political and economic capitals are concerned
716 by flooding, in particular due to their proximity to coastal lagoons fed by important
717 watersheds (e.g. Lagos in Nigeria, Cotonou in Benin, Lomé in Togo, Abidjan in Ivory Coast,
718 etc.). Local governments therefore require information to implement appropriate flood

719 management measures. However, the acquisition and maintenance of environmental and
720 climate observation networks in these developing regions is very challenging, despite their
721 vulnerability to climate variability and change (Ampadu et al., 2013; Eku-Wei, 2018 ; Dinku,
722 2019 ; Brocca et al., 2020). As such, WL timeseries in West-African lagoons are rare or non-
723 existent. The observations and diagnostics presented in this study contribute to a better
724 understanding of the dynamics of the Nokoué Lagoon, and form a scientific base to
725 inform an improved management of flood risks of the adjacent low-lying coastal cities.
726 Indeed, our study demonstrates that a flood early warning system must not only
727 consider the hydrological regime of the catchment (Sô and Ouémé rivers), but also the
728 propagation and non-linear interactions of the ocean tide that produces significant WL
729 fluctuations of Nokoué Lagoon, in particular at fortnightly periods during flood season.
730 In a second step, this flood warning system should also include seiches that give rise to
731 high frequency WL oscillations which can cause additional surges.

732

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740

741

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