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1 **Water mass circulation and residence time using Eulerian approach in a**
2 **large coastal lagoon (Nokoué Lagoon, Benin, West Africa).**

3
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29 **Abstract**

30 Seasonal water circulation and residence times in the large (150 km²) and shallow (1.3 m
31 average dry season depth) Nokoué Lagoon (Benin) are analyzed by means of numerical simulations
32 using the three-dimensional SYMPHONIE model. The average circulation during the four primary
33 hydrological periods throughout the year are studied in detail. Despite the lagoon's shallowness,
34 significant disparities between surface and bottom conditions are observed. During the flood season
35 (September-November), substantial river inflow (~1200 m³/s) leads to nearly barotropic currents (~7
36 cm/s), 'directly' linking rivers to the Atlantic Ocean. Rapid flushing results in short water residence
37 times ranging from 3 to 16 days, with freshwater inflow and winds driving lagoon dynamics. During the
38 salinization period (December-January) the circulation transforms into an estuarine pattern,
39 characterized by surface water exiting and oceanic water entering the lagoon at the bottom. Average
40 currents (~2 cm/s) and recirculation cells are relatively weak, resulting in a prolonged residence time of
41 approximately 4 months. Circulation during this time is dominated by tides, the ocean-lagoon salinity
42 gradient, wind, and river discharge (~100 m³/s). During low-water months (February to June), minimal
43 river inflow and low lagoon water-levels prevail. Predominant southwest winds generate a small-scale
44 circulation (~3 cm/s) with a complex pattern of multiple recirculation and retention cells. Residence
45 times vary from 1 to 4 months, declining from February to June. During the lagoon's desalination season
46 (July-August), increasing river inflows again establish a direct river-ocean connection, and average
47 residence times reduce to ~20 days. Notably, a critical river discharge threshold (~50-100 m³/s) is
48 identified, beyond which the lagoon empties within days. This study highlights how wind-driven
49 circulation between December and June can trap water along with potential pollutants, while river
50 inflows, tides, and the ocean-lagoon salinity gradient facilitate water discharge. Additionally, it explores
51 the differences between residence and flushing times, as well as some of the limitations identified in the
52 simulations used.

53 **Keywords:** Lagoon Circulation; Residence time; Nokoué Lagoon; Numerical modelling; Forcings;

54

55

56 **1. Introduction**

57 Coastal lagoons account for approximately 13% of the world's coastal zones (Kjerfve, 1994). They
58 play a crucial role as transition zones between land and ocean, marked by significant spatio-temporal
59 variations in physical, biogeochemical, and ecological parameters (Pérez-Ruzafa et al., 2019; Du et al.,
60 2019; Torres et al., 2020). Lagoons provide a wide range of ecosystem services, supporting flood
61 prevention, food production, biodiversity preservation, and economic activities such as fishing, tourism,
62 aquaculture, sand extraction, transportation, and more (Newton et al., 2018). Although they are often
63 protected as wetlands, lagoons remain vulnerable to pressures related to climate change and human
64 activities.

65 A thorough understanding of water mass circulation and residence time within lagoons is essential
66 to assess the environmental and ecological consequences of their exploitation. The intricacies of water
67 movements influence the dispersion of nutrients, contaminants, and other substances, with notable
68 impacts on water quality and ecosystem well-being (Mohanty, 2009; Lane et al., 2011; Béjaoui et al.,
69 2016). The water residence time, in turn, allows for the assessment of nutrient and pollutant retention
70 within the lagoons, as well as their potential concentration or degradation. Furthermore, water
71 circulation and residence times have the potential to shape habitats for lagoon-dwelling flora and fauna,
72 as well as the economic activities that depend on them (Balotro, 2003; Sylaios et al., 2006; Ferrarin et
73 al., 2013; Panda et al., 2015).

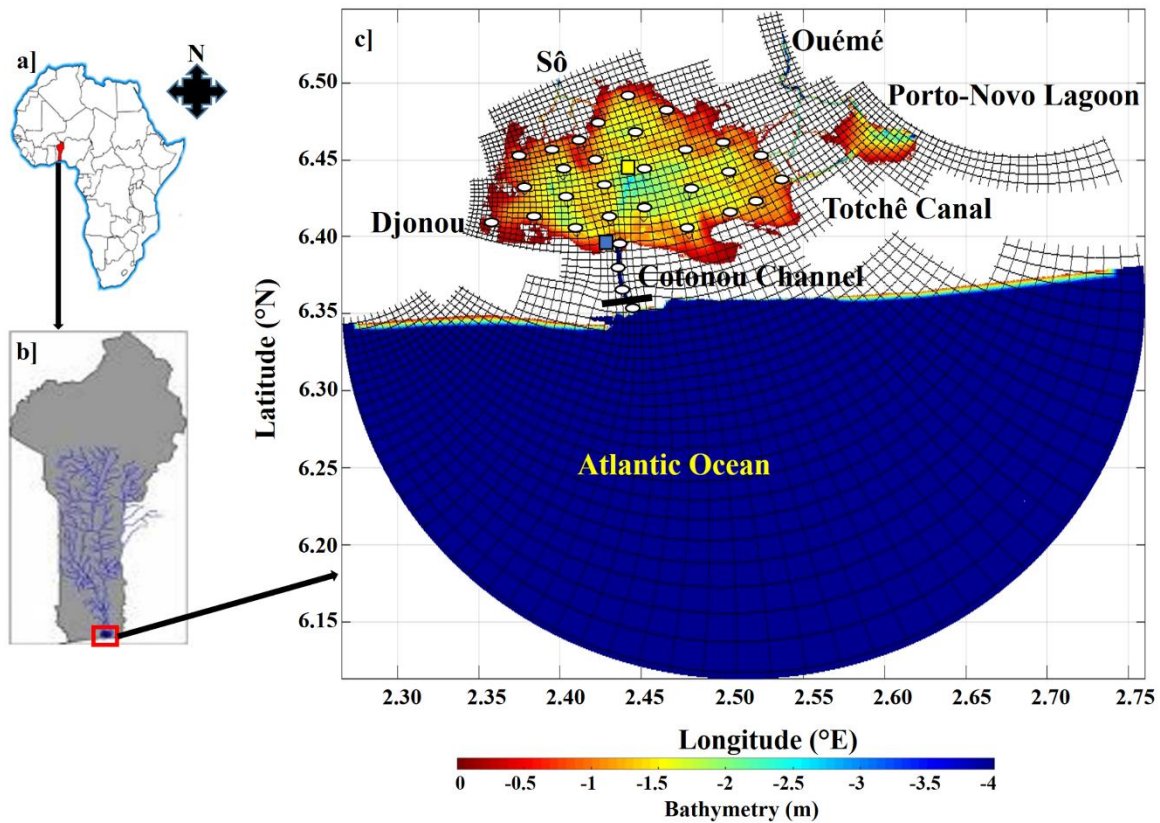
74 Coastal lagoons are subject to a variety of physical forcings that influence their dynamics and the
75 residence times of water masses. These physical drivers include freshwater inflow from catchments, the
76 intrusion and propagation of ocean tide through inlets, wind effects, or evaporation-precipitation fluxes
77 (Balotro, 2003; Lovato, 2010; O'Callaghan, 2011; Morales, 2020). Across various frequencies,
78 including semi-diurnal, diurnal, and fortnightly cycles, tides can lead to fluctuations in water levels and
79 alternating currents between the lagoon and the ocean (Sylaios et al., 2003; O'Callaghan et al., 2007).
80 These ocean-lagoon exchanges are typically accompanied by residual currents resulting from non-linear
81 interactions between tidal flow and local topography. These currents are important in the dispersion of
82 salt or phytoplankton, the transport of pollutants and the generation of turbidity maxima (Maier-Reimier,
83 1977; Robinson 1981; Sylaios et al., 2003; O'Callaghan et al., 2007; Du et al., 2019). Furthermore, the
84 seasonal variation in freshwater inflows associated with precipitation and river flow regimes can impact
85 lagoon dynamics in two key ways: i) by diluting the saltwater from the ocean and the resulting density
86 gradient that drives gravitational circulation, and ii) by creating, at seasonal scales, river-inlet
87 connections contributing to the flushing process (Pritchard, 1952; Lerczak and Geyer, 2006;
88 O'Callaghan et al., 2007; Sassi, 2013). Semi-permanent seasonal winds give rise to intricate circulation
89 patterns, contingent upon factors such as basin shape, wind direction, the vertical extent of turbulence,
90 and variations in basin bathymetry (Geyer, 1997; Lovato, 2010; O'Callaghan, 2011). These combined

91 processes collectively influence lagoon dynamics, the distribution and dispersion of water masses,
92 nutrients and pollutants, as well as the residence times of these substances within the lagoon.

93 In West Africa, the coastal zone along the Gulf of Guinea is characterized by a series of coastal
94 lagoons (Allersma and Tilmans, 1993; Adite and Winemiller, 1997; Lalèyè et al., 2007; Adite et al.,
95 2013) that provide essential ecosystem services to local communities (Pérez-Ruzafa et al., 2011;
96 Djihouessi et al., 2017; Newton et al., 2018). Additionally, these lagoons serve as sanctuaries, feeding
97 grounds, breeding sites, and nurseries for a diverse array of aquatic species (Pérez-Ruzafa et al., 2011;
98 Djihouessi et al., 2017; Panda et al., 2015; Newton et al., 2018). Among West African lagoons, Nokoué
99 Lagoon, located in southeastern Benin (Fig. 1), stands out as one of the most biologically productive in
100 the region (Lalèyè et al., 1995, 2003, 2007).

101 The Nokoué Lagoon, housing the largest lacustrine villages in West Africa, is subject to significant
102 natural variability, characterized by major seasonal changes in its physico-chemical parameters driven
103 by the hydrological regime (e.g. Djihouessi and Aina, 2018). Notably, the lagoon's salinity exhibits
104 significant seasonal fluctuations (Okpeitcha et al., 2022), leading to considerable alterations in the
105 composition and abundance of its ecosystem, ranging from plankton (Chaigneau et al., 2023) to fish
106 (Lalèyè et al., 2003). Recent studies, based on an intensive observational monitoring network unique in
107 the region and the development of simplified models, have contributed to a better understanding and
108 description of the Nokoué Lagoon's functioning (e.g. Okpeitcha et al., 2022; Chaigneau et al., 2022;
109 2023; Morel et al., 2022). However, the intricate water mass circulation, crucial for the redistribution of
110 physico-chemical properties and larval transport (Avigdor and Mark, 1997; Mohanty, 2009), remains
111 undocumented due to the challenges of obtaining observational data in this shallow and exploited
112 environment. The aim of our study is to address this gap using realistic three-dimensional numerical
113 simulations.

114 Due to urban development and strong population growth in the study region, the Nokoué Lagoon
115 faces substantial anthropogenic pressure (Dovonou et al, 2011; Zandagba et al. 2016), evident in
116 elevated levels of pollutants including heavy metals, pesticides and fecal bacteria (Lalèyè et al., 1997;
117 Ogutu - Ohwayo et al. 1997; Aina et al., 2012a; 2012b; Adjahouinou et al., 2012, 2014; Yehouenou,
118 2013). The fate of these pollutants, which are notably associated with wastewater discharge or rainwater
119 runoff from the shores, remains a major concern, given that their concentrations are prone to being
120 elevated in specific locations. This situation mirrors that of other lagoons influenced by reduced
121 freshwater inflow or substantial water retention (Swift and Bower, 2003; Sale et al., 2011; Baohong et
122 al., 2013; Lucinde et al., 2020; Peng et al., 2021). Hence, our study also aims to document water
123 residence times in Nokoué Lagoon on seasonal scales in order to better understand the fate of these
124 pollutants. Ultimately, through a series of numerical simulations, the final goal of this research is to
125 examine the responsiveness of circulation and residence times to tidal influences, wind patterns, and the
126 salinity gradient existing between the ocean and the lagoon.



128

129 Figure 1: Location of the Nokoué Lagoon: a) Benin in West Africa; b) Nokoué Lagoon and its
 130 watershed; c) Bathymetry, measuring stations and model domain. The white circles show the positions
 131 of the 31 CTD stations, the blue and yellow squares represent the water level and temperature stations
 132 respectively, and the black line is the ADCP section where lagoon-ocean water exchange are measured.
 133 The model grid shown is 1 point out of 10.

134

135 2. Materials and methods

136 2.1. Characteristics of the study area

137 Located in southeastern Benin, Nokoué Lagoon stretches approximately 20 km from east to
 138 west and 11 km from south to north, covering an area of around 150 km² and maintaining an average
 139 depth of 1.3 m during low water, which increases to approximately 2.5 m during the flood season (Texier
 140 et al., 1980; Mama et al., 2011; Djihouessi et al., 2019; Chaigneau et al., 2022). The climate is sub-
 141 equatorial defined by two alternating rainy periods (May to mid-July and September to October) and
 142 two dry seasons (November to April and mid-July to August). On an annual scale, the prevailing winds
 143 are characterized by southwesterly monsoon winds (Guèdjè et al., 2019), maintaining a relatively modest
 144 average speed of approximately 3 m/s. These winds emanate from the retroflexion of the trade winds.

145 From December to February, *harmattan* wind events originating from the northeast and typically lasting
146 for a few days can occur, with average intensities of around 2 m/s (Guèdjè et al., 2019).

147 Nokoué Lagoon is fed by two principal rivers, the Ouémé and the Sô (Fig. 1c), flowing into the
148 northern part of the lagoon. Their catchment areas are approximately 50000 km² and 1000 km²
149 respectively (Mama et al., 2011; Djihouessi et al., 2017). Cumulative river flow is in the range of a few
150 tens of m³/s during the low-water period (December-July) and peak at around 1200 m³/s during the flood
151 peak (September-November). This surge in flow and its interaction with tides cause the average lagoon
152 level to rise by approximately 0.9 m between the two seasons (Chaigneau et al., 2022; Morel et al.,
153 2022). A third river, the Djonou, contributes a minor amount of freshwater to the southwestern part of
154 the lagoon, although its flow is negligible compared to that of the Sô and Ouémé rivers (Djihouessi and
155 Aina, 2018). In its southern part, Nokoué Lagoon is connected with the Atlantic Ocean through the
156 Cotonou channel, measuring approximately 300 m in width and 4 km in length (Texier et al., 1980).
157 This channel facilitates the exchange of fresh and saltwater. Consequently, the average salinity of the
158 lagoon fluctuates from near 0 during high-water periods to approximately 25 during low-water periods.
159 Even slight changes in river flow can result in significant shifts in lagoon salinity during these low-water
160 periods (Okpeitcha et al., 2022, 2024). Towards the east, via the 4 km-long Totché canal, Nokoué
161 Lagoon is connected to Porto-Novo Lagoon. This link extends further eastward through a narrow coastal
162 canal that eventually flows into the Atlantic Ocean near Lagos, Nigeria, located about 100 km away
163 (Texier et al., 1980).

164

165 **2.2. SYMPHONIE model and configuration**

166 The three-dimensional SYMPHONIE free-surface model is used in this study. This model,
167 widely used for coastal ocean modelling (e.g. Estournel et al., 2001; 2005; 2012; Auclair et al., 2001;
168 Marine et al., 2008, 2013; Ulses et al., 2008; Hu et al, 2009; Bouchette et al., 2010; Michaud et al., 2012;
169 Herbert et al., 2011; Onguéné, 2015; Loisel et al., 2017; Nguyen-Duy et al., 2021), is based on the
170 discretized primitive equations on a curvilinear bipolar "Arakawa C" grid (Arakawa and Lamb, 1977)
171 using the finite difference and energy conservation method (Marsaleix et al., 2006; 2008). The k-epsilon
172 turbulent closure scheme, including the wave current effect, was implemented according to Costa et al.
173 (2017). The configuration used for this study encompasses the open ocean, Cotonou channel, Nokoué
174 Lagoon, rivers (So, Ouémé and Djonou) and Porto-Novo lagoon, which closes off towards Nigeria. The
175 horizontal grid features dimensions of 563×646 points, complemented by 10 generalized sigma vertical
176 levels. Mesh size varies from 30 m within the lagoon to 200 m offshore, with finer resolution in the
177 channel and coarser resolution in the open ocean (Fig. 1c). The turbulent closure scheme, important
178 for the vertical redistribution of tracers and momentum, is following the k-epsilon turbulent
179 scheme (Michaud et al., 2012). Bottom friction is taken into account using the logarithmic profile
180 approach and the definition of a roughness parameter Z_0 (Blumberg and Mellor, 1987). For the

181 results presented below we chose a typical value for the muddy bottom condition in the lagoon
182 with $Z_0 = 5 \cdot 10^{-4}$ m (see also below and discussion in section 4.2).

183 The forcings used in the reference simulation are, on one hand, large-scale three-dimensional
184 ocean forcings (temperature, salinity, free surface elevation, currents) from the MERCATOR system
185 based on the NEMO model (Maraldi et al., 2013). Additionally, tidal forcing is applied from the
186 FES2014 Tidal Atlas, considering the 9 main harmonic components within the domain (M2, N2, S2,
187 K2, K1, O1, P1, Q1 and M4). The astronomical tidal potential was implemented in the moment
188 equations (Peraud et al., 2008).

189 On the other hand, atmospheric forcings at the air/sea interface (radiative fluxes, heat fluxes,
190 wind shear stresses) are calculated, in the SYMPHONIE model, from bulk formulae using three-hourly
191 fields from the ECMWF meteorological model (Seyfried et al., 2017).

192 Finally, the river discharge used to force the model is estimated during flood periods from
193 observed water level differences between the lagoon and the ocean, using an inverse method developed
194 by Morel et al. (2022). Fluxes during low water periods are more challenging to estimate and required
195 calibration through sensitivity analyses. A minimum flux of $7.5 \text{ m}^3/\text{s}$ was necessary to realistically
196 simulate lagoon desalination near the rivers and reproduce the observed spatio-temporal distribution of
197 salinity at seasonal scales (Okpeitcha et al., 2022; 2024). Salinity serves as a key tracer for the
198 ecosystem, and the accurate modeling of its variability (Okpeitcha et al., 2024) suggests that the seasonal
199 exchanges of water between the watersheds and ocean, as well as the seasonal lagoon circulation and
200 residence times, are realistically represented. The recalibrated river discharges are introduced through
201 the lateral conservation conditions of volume and salinity.

202 The SYMPHONIE model operates in "splitting mode" with a barotropic time step of ~ 3 s
203 (external mode) and a baroclinic time step of ~ 28 s (internal mode). A period of two years was modelled
204 (October 2016 to December 2018), with the initial year (October 2016 – October 2017) considered the
205 model's spin-up. Consequently, this study focuses on analyzing the 15 months of simulation (October
206 2017 - December 2018), which constitutes the reference simulation labeled as *Ref*.

207 In order to explore the influence of key driving factors on the circulation and residence times
208 within Nokoué Lagoon, three additional simulations were performed alongside the reference simulation
209 (*Ref*):

- 210 • *NoTide* Simulation (*NoTide*): This simulation was run without tidal forcing, omitting
211 the influence of tides on the system.
- 212 • *NoSal* Simulation (*NoSal*): In this scenario, the dependence on salinity gradients was
213 removed. Salinity no longer impacts the density equation of state, altering its influence
214 on the system.

- *NoWind Simulation (NoWind)*: This simulation involved the exclusion of wind forcing from the moment equations, while retaining its significance for mixing assessment.

The primary objective of these simulations was to assess how these key driving factors impact the dynamics of the lagoon. All other external forces and parameters remained identical to the *Ref* simulation. Model outputs were stored at high frequency of approximately 30 minutes and were subsequently used to compute monthly or seasonal averages. Note that these simulations were also used by Okpeitcha et al. (2024) to study the mechanisms involved in the seasonal variations of the salinity in Nokoué Lagoon.

223

2.3. *In-situ data*

Between December 2017 and December 2018, 13 monthly multidisciplinary observation campaigns were carried out within the lagoon. These campaigns involved the collection of diverse physico-chemical parameters across 31 uniformly distributed stations positioned throughout the lagoon (see Fig. 1c, white circles). The focus here is on the vertical salinity profiles obtained at these stations through the use of a Conductivity Temperature Depth (CTD) probe (Valeport MIDAS CTD+ 300). The CTD probe operated at a frequency of 8 Hz, capturing data at intervals of approximately 0.1 dbar (equivalent to around 10 cm) across the water column, ranging from the water's surface to the lagoon bottom. Depth at the stations varied between approximately 0.5 meters and 2.5 meters in low water period, as illustrated in Fig. 1c. For each of the 12 monthly surveys, salinity data from the 31 stations were spatially interpolated onto a regular grid of resolution $\sim 100 \text{ m} \times 100 \text{ m}$, using an objective interpolation scheme (Bretherton et al., 1976; McIntosh, 1990; Wong et al., 2003).

Water exchanges between the Atlantic Ocean and the lagoon were assessed at the Cotonou channel through monthly measurements spanning December 2017 to October 2018 using an acoustic Doppler current profiler (ADCP Teledyne RDI WorkHorse 1200-kHz). Installed on a motorized vessel, this instrument captured vertical current profiles at intervals of 1 second along a nominal section oriented transversely to the channel's banks (black line in Fig. 1c). During each monthly campaign, the section was run repeatedly for more than 13 hours, to cover an entire semi-diurnal tidal cycle (which is the main tidal component along the Benin coast). For each of these sections, completed in less than 5 minutes, integration of the currents between the two banks of the channel is used to determine the inflow and outflow through the section. These flow values obtained for each individual section were subsequently averaged over time (~ 13 hours) to derive an average flow (with a ± 1 standard deviation range) between the lagoon and the ocean. This averaging process served to mitigate the influence of semi-diurnal tidal fluctuations. However, the duration of these monthly ADCP campaigns is not sufficient to resolve the

248 longer tide components such as the diurnal components, which is significant too. Thus, the determined
249 variability, based on semi-diurnal components only, is likely slightly underestimated in the observations.

250 To monitor fluctuations in water levels within the lagoon, we established a station located in the
251 southern region (blue square in Fig. 1c). This station was equipped with a pressure sensor (Onset HOBO
252 U20L-01 WL) positioned 20-30 cm above the bottom. The sensor was enclosed within a perforated PVC
253 tube with an external diameter of 7 cm. Data collection was conducted continuously at 20-minute
254 intervals from February 2018 to January 2020. The measurements offer a typical accuracy of ± 1 cm,
255 with a maximum error of 2 cm (Wilson et al., 2016; Guragai et al., 2018; Chaigneau et al., 2022).
256 Additionally, in the central area of the lagoon, a station was established for the purpose of high-
257 frequency temperature recording (yellow square in Fig. 1c). Near-surface temperature readings were
258 acquired every 30 minutes spanning the period from February 2018 to January 2020.

259

260 *2.4. Residence times of water in the lagoon*

261

262 Multiple definitions and methodologies exist for estimating relevant time scales crucial for assessing
263 a lagoon's inherent ability to renew its water masses (Bolin and Rodhe, 1973; Takeoka, 1984;
264 Zimmerman, 1988; Monsen et al., 2002; Abdelrhman, 2002). These time scales can be either global,
265 offering representation for the lagoon as a whole, or local, spatially resolved across lagoon. These
266 estimates can be derived using either Lagrangian or Eulerian approaches (Monsen et al., 2002; Cucco et
267 al, 2009).

268 In this study, a local residence time (T_R) is computed using a Eulerian approach (e.g. Cucco and
269 Umgiesser, 2006; 2009). This metric is established at every grid point (x,y) of the model, and pertains
270 to the duration required for the concentration of a passive and conservatively dissolved substance
271 ($C(x,y,t)$) -initially introduced into the current field with a concentration $C_0(x,y)$ - to significantly
272 decrease. Under the hypothesis of exponential decay (as in Delhez et al., 2004; 2014; Mudge et al, 2008;
273 Cucco et al., 2009; Liu et al., 2010; Umgiesser et al., 2014; Peng et al., 2021), the formulation is
274 represented as:

$$275 \quad C(x, y, t) = C_0(x, y)e^{-\alpha t} \quad (5)$$

276 Consequently, T_R is defined by $T_R = \frac{1}{\alpha}$, signifying the time necessary for the initial concentration of the
277 conservative substance to decrease by an exponential factor.

278 Subsequently, the local residence time will be estimated for different time periods by
279 homogeneously seeding the lagoon with a tracer of arbitrary concentration ($C_{o(x,y)} = I$) at the start of
280 each period. These introductions of tracer occur every 15 days between October 2017 and October
281 2018. For each seeding event, the progression of the tracer's concentration is tracked for over 6 months.
282 This comprehensive monitoring facilitates the construction of maps ($T_R(x,y)$) illustrating the spatial
283 distribution of Eulerian residence times.

284

285

286 3. **Results**

287 3.1. **Model validation**

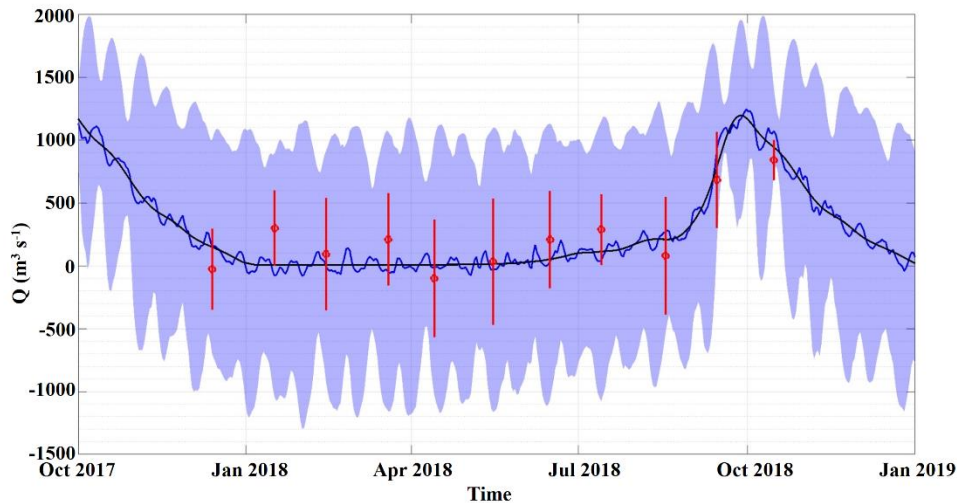
288 The aim of this Section is to validate the reference simulation (*Ref*) by comparing it with in-situ data
289 encompassing flows within the Cotonou channel, as well as measurements of water level, temperature,
290 and salinity within the Nokoué Lagoon.

291

292 a- **Flows within the Cotonou channel**

293 Fig. 2 shows the time series of channel-average flow modelled by the *Ref* simulation within the
294 Cotonou channel, juxtaposed with the ADCP measurements during the 11 field campaigns. The
295 simulated flows show strong daily variability around the mean flow, during both low-water periods (~ 30
296 ± 1000 m³/s) and flood periods ($\sim 1200 \pm 800$ m³/s). Average daily flows aligns relatively well to the
297 river flows forcing the model, yet they exhibit notable variability. This variability occurs across (semi-
298) diurnal time scales as well as at approximately 14-day intervals, originating from the interplay between
299 ocean tides and river flows (e.g. Morel et al., 2022). The modelled mean flows approximate the observed
300 mean flows, although the variability attributed to tidal signals, observed during the campaigns (± 300 -
301 400 m³/s), is somewhat lower than the simulated daily variability. It is worth noting that these
302 discrepancies in variability might partially stem from the ADCP's flow sampling, which covers only a
303 portion of the day and cannot replicate the diurnal modulation of the semi-diurnal tide. Metrics such as
304 the correlation coefficient, mean difference, normalized mean square error, and ratio of standard
305 deviations between the two datasets are calculated at 0.84, 26 m³/s, 58%, and 0.71, respectively. The
306 possible impact of stronger tidal currents in the model on our results is further discussed in Section 4.

307



308

309 Figure 2: Temporal variation in Cotonou channel flows and total river discharges. The blue curve and
 310 shaded area represent the daily mean ± 1 standard deviation of modeled flows. The red circles and
 311 vertical bars represent the mean ± 1 standard deviation of observed flows for each of the 11 ADCP
 312 campaigns. The black curve represents the total river inflow used to force the numerical simulation. A
 313 positive flow corresponds to a net outflow from Nokoué Lagoon to the Atlantic Ocean, while a negative
 314 flow corresponds to a net inflow from the ocean into the lagoon.

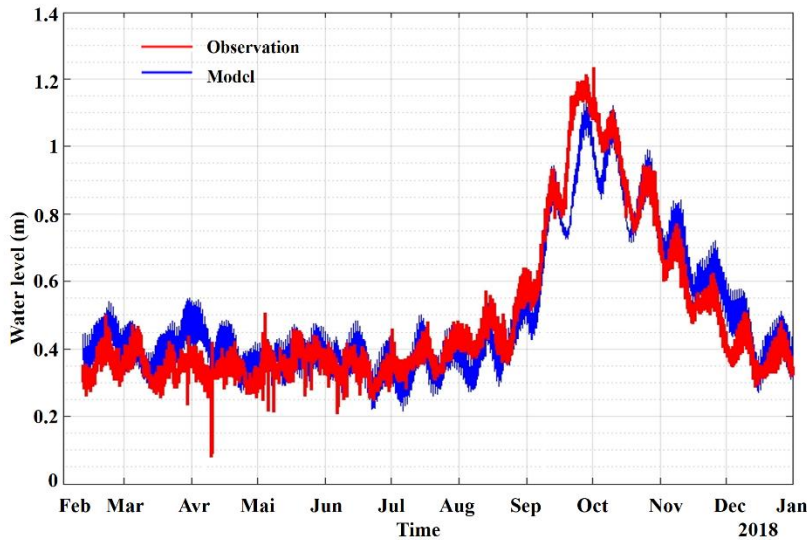
315

316 ***b- Water level in the lagoon***

317 Fig. 3 shows the time series of observed and modelled water levels in the south of the lagoon.
 318 The observations show multi-frequency variations, ranging from a few hours (e.g., seiches or semi-
 319 diurnal tides) to seasonal scales, as previously outlined (Chaigneau et al., 2022). Notably, these
 320 observations showcase consistent fortnightly water level oscillations, generated by nonlinear
 321 interactions involving oceanic spring and neap tides coupled with river dynamics (Morel et al., 2022).
 322 Additionally, there is a seasonal surge of approximately 80 cm observed at the peak of flooding in
 323 October. These mechanisms are accurately mirrored by the model, although the modeled elevation
 324 during peak flooding is slightly lower than observed. The divergence in mean elevation during the flood
 325 season between the model and observations might be attributed to several factors, such as the lack of
 326 dissipation in the channel during this time of the year (possibly due to structures like bridge piers that
 327 generate hydraulic surges not considered by the model). It is also plausible that the river flows forcing
 328 the model might not be sufficient during flood periods to attain the observed water level. However, it is
 329 worth noting that during this period, we will later demonstrate that the lagoon's rapid flushing results in
 330 minimal water retention. Hence, even if the modeled water level exhibits a lower peak elevation during
 331 flooding, it does not significantly impact the estimates of residence and flushing times for this season.

332 The correlation coefficient, mean difference, standardized mean square error, and ratio of standard
333 deviations between the two timeseries are of 0.94, 8 mm, 14% and 0.89, respectively.

334



335

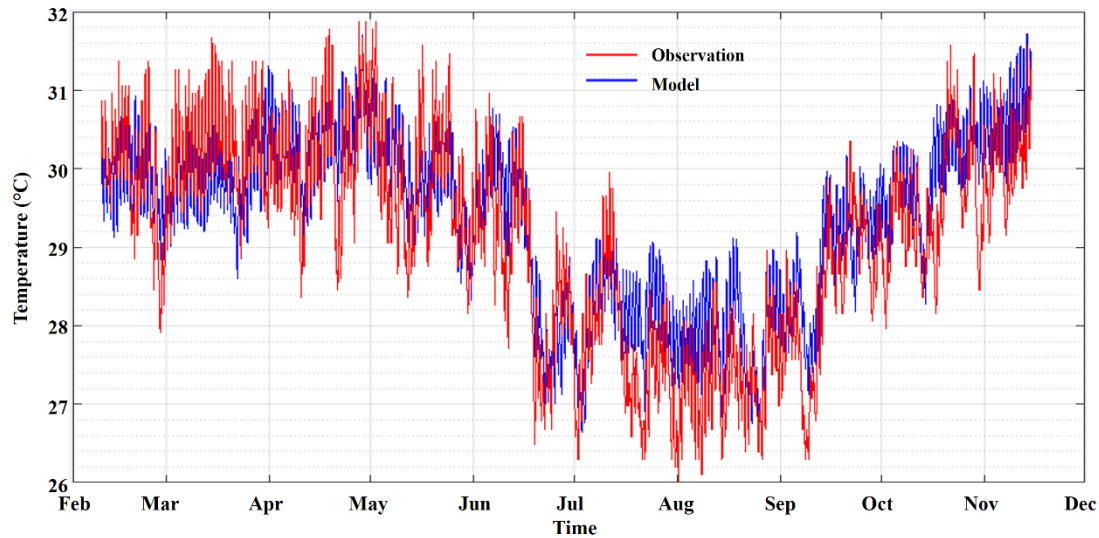
336 Figure 3: Time series of observed (red line) and modelled (blue line) water levels south of the lagoon.

337

338 *c- Temperature at the center of the lagoon*

339 Fig. 4 shows temperature variations at the center of Nokoué Lagoon. Measured and modelled
340 temperatures compare well, even though the model slightly overestimates high-frequency tidal
341 variations. Temperatures span from a minimum of 27-29°C during the period between mid-June and
342 mid-September to a peak of 30-31°C from November to May (Fig. 4). The correlation coefficient, mean
343 difference, normalized mean square error, and ratio of standard deviations between the two time series
344 are 0.89, 0.25°C, 2%, and 0.84, respectively. By filtering out the high-frequency tide-induced variations,
345 the low-frequency fluctuations exhibit an improved correlation with a correlation coefficient, mean
346 difference, normalized mean square error, and ratio of standard deviations reaching 0.96, 0.25°C, 1%,
347 and 0.87. These statistical measures affirm the model's adeptness in replicating the observed temporal
348 temperature dynamics.

349



350

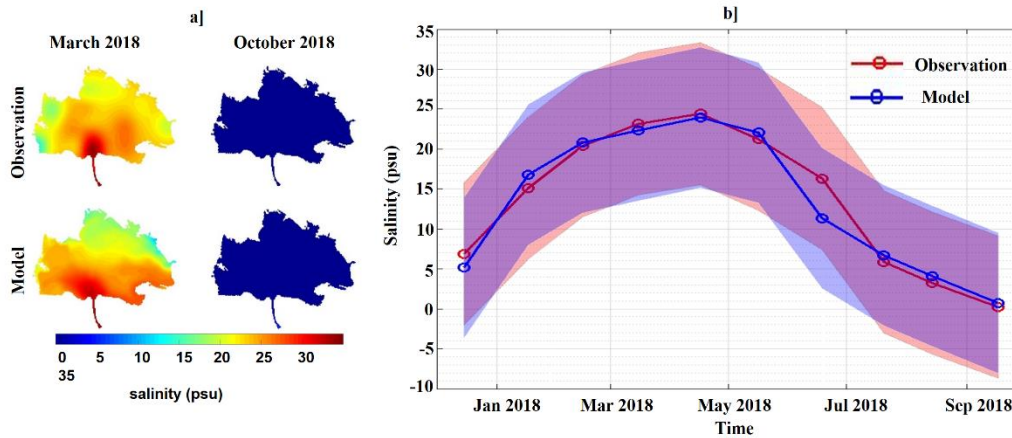
351 Figure (4): Temporal evolution of observed (red) and modeled (blue) temperature at the center of
 352 Nokoué Lagoon between February and December 2018.

353

354 *d. Salinity in the lagoon*

355 The model also captures well the observed spatial distribution of salinity, particularly evident in
 356 March when the lagoon exhibits higher salinity levels (Fig 5a). The correlation coefficient, mean
 357 difference, normalized root mean square error, and ratio of standard deviations between the model and
 358 observations are approximately 0.70, 0.14 psu, 12%, and 0.78, respectively. In particular, in October,
 359 the model aligns closely with observation as the salinity distribution features near-zero values within
 360 the lagoon. Low-frequency fluctuations in salinity, observed to shift between the low-water period (~25
 361 psu) and the flood period (~0 psu), are accurately replicated by the model (Figure 5b). On a seasonal
 362 scale, the correlation coefficient, mean difference, standardized squared error, and ratio of standard
 363 deviations between the two timeseries are 0.97, 0.28 psu, 10%, and 0.98, respectively. These findings
 364 demonstrate the model's capability to faithfully reproduce the observed variations in salinity, both
 365 spatially and seasonally. Readers seeking more detailed information on the *Ref* simulation's capability
 366 to accurately model the spatio-temporal variability of the salinity at monthly scales are referred to
 367 Okpeitcha et al. (2024).

368



369

370 Figure 5: The salinity regime in the lagoon: a) Spatial distribution of observed (top row) and modeled
 371 (bottom row) surface salinity in March and October 2018; b) Monthly trend in mean salinity in the
 372 lagoon, for observations (red line) and model (blue line). Shaded areas correspond to ± 1 standard
 373 deviation around mean values.

374 As evidenced above, the *Ref* simulation reproduces the major evolution patterns of observed
 375 flows, water levels, temperature, and salinity distribution within the lagoon (see also Okpeitcha et al.,
 376 2024). In particular, the satisfactory representation of spatio-temporal variability of salinity is of major
 377 importance when evaluating residence time using Eulerian or Lagrangian tracers. While acknowledging
 378 limitation in the model's representation of high-frequency currents in the Cotonou channel, whose
 379 possible impact is discussed in Section 4, the *Ref* simulation is estimated to give a satisfactory
 380 representation of the lagoon circulation and to be reliable for estimating residence time.

381

382 3.2. Lagoon circulation and sensitivity to different drivers

383 a- Seasonal circulation

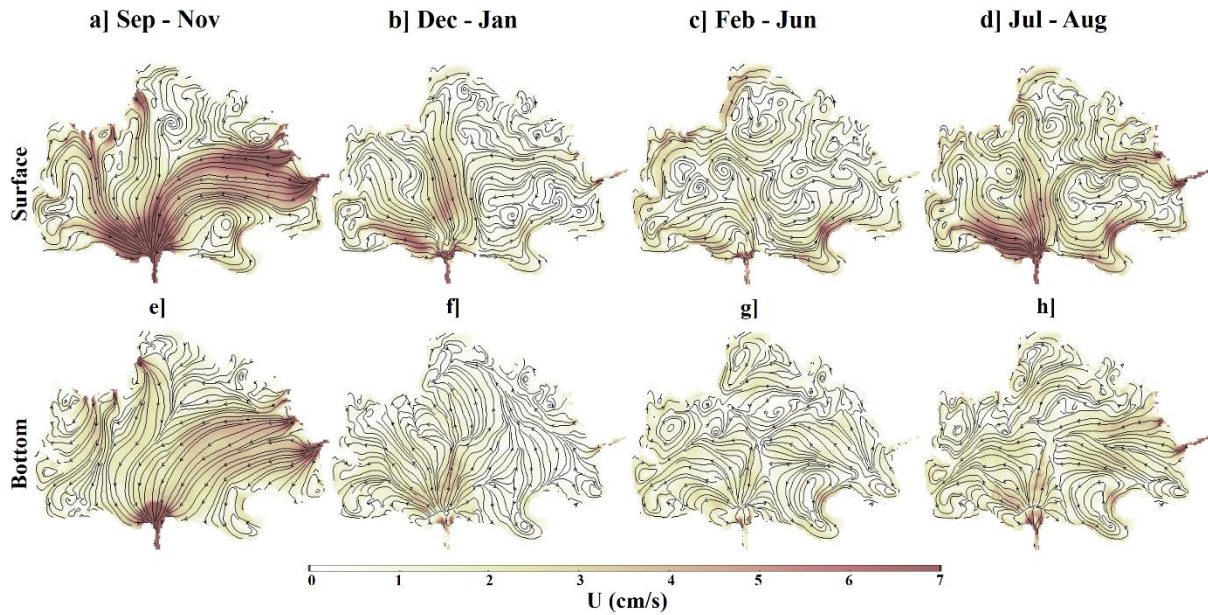
384 Fig. 6 shows seasonal variations in surface (top panel) and bottom (bottom panel) circulations for
 385 four distinct periods. During the flood period (September-November), the substantial inflow of
 386 freshwater ($\sim 1200 \text{ m}^3/\text{s}$) from the Sô and Ouémé rivers results in relatively strong mean currents (>7
 387 cm/s) within the lagoon, establishing a connection between the rivers and the Cotonou channel (Fig. 6a).
 388 The circulation pattern exhibits quasi-barotropic behavior, with bottom currents mirroring those at the
 389 surface, albeit at slightly reduced intensities ($\sim 4 \text{ cm/s}$) (Fig. 6e). Notably, the mean outflow through the
 390 channel is particularly vigorous during this phase of high water levels, with average surface outflow
 391 currents of approximately $\sim 70 \text{ cm/s}$ and bottom outflow currents of about $\sim 35 \text{ cm/s}$. This pronounced
 392 outflow significantly curtails the impact of tidal influence in the southern part of the lagoon during this
 393 period.

394 Subsequent to the flood period, a transitional phase (December-January) occurs, characterized by a
395 sharp reduction in freshwater inflow ($\sim 100 \text{ m}^3/\text{s}$, Fig. 2) and an increase in salinity (Fig. 5; [Okpeitcha et](#)
396 [al., 2022; 2024](#)). During this period, surface circulation within the lagoon weakens significantly (~ 2
397 cm/s), though the connection between the rivers and the Cotonou channel remains discernible (Fig. 6b).
398 Distinct recirculation cells become apparent to the southeast of the lagoon, implying water retention in
399 that region. The circulation pattern exhibits vertical shear, with a surface outflow of approximately ~ 5
400 cm/s and a bottom inflow of around $\sim 2 \text{ cm/s}$ (Fig. 6f). This pattern is typical for stratified estuarine and
401 lagoon circulations, where saltwater infiltrates in the bottom layer while freshwater flows seaward at the
402 surface.

403 Throughout the low-water season (February-June), river discharge is minimal ($< 10 \text{ m}^3/\text{s}$, as
404 indicated in Fig. 2), resulting in peak salinity levels (Fig. 5b; [Okpeitcha et al., 2022; 2024](#)). During this
405 period, surface circulation becomes more complex, marked by the presence of numerous recirculation
406 and water retention cells. These average recirculation cells typically exhibit scales on the order of few
407 kilometers. Additionally, a northward current emerges along the western periphery of the lagoon (~ 3
408 cm/s), while discernible west-east connections establish in the central and southern sectors. Near the
409 bottom, circulation maintains this complexity, albeit being influenced by an east-west current ($\sim 1 \text{ cm/s}$).
410 Oceanic water inflow persists in the south-western region of the lagoon.

411 Finally, during the July-August desalination period (Fig. 6d), river inflow to the lagoon increase
412 again ($> 100 \text{ m}^3/\text{s}$, Fig. 2), and the more direct connection between the rivers and the Cotonou channel
413 are gradually re-established ($\sim 4 \text{ cm/s}$). At the bottom, circulation is similar to that observed during low-
414 water periods, with an east-west flow ($\sim 1 \text{ cm/s}$) and a penetration of water from the Cotonou channel
415 towards the south-west of the lagoon.

416



417

418 Figure 6: Mean seasonal surface (top panel) and bottom (bottom panel) circulation. a & e] flood period
 419 (September-November), b & f] salinization period (December-January), c & g] low-water period
 420 (February-June), d & h] desalination period (July-August). The colored background corresponds to
 421 current intensity, while streamlines are shown in black.

422

423 ***b- Sensitivity of lagoon circulation to wind, tide and salinity gradient***

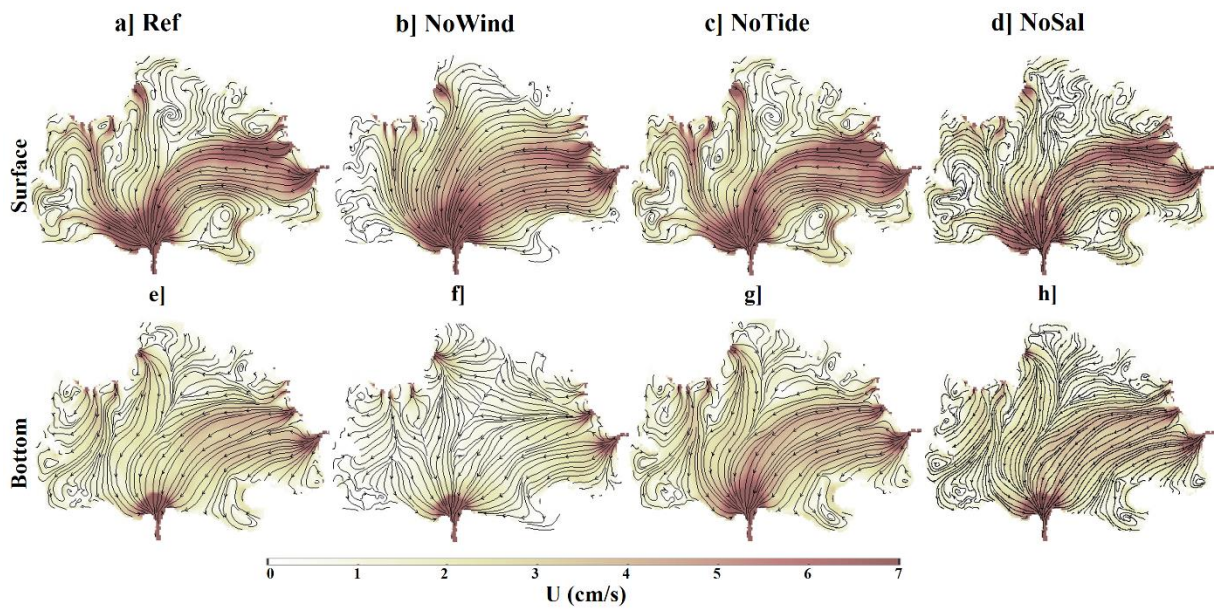
424 During the flooding period, prevailing winds across the lagoon primarily originate from the
 425 southwest as monsoon or trade winds, averaging around ~ 2.5 m/s. The *NoWind* simulation results in a
 426 ~ 1 cm/s increase in surface currents (Fig. 7b) and a ~ 1 cm/s decrease in bottom currents (Fig. 7f)
 427 compared to *Ref* (Fig. 7a and 7e). This significant difference is attributed to the wind-induced creation
 428 of a baroclinic circulation in the direction of the wind at the surface and in the opposing direction at the
 429 bottom (Bernardi et al., 2012; Cerralbo et al, 2016; Peng et al., 2021). This phenomenon moderates the
 430 north-south circulation on the surface and intensifies it at the bottom in *Ref*.

431 In contrast, the *NoTide* simulation (Fig. 7c and 7g) does not show a significant difference in
 432 circulation compared to *Ref* (Fig. 7a and 7e). However, the connection between the Sô and the Cotonou
 433 channel is slightly reinforced in the absence of tidal effects. This suggests that the tide tends to promote
 434 an average penetration of oceanic water predominantly from the southwest, as already noted above. In
 435 the case of the *NoSal* simulation (Fig. 7d and 7h), the exclusion of the salinity gradient influence within
 436 the forcings yields a minor decrease in surface circulation along the main current pathway connecting
 437 the Sô River to the Cotonou channel. Conversely, an increase in bottom currents is observed in the

438 southern part, in comparison to the *Ref* simulation (Figs. 7a and 7e). This underscores the role of the
 439 salinity gradient in shaping the circulation, although its impact remains relatively minor.

440 During the flood period, freshwater inflow is the main driving force behind circulation, along with
 441 wind, while the tide and salinity gradient play a lesser role in mean circulation.

442



443

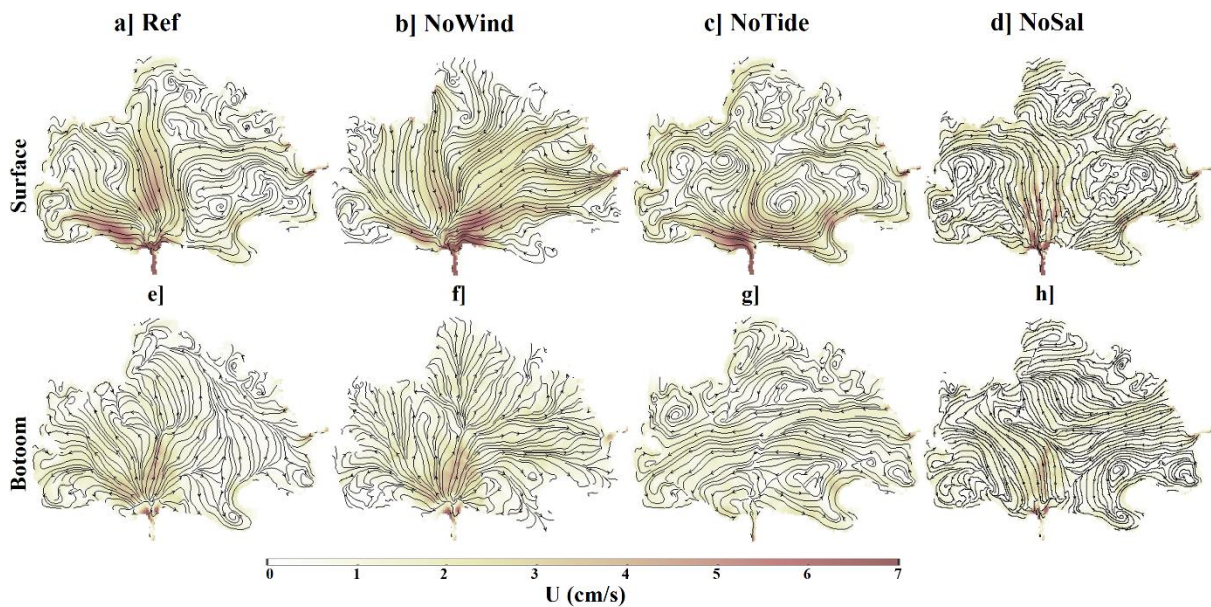
444 Figure 7: Influence of tide, wind and salinity gradient on surface and bottom circulation during flooding
 445 (September-November): a & e] Simulation *Ref*, b & f] Simulation *NoWind*, c & g] Simulation *NoTide*, d
 446 & h] Simulation *NoSal*. The majority of winds come from the south-west of the lagoon (averaging ~ 2.5
 447 m/s). Average river discharge during this period is $\sim 700 \text{ m}^3/\text{s}$.

448 During the salinization periods, river inflow significantly reduces ($\sim 100 \text{ m}^3/\text{s}$), and prevailing
 449 winds maintain a southwestern direction at approximately 2.6 m/s (wind rose in Fig. 8). During this
 450 phase, we observe only three occurrences of north-easterly wind events (harmattan), each lasting 1-3
 451 days. Within this timeframe, the *NoWind* simulation (Fig. 8b) displays increased surface currents,
 452 rendering the river-channel connections more pronounced than those in the *Ref* simulation (Fig. 8a). At
 453 the bottom (Fig. 8f), changes in circulation are also apparent compared to the *Ref* scenario (Fig. 8e),
 454 particularly in the northeastern area where bottom waters exhibit increased propagation towards the
 455 channel in the *NoWind* case. Hence, winds once again dampen surface and bottom circulation, especially
 456 in the northeastern region of the lagoon. In the *NoTide* simulation (Fig. 8c), surface recirculation and
 457 water retention cells intensify in contrast to the *Ref* case (Fig. 8a), while at the bottom (Fig. 8g), the
 458 absence of tidal effects leads to circulation patterns characterized by the emergence of east-west
 459 connections. Similarly, the *NoSal* simulation (Figs. 8d and 8h) reveals that removing the salinity gradient
 460 effect affects the circulation structure at both the surface and, more prominently, at the bottom, in

461 comparison to the *Ref* case (Figs. 8a and 8e). This shows that baroclinic flows induced by (horizontal
 462 and vertical) salinity gradients play a significant role, particularly at the bottom, in the progression of
 463 brackish water towards the eastern reaches of the lagoon.

464 Beyond the contribution of river inflows, the interplay of the tide, salinity gradient, and wind
 465 significantly shapes the circulation patterns during the salinization period. This results in surface and
 466 bottom exchanges between the lagoon and the ocean, as well as in the organization of circulation
 467 structures within the lagoon, including the emergence of east-west connections and the formation of
 468 recirculation cells.

469



470

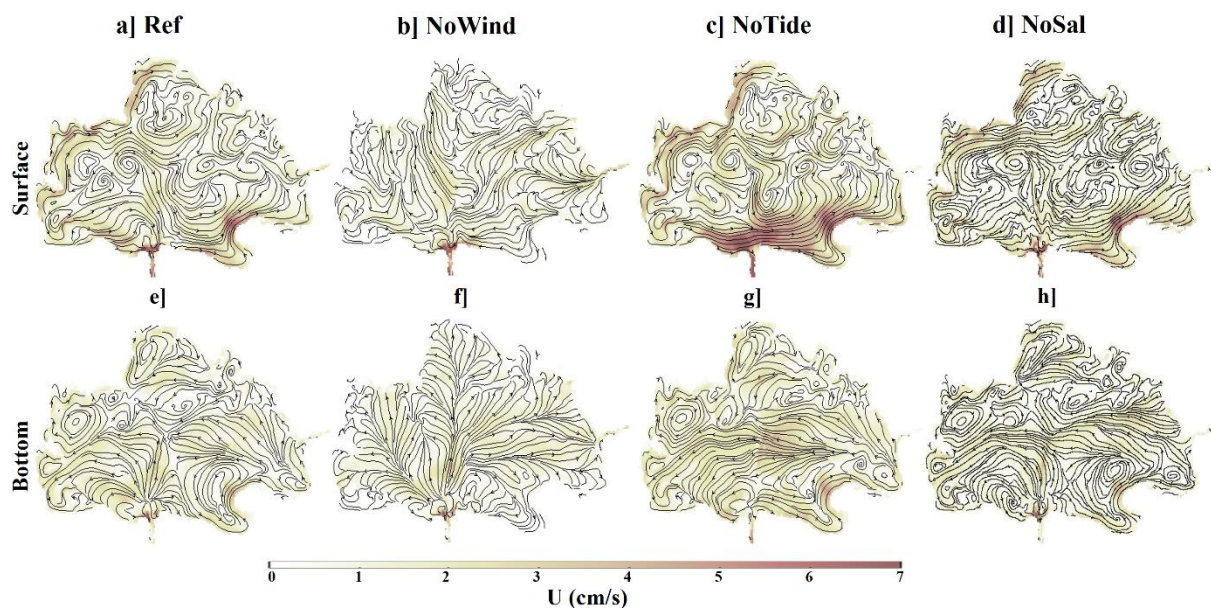
471 Figure 8: Influence of tide, wind and salinity gradient on surface and bottom circulation during
 472 salinization (December-January): a & e] Simulation *Ref*, b & f] Simulation *NoWind*, c & g] Simulation
 473 *NoTide*, d & h] Simulation *NoSal*. The majority of winds come from the south-west of the lagoon
 474 (averaging ~ 2.6 m/s). Average river inflow during this period is ~ 100 m³/s.

475 During the low-water period (February-June), characterized by the lowest flows of the year (~ 10
 476 m³/s), prevailing winds average around ~ 3.3 m/s, predominantly from the southwest. The *NoWind*
 477 simulation (Fig. 9b) reveals a shift in the surface circulation pattern, marked by the emergence of river-
 478 channel connections and the vanishing of recirculation and water retention cells, contrasting with the
 479 *Ref* simulation (Fig. 9a). This implies that wind-induced circulation fosters instabilities and eddies,
 480 thereby promoting the emergence of recirculation zones at the surface (Fig. 9b). At the bottom (Fig. 9f),
 481 the *NoWind* simulation also leads to circulation alterations, including the dissolution of recirculation and
 482 retention cells. When eliminating the tide (*NoTide*), the surface circulation (Fig. 9c) remains largely
 483 unchanged compared to *Ref* (Fig. 9a), except in the vicinity of the channel where exchanges with the

484 ocean are considerably weaker. Meanwhile, the *NoTide* simulation (Fig. 9g) shows that the absence of
 485 tides marginally modifies the bottom circulation, reinforcing the observed east-west flow during this
 486 period (Fig. 9e). As for the *NoSal* simulation (Figs. 9d and 9h), the removal of salinity-dependent effects
 487 slightly enhances the complexity of the surface circulation structure, while at the bottom, the east-west
 488 flow gains some strength compared to *Ref* (Figs. 9a, 9e) during this interval. It is noteworthy that during
 489 this phase, the lagoon's salinity becomes more spatially uniform, with horizontal salinity gradients being
 490 less pronounced compared to the salinization period (Okpeitcha et al., 2022; 2024). Additionally, the
 491 efficacy of the wind-driven mixing process weakens the salinity gradient resulting from the convergence
 492 of modest river input and the saltier ocean water.

493 Consequently, wind influence emerges as the primary driver for lagoon circulation during the
 494 low-water period, particularly in terms of turbulence generation and the formation of recirculation
 495 structures. The effects of the tide and salinity gradient are small during this time of the year, except in
 496 the immediate vicinity of the channel.

497



498

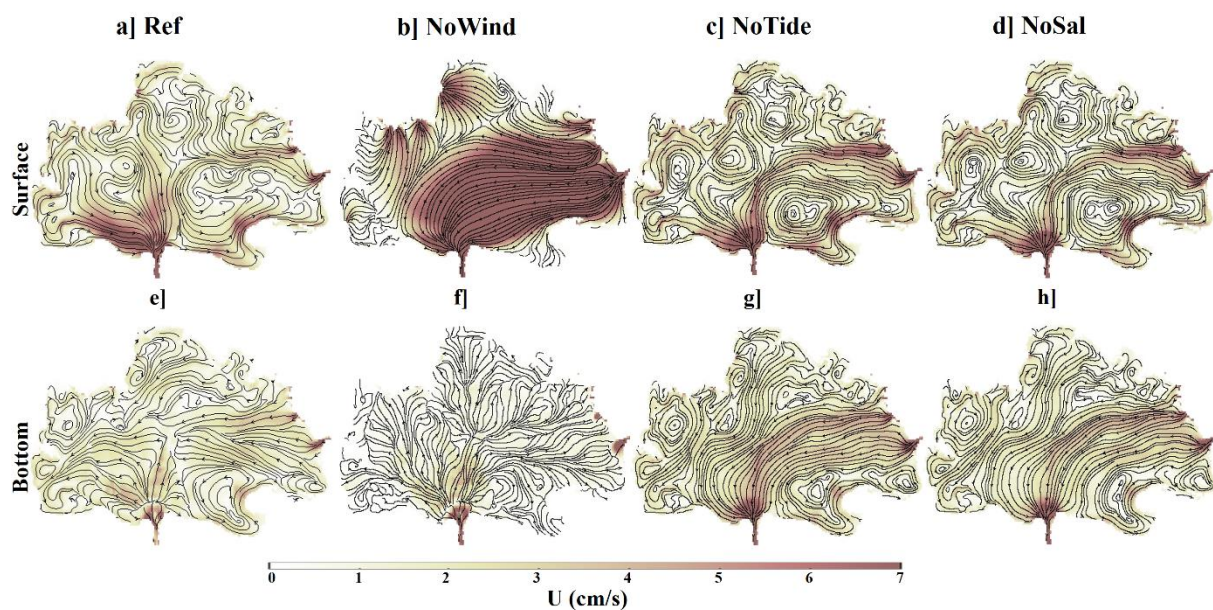
499 Figure 9: Influence of tide, wind and salinity gradient on surface and bottom circulation during low
 500 water (February-June): a & e] Simulation *Ref*, b & f] Simulation *NoWind*, c & g] Simulation *NoTide*, d
 501 & h] Simulation *NoSal*. The majority of winds come from the south-west of the lagoon (averaging ~ 3.3
 502 m/s). Average river inflow during this period is ~ 10 m³/s.

503 In the desalination period (July-August), river flow gradually increases (~ 200 m³/s),
 504 accompanied by prevailing southwesterly winds with an average intensity of ~ 3.7 m/s (wind rose in Fig.
 505 10). This period is marked by significant changes in circulation dynamics. The *NoWind* simulation (Fig.
 506 10b) depicts a notable difference in current patterns, displaying a pronounced Ouémé-channel

507 connection compared to *Ref* (Fig. 10a). At the bottom (Fig. 10f), a dominance of water entry via the
 508 channel is observed, and the east-west flow component distinctive to *Ref* (Fig. 10e) vanishes. During
 509 this phase, winds notably attenuate surface circulation and reshape bottom currents, generating
 510 recirculation cells. The *NoTide* and *NoSal* simulations have relatively smaller effects on circulation. In
 511 the *NoTide* simulation (Fig. 10c), surface recirculation cells to the west of the lagoon gain slight
 512 intensity, inhibiting a more direct connection between the Sô and the channel seen in *Ref* (Fig. 10a).
 513 Meanwhile, at the bottom (Fig. 10g), the absence of tides leads to an enhanced river-channel connection
 514 compared to *Ref* (Fig. 10e). Similar to the tide, the *NoSal* simulation showcases a comparable influence
 515 due to the absence of the salinity gradient effect (Fig 10h).

516 In summary, during the desalination period, the interplay of wind and river inflow significantly
 517 shapes circulation patterns, with wind playing a decisive role. On the other hand, the tide and salinity
 518 gradient assume secondary roles in the circulation dynamics, similar to the low water period.

519



520

521 Figure (10): Figure 10: Influence of tide, wind and salinity gradient on surface and bottom circulation
 522 during desalination (July-August): a & e] Simulation *Ref*, b & f] Simulation *NoWind*, c & g] Simulation
 523 *NoTide*, d & h] Simulation *NoSal*. The majority of winds come from the south-west of the lagoon
 524 (averaging ~ 3.7 m/s). Average river inflow during this period is ~ 200 m³/s.

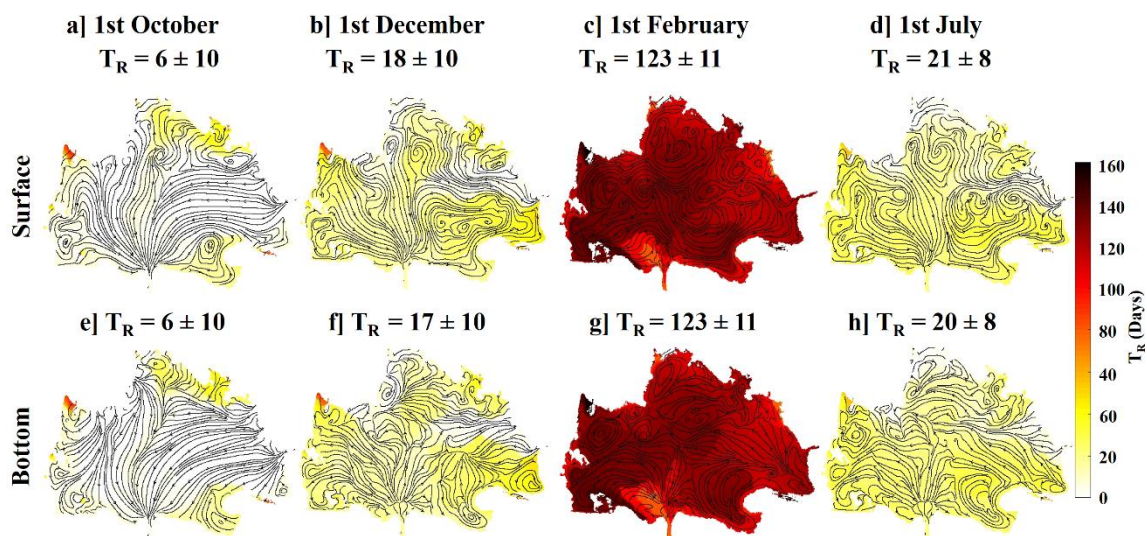
525

526 3.3. Residence times of water masses in Nokoué Lagoon

527 a- Local residence time

528 Fig. 11 illustrates the spatial distribution of water mass residence times (T_R) for both surface and
529 bottom layers, along with the corresponding mean circulation patterns, during various periods in the *Ref*
530 simulation. During the flood season in October (Figs. 11a and 11e), surface and bottom water residence
531 times are notably short (<7 days) across most of the lagoon. These short residence times result directly
532 from the strong river inflow, establishing a direct link with the channel exit, as indicated by the previous
533 circulation diagrams (Fig. 6a and 6e). However, sheltered areas in the north and south of the lagoon
534 exhibit extended residence times (sometimes exceeding 1 month). As the salinization period commences
535 in early December (Fig. 11b and 11f), the influence of river inputs partially diminishes, and the
536 emergence of recirculation cells contributes to slightly longer residence times at both the surface
537 (average ~18 days) and bottom (average ~17 days). Areas of water retention identified during the flood
538 period expand, and new retention zones emerge at the lagoon's western and eastern edges. Moving into
539 the low-water period in February (Fig. 11c and 11g), residence times for surface and bottom water reach
540 several months (average ~123 days). Recirculation and retention cells span the entire lagoon, even
541 extending far from the edges. With the exception of small regions close to the Cotonou channel or river
542 mouths, residence times are uniform throughout the lagoon. Finally, as the desalination period initiates
543 in early July (Fig. 11d and 11h), both surface and bottom water residence times significantly reduce
544 again (average ~21 days for surface and ~20 days for bottom). This decrease is attributed to the
545 increasing influx of river water, favoring reconnections to the ocean. As would be expected, longer T_R
546 values correspond to periods characterized by recirculation cells, while shorter T_R values coincide with
547 times of direct river-channel connections influenced by river inflows. Finally, it is also noteworthy that
548 the average T_R across the lagoon remains nearly identical between the surface and the bottom, with only
549 minor vertical disparities.

550
551



552

553 Figure 11: Local water-mass residence times (T_R , in days) and associated mean circulation. T_R were
554 obtained for a passive tracer deployment on: a & e] 1st October, b & f] 1st December, c & g] 1st February,
555 d & h] 1st July.

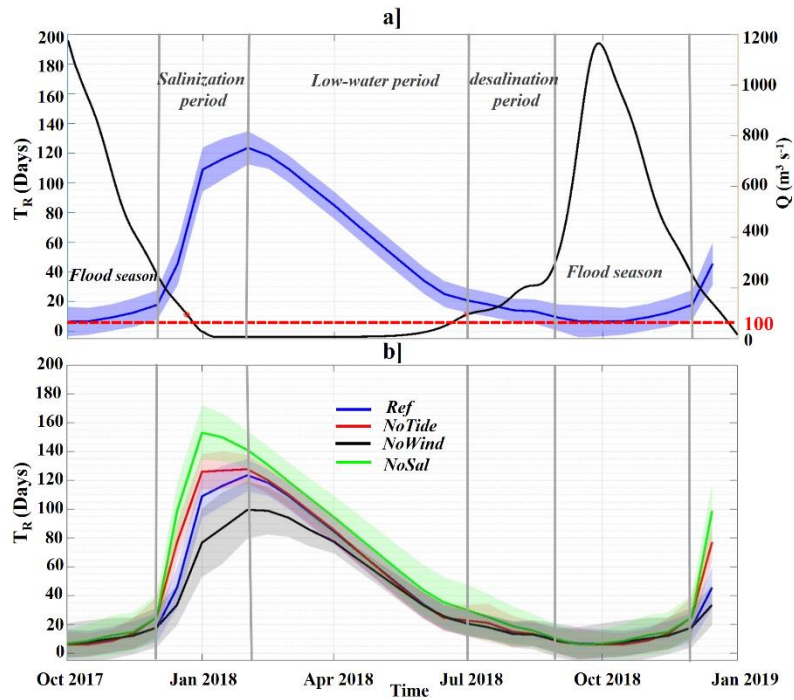
556

557 ***b- Seasonal cycle of mean residence times and sensitivity to different forcings***

558 Fig. 12a shows the seasonal cycle of average residence times obtained in the *Ref* simulation at two-
559 week intervals. This figure shows that during salinization and low-water periods (December-June),
560 average T_R are much longer (4 to 1 month), due to low river inflows and complex circulation
561 characterized by water retention cells. Conversely, during desalination and flood periods (July-
562 November), average T_R contract to just a few days, attributable to strong freshwater influx from rivers
563 and a nearly barotropic circulation oriented towards the ocean. Notably, the mean T_R exhibits a rapid
564 and consistent decline from February to July.

565 Fig. 12b illustrates the impact of the main drivers (river inflow, tide, wind, and salinity gradient) on
566 the mean T_R dynamics. From May to November, all simulations consistently yield similar average T_R
567 values, associated with the sudden raise of the river flows and rapid flushing of the lagoon at the
568 beginning of the wet season. In contrast from November to May, during the salinization and low water
569 periods, T_R is more affected by other forcings. The *NoWind* simulation results in shorter residence times,
570 reaching up to 50 days less than those of *Ref*. In contrast, the omission of the salinity gradient effect in
571 the lagoon dynamics yields a mean T_R (*NoSal*) that surpasses mean T_R (*Ref*) by approximately 10 to 50
572 days. Similarly, when the tide is absent, the mean T_R (*NoTide*) extends by approximately 15 to 30 days
573 compared to mean T_R (*Ref*) but only between December to February. Thus, winds and baroclinic effects
574 related to salinity gradients have a more significant impact on the average T_R than the tide-induced
575 circulation.

576



577

578

579 Figure 12: a) Seasonal cycle of the lagoon's mean surface residence time (in blue, the curve is very close
 580 for the bottom). River flows are shown in black (right axis), b) Sensitivity of mean surface residence
 581 time (T_R) in the lagoon to different forcings: *Ref* (blue), *NoWind* (black), *NoTide* (red) and *NoSal*
 582 (green). Shaded areas correspond to ± 1 standard deviation around the mean values.

583

584 4. Discussion

585 4.1. Seasonal circulation and residence times

586 The circulation patterns within the Nokoué Lagoon exhibit significant seasonal variations, primarily
 587 influenced by fluctuations in river flow. These seasonal shifts in circulation are also associated with
 588 marked variations in other parameters, such as water levels (Chaigneau et al., 2022; Morel et al., 2022),
 589 salinity (Okpeitcha et al., 2002; 2024), or turbidity of the water column (Ntangyong et al., under review).
 590 These fluctuations, directly influenced by seasonal monsoonal precipitation that drives river flow,
 591 strongly impact ecosystem characteristics and variability, from plankton (e.g. Chaigneau et al., 2023) to
 592 fish populations (Lalèyè et al., 1995; 2003; 2007). However, our results indicate that circulation patterns
 593 are further influenced, to varying degrees depending on the season, by additional factors such as oceanic
 594 tides, wind patterns, and baroclinic effects arising from salinity gradients. The seasonal circulation
 595 forced by these external factors significantly impacts the residence times of water-masses and tracers
 596 within the lagoon, as also suggested from salinity studies (e.g., Okpeitcha et al., 2024). This may have
 597 important implications for both pollutant dynamics and ecosystem equilibrium within the lagoon,
 598 associated with nutrient cycling and primary productivity (Lane et al., 2011; Rodhe, 1992).

599 For instance, our results highlight that during periods of low water, mean currents tend to be
600 relatively weak. This weak circulation fosters the formation of recirculation cells that effectively trap
601 water within the lagoon, thereby extending residence times to several months. These rather long
602 residence times, could lead to pollutant accumulation, potentially posing risks to ecosystem health and
603 biodiversity. Conversely, during high water periods, intensified and nearly barotropic currents are
604 observed, establishing direct connections between the rivers and the Cotonou channel and facilitating
605 the efficient discharge of water towards the ocean. This results in significantly shorter residence times,
606 often spanning only a few days that may result in rapid flushing of pollutants, potentially reducing their
607 accumulation and mitigating adverse effects on aquatic life.

608 Furthermore, the transition between these two seasonal extremes is characterized by a sharp and
609 consistent decline in mean T_R from February to July. This linear trend underscores the role of river flow,
610 particularly during the June-July period when discharge rates typically range from 50 to 100 m³/s, in
611 efficiently flushing water out of the lagoon and exerting dominant control over residence times even
612 throughout much of the low-water season. Similarly, at the end of flood period, T_R begins to sharply
613 increase when river discharge falls below approximately 100 m³/s. These findings corroborate recent
614 studies highlighting the existence of a critical threshold of river discharge, typically between 50-100
615 m³/s, necessary for effective lagoon flushing. For instance, using a simplified box model, Okpeitcha et
616 al. (2022) estimated that a modest increase in river discharge of 10-15 m³/s during the dry season could
617 yield a substantial 30% reduction in salinity, with complete desalination occurring at discharge rates
618 surpassing ~50-60 m³/s. Based on these results, Okpeitcha et al. (2024) used the realistic SYMPHONIE
619 model and similar simulations than used here, revealing that river discharge exceeding 100 m³/s rapidly
620 reduced average salinity to below ~5 within few days, aligning closely with the abbreviated residence
621 times observed in the present study.

622

623 ***4.2. Impact of external drivers and identified limitations***

624 Our results emphasized the impact of external forcings, (tides, winds, and salinity gradients) on
625 average T_R , particularly during the salinization and low water periods spanning from November to May.
626 Winds play a role in retaining water masses within the lagoon, while river inflow, tides, and salinity
627 gradients promote evacuation. We will now briefly discuss each mechanism separately and highlight
628 some limitations of our simulations.

629 The *NoTide* simulation results in longer T_R , extending from 15 to 30 days beyond those of the *Ref*
630 simulation during December-January, with the most significant disparities observed at the onset of the
631 salinization phase in December (Figure 12). This underscores the significant role of tide-induced flow
632 in facilitating partial water renewal within the lagoon, particularly near the mouth of the Cotonou
633 channel, where tidal influence is most pronounced. Non-linear interactions among tides, river flow, and

634 friction within the Cotonou channel influence fluxes (e.g., Morel et al., 2022) and thus T_R . Notably this
635 mostly leads to a delay in T_R increments when tides are considered (Figure 12). This 2-month period
636 (December-January) corresponds to the adjustment time of the lagoon under the tidal effect, before the
637 average salinity of the lagoon reaches equilibrium (Okpeitcha et al., 2024).

638 As explained above, the present simulations considered an a typical roughness parameter Z_0 for
639 which tidal flows in the Ref simulation appear stronger than those observed from ADCP data (Fig. 2),
640 so that the Ref simulation overestimates the effect of tides. As discussed above, this effect is limited to
641 the beginning of the salinization period and increases exchanges mostly near the channel mouth. A more
642 realistic global T_R evolution curve would thus lay somewhere between the blue and red curves on Fig.
643 12. We limited the scope of the study to the present simulations, but to further limit the tidal fluxes in
644 the channel, additional work is necessary and several approaches are possible. First, increasing Z_0 within
645 the channel is the first obvious choice, but the present value leads to equivalent bottom friction that are
646 already pretty high in the channel ($C_D \sim 5 \cdot 10^{-3}$). Higher values can thus become unrealistic and has also
647 limited impact on the fluxes since, in our baroclinic simulations, velocity reduction by bottom roughness
648 is limited to the bottom boundary layer, whose thickness is determined by the turbulent closure scheme.
649 Thus using alternative closure schemes, more adapted to represent the effect and extension of the
650 turbulent bottom boundary layer, is probably necessary too. Another possibility is to modify the water
651 depth. The channel being narrow, the strong lateral depth variations are not well represented in the
652 model. Increasing the resolution requires much more computation time, but it is possible to modify the
653 bathymetry (slightly decrease the depth in some areas) to limit the fluxes. Finally, it may also be
654 important to consider the dissipation and limitation of fluxes associated with bridge pillars (there are
655 three bridges along the channel). In a structured grid model such as SYMPHONIE this can be done by
656 imposing frictional effects over the whole water column close to each pillar position, but the tuning of
657 the frictional coefficient is unclear for now.

658 In a similar context, it is important to highlight the presence of artificial fishing parks, referred
659 to as "acadjas" (Chaffra et al., 2020; Niyonkuru et Lalèyè, 2010; Welcomme, 1972), within the lagoon.
660 These acadjas are composed of a multitude of branches and aim to mimic the natural mangrove habitat.
661 Occupying approximately 16% of the total area of the lagoon (Chaffra et al., 2020), these artificial
662 structures provide refuge and breeding areas for fishes (Villanueva et al., 2006). However, it is important
663 to consider the physical implications of these structures, as they are likely to impede surface winds and
664 induce additional dissipation in the water column. While our study did not incorporate this dissipation
665 due to the intricate nature and small size of the individual brush parks, it could potentially impact the
666 lagoon's hydrodynamics. Therefore, further model calibration studies would be necessary to fine-tune
667 the simulations and achieve even more accurate results by accounting for dissipation in both the Cotonou
668 channel and that induced by the acadjas within the lagoon.

669 During periods of salinization and low water levels, the *NoSal* simulation exhibited longer T_R ,
670 extending by approximately 10 to 50 days compared to those of the *Ref* simulation. This underscores
671 the significant contribution of baroclinic flows driven by salinity gradients to the replenishment of water
672 masses within the lagoon. Okpeitcha et al. (2024) observed that this baroclinic circulation increases salt
673 influx at the mouth of the channel in the southern part of the lagoon, and facilitates its redistribution
674 throughout the lagoon via high-frequency processes. Consequently, without the influence of salt
675 gradients, the lagoon experiences a lower increase in salinity (Okpeitcha et al., 2024), indicative of its
676 tendency to retain fresh waters and thereby prolong the residence time.

677 In contrast, the *NoWind* simulation demonstrates shorter T_R , ranging from 2 to 50 days less than
678 those of the *Ref* simulation, indicating that wind plays a role in enhancing water retention within the
679 lagoon. With the prevailing southwest wind regime, wind-induced circulation tends to counteract the
680 flow induced by river discharge, typically oriented from north to south in the lagoon. These wind-
681 induced currents generate a baroclinic circulation pattern characterized by a surface current aligned with
682 the wind direction and a reverse flow at the bottom. This finding is consistent with similar observations
683 reported in other studies (e.g., Bernardi et al., 2012; Cerralbo et al., 2016; Lacy et al., 2003; O’Callaghan
684 and Stevens, 2011). Furthermore, the wind-induced circulation, in conjunction with its non-linear
685 interaction with tides and baroclinic gravity currents, fosters mesoscale instabilities that contribute to
686 water retention. Interestingly, as previously highlighted by Okpeitcha et al. (2024) based on salinity
687 analysis, an additional simulation (not presented here) driven by seasonal (low-frequency) winds yielded
688 a circulation and T_R very similar to the *Ref* simulation. This suggests that the high-frequency variations
689 of wind play a minor role in the lagoon’s circulation dynamics. This unexpected finding suggests that
690 the persistent winds generate small-scale circulations, potentially through shear instabilities or under the
691 influence of topography. This is confirmed by Figs. 7-10 which exhibit the generation of mean
692 horizontal recirculation patterns at a small scale when considering the influence of wind, whereas these
693 features are absent in the *NoWind* configuration. This eddying circulation, induced primarily by low-
694 frequency southwest winds, contributes to increased retention and T_R within the lagoon, as well as to
695 the redistribution of salt (Okpeitcha et al., 2024).

696 In this study, we utilized wind forcing with a relatively coarse spatial resolution of $\frac{1}{4}^\circ$ (~25 km)
697 from ECMWF, which was then interpolated onto our simulated domain. However, numerous studies
698 have highlighted the significant impact of wind spatial resolution on surface dynamics in semi-enclosed
699 basins or coastal oceans (Duy et al., 2022; Cerralbo et al, 2016). Given that wind plays a crucial role in
700 influencing the circulation and residence times (T_R) of the Nokoué Lagoon, future investigations should
701 explore the sensitivity of lagoon dynamics to the spatial resolution of wind data. Additionally, our
702 simulations did not incorporate wave dynamics and its influence on the circulation. Although wave
703 characteristics in the Nokoué Lagoon remain undocumented, recent field observations suggest typical

704 significant wave heights of 0.2 m, with an increase to 0.4 m during the afternoon, possibly influencing
705 the circulation and residence times.

706

707 **4.3. Relationship between mean residence times and lagoon flushing times**

708 As previously mentioned, various time scales can be used to estimate water retention in coastal
709 systems (e.g., Zimmerman, 1976; Takeoka, 1984; Monsen et al., 2002). Here, we compare and discuss
710 the results obtained from local residence times (T_R), derived from the decrease of tracer concentration
711 in the Nokoué Lagoon, with flushing times (T_f), which characterize the overall exchange properties of
712 the lagoon.

713

714 Flushing time (T_f) is a commonly used metric for assessing water renewal in a lagoon,
715 representing the duration required to completely replace the volume of water in the system. This renewal
716 process involves incoming flows (Q_e) from rivers and outgoing flows (Q_s) through the channel
717 connecting the lagoon to the ocean (e.g., Andréfouët et al., 2001; Geyer et al., 2000). Under steady-state
718 conditions and assuming instantaneous and thorough mixing of water within the lagoon (essentially
719 functioning as a continuously stirred tank), $Q_e = Q_s = Q$, and tracer concentration in the lagoon decrease
720 exponentially at a rate given by the timescale $T_f = V/Q$, where V denotes the volume of water in the
721 lagoon (Umgiesser et al., 2014; Du et al., 2016; Monsen et al., 2002; Koutitonsky et al., 2004; Dyer,
722 1973). Interestingly, this also corresponds to the time necessary to entirely empty the lagoon if water
723 flows unidirectionally from the entrance to the outlet without mixing, effectively pushing the water
724 within the lagoon towards the outlet like a piston.

725 Applied to the Nokoué Lagoon, T_f would be approximately 340 days during the low water period
726 (with $V \sim 2.35 \times 10^8 \text{ m}^3$ and $Q \sim 8 \text{ m}^3/\text{s}$), and less than 4 days during the flood season (with $V = 3.25 \times$
727 10^8 m^3 and $Q \sim 1100 \text{ m}^3/\text{s}$). These calculated T_f values are significantly longer than the T_R values obtained
728 during low water periods. This disparity arises from the strong and erroneous assumptions of stationarity
729 and homogeneity. Indeed, first in the Nokoué Lagoon the circulation patterns is complex (exhibiting
730 retention areas and strong spatial variations of mixing properties within the lagoon) but second and of
731 primary importance river discharge, water levels, and consequently volume significantly vary over time
732 on much shorter scales than the estimated T_f (e.g., Chaigneau et al., 2022; Morel et al., 2022).

733 Therefore, it is imperative to take into account the non-stationarity of the system and the notable
734 volume and discharge fluctuations during the emptying phase. In this case, the change in volume is
735 mathematically represented as follows:

$$736 \frac{dV}{dt} = Q_e - Q_s \quad (1)$$

737 By definition of the flushing time in the no mixing context, we have:

738 $\int_t^{t+T_f} Q_s dt = V(t) \quad (2)$

739 Using equation (1):

740 $\int_t^{t+T_f} (Q_e - \frac{dV}{dt}) dt = V(t) \quad (3)$

741 This gives :

742 $\int_t^{t+T_f} Q_e dt = V(t + T_f) \quad (4)$

743 This final equation signifies that the flushing time aligns with the moment when the quantity of water
 744 introduced into the lagoon by the rivers within the time interval from t to $t+T_f$ becomes equivalent to
 745 the lagoon's volume V . Knowing $Q_e(t)$ and $V(t)$, both of which can be assessed at each model time step,
 746 equation (4) allows to compute the flushing time along with its temporal evolution. A similar approach
 747 can be used in the context of complete mixing and it can be shown that similarly to the traditional
 748 definition the refined calculation of T_f proposed here corresponds to both the timescale of an exponential
 749 decrease in the context of complete mixing in the lagoon or to the timescale of entire emptying in the
 750 context of no mixing, taking time evolution of the fluxes into account.

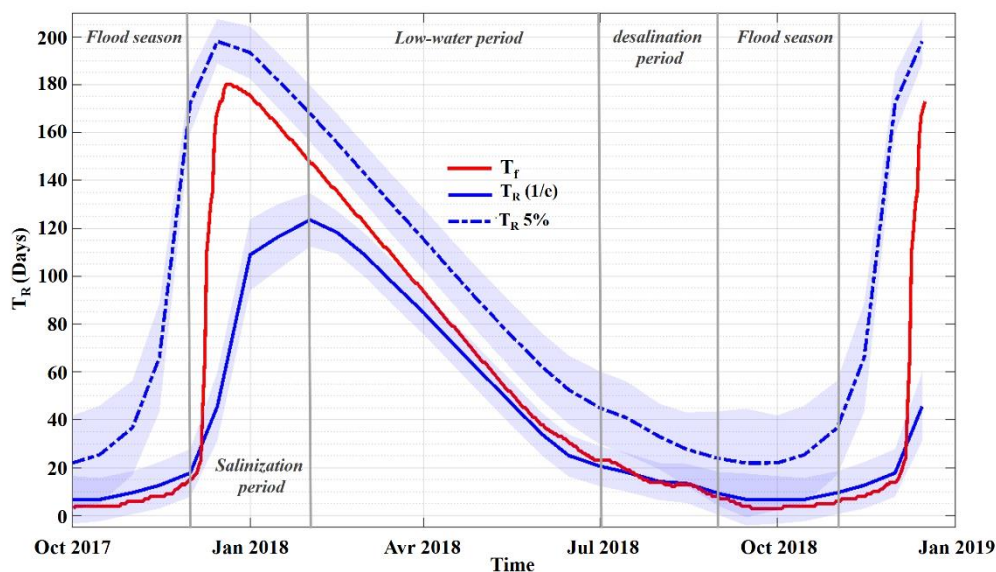
751 Fig. 13 shows the seasonal cycle of both the obtained flushing time (T_f) and the average
 752 residence times T_R , estimated at two key points: when the initial tracer concentration decreases to an
 753 exponential factor ($1/e \sim 36.8\%$, as depicted in Fig. 12a), and when it diminishes to 5% of its initial
 754 value, a situation for which the lagoon is almost entirely emptied from its initial waters. At the lagoon
 755 scale, the flushing time T_f (red curve) varies from a few days to 6 months in connection with the
 756 hydrological cycle. The lagoon thus rapidly renews during flood periods (~ 3 days), while during periods
 757 of salinization and low-water, this time is much longer (up to 6 months) due to low river flows. A steady
 758 decrease slope of T_f (from ~ 5 to ~ 1 month) is noticeable between February and July, indicating once
 759 again the predominant role of June-July river flows in lagoon flushing during the low-water season.
 760 Indeed, the waters tend to remain trapped in the lagoon (very long T_f and T_R) until the threshold flow is
 761 reached (in July) at $\sim 50-100 \text{ m}^3/\text{s}$ (Figure 12a), beyond which the lagoon's water is rapidly renewed.
 762 This is consistent with the critical flow rate of $\sim 60 \text{ m}^3/\text{s}$ estimated by Okpeitcha et al. (2022) from
 763 observations of salinity variations.

764 Both T_f and T_R ($1/e$) exhibit similar seasonal variations, yet T_f , here associated with the
 765 exponential decay and complete mixing context, significantly exceeds T_R ($1/e$) during periods of low
 766 water. T_R ($1/e$) $<$ T_f can be expected since river waters only gradually mix with waters from the rest of
 767 the lagoon, so that there is a delay for mixed waters to reach the channel mouth, depending on the
 768 circulation intensity at the lagoon scale. The difference reaching up to 3 months during the salinization

769 period, this indicates very weak circulation and exchanges within the lagoon in the low water season.
 770 Alternatively, Fig. 13 also shows that T_f , now associated with the entire flushing in the no mixing
 771 context, is always below T_R 5% (the time required to achieve a 95% -almost complete- decrease of the
 772 initial tracer concentration). This is again expected since the occurrence of mixing in the lagoon induces
 773 retention of initial waters in the lagoon. Notably, aside from the sharp increase period observed in
 774 December, the difference between T_f and T_R 5% remains relatively constant, typically spanning 20-30
 775 days, indicating that mixing tends to prolong the retention of tracers by approximately 1 month.

776 To conclude, the circulation is the major ingredient controlling the residence time in the lagoon:
 777 it is intense in the wet season, connecting river mouths to the channel and the ocean, leading to a rapid
 778 flushing of the lagoon. It is weak during the low water season, leading to residence times controlled by
 779 the arrival of the first river floods at the beginning of the wet season. Mixing at local scales has a
 780 significant impact on the residence time at the beginning of dry season, extending it by about 1 month.
 781 Flushing time calculation proposed here, which incorporate variable flows and volumes, offer more
 782 precise estimates compared to those relying on assumptions of stationarity. Additionally, other
 783 significant metrics and methodologies for pollutant monitoring can be employed, such as those using
 784 Lagrangian transport. In these approaches, local residence times are defined at specific points in the
 785 lagoon as the transit time of particles from each location to the channel outlet (Delhez et al., 2014; Cucco
 786 et al, 2009). These diagnostics can provide additional insights beyond the Eulerian diagnostics used here
 787 and warrant further exploration in future research to achieve a comprehensive understanding of the
 788 residence time characteristic of the Nokoué Lagoon.

789



790

791 Figure (13): The seasonal cycle of flushing time T_f (red curve) and average residence time T_R
792 corresponding to the time for the initial concentration to decrease to an exponential factor ($1/e \sim$
793 36.8%), and 5%.

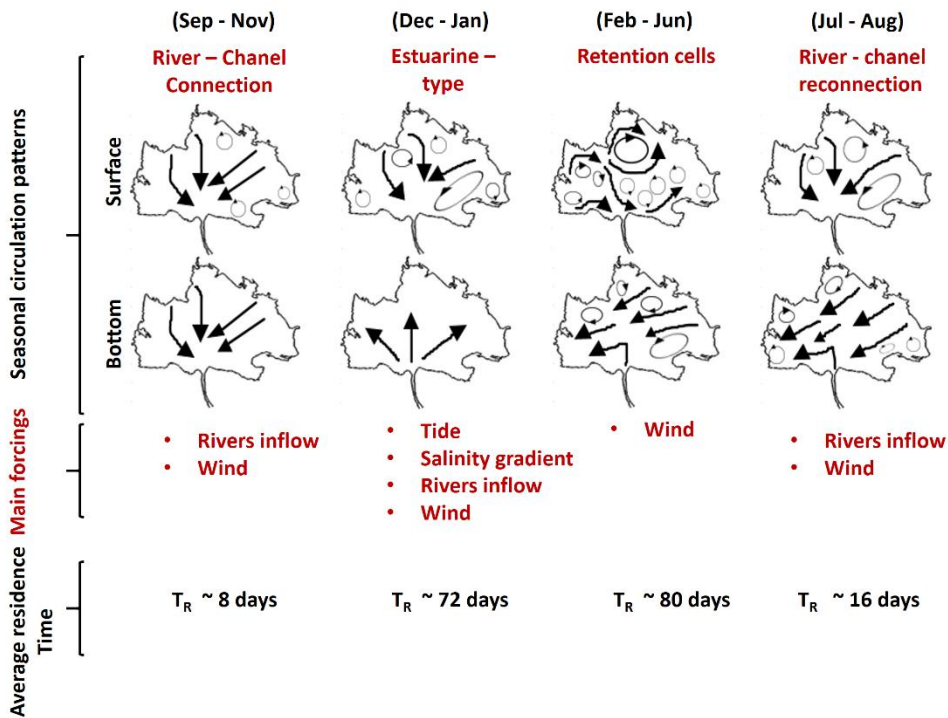
794

795 **5. Conclusion**

796 This study used advanced numerical simulations from the SYMPHONIE model to achieve three
797 key objectives: investigating seasonal circulation variations in the Nokoué Lagoon, identifying the
798 driving factors of the circulation fluctuations, and quantifying residence times.

799 The high-water period (September-November) features direct river-channel connections driven
800 by significant river inflow and wind dynamics, resulting in a 8-day average residence time. During the
801 salinization phase (December-January), a two-layer estuarine circulation pattern develops, influenced
802 by tide, salinity gradient, and wind. During this phase, water residence times within the lagoon increase
803 to ~4 months. The low-water period (February-June) exhibits wind-driven recirculation cells and
804 residence times of 1-4 months. The desalination period (July-August) brings back direct river-channel
805 connections, reducing residence times to 20 days. Figure 14 provides a succinct summary of the average
806 lagoon circulation and residence time on a seasonal scale. Key findings highlight a critical flow threshold
807 of ~50-100 m^3/s in June-July, above which the lagoon experiences a rapid water renewal and controlling
808 the residence time of waters for most of the preceding low water season. Sensitivity analyses emphasize
809 the southwest wind's role in retaining water during the salinization and low-water periods (December-
810 June), while river inflow, tide, and salinity gradient promote water evacuation during the desalination
811 and high-water periods (July-December). We have also identified weaknesses in our simulations, which
812 are not expected to drastically modify our conclusions, but it seems interesting to refine the dissipation
813 of tides within the Cotonou channel or to better incorporate the influence of fishing parks on wind and
814 currents due to fishing parks within the Lagoon.

815



816

817 Figure 14: Graphical abstract of average seasonal traffic patterns and average seasonal residence time.

818 Our findings indicate potential risks of pollutant accumulation, particularly during low-water
819 periods (December-June) when water residence times can extend for several months. This risk is most
820 pronounced along the lagoon's shorelines, where contaminant inputs are more likely to occur. These
821 results have significant implications for understanding the dynamics of the Nokoué Lagoon and,
822 importantly, for predicting the fate of contaminants. While our Eulerian residence time approach offers
823 valuable insights, augmenting it with a Lagrangian perspective - tracing water parcel trajectories until
824 exiting the study area – could lead concrete understanding of particulate and dissolved waste residence
825 times originating from lakeside villages and urbanized shores. In the future, like many other coastal
826 zones, Nokoué Lagoon and its watershed are expected to experience a significant increase in human
827 impact, including dredging, construction of artificial islands, installation of dams, and flow regulation
828 measures. The simulations developed in our study offer a framework for evaluating the impact of such
829 developments on lagoon ecosystem functioning, thereby facilitating decision-making processes.

830

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- Abdelrhman A. M. (2002). Modeling How a Hurricane Barrier in New Bedford Harbor, Massachusetts, affects the hydrodynamics and residence Times. *Estuaries*, 25 (2) , 177-196. <https://link.springer.com/article/10.1007/BF02691306>
- Adite A., Winemiller K. O. (1997). Trophic ecology and ecomorphology of fish assemblages in coastal lakes of Benin, West Africa. *ECOSCIENCE*, 4(1), 6-23. <https://doi.org/10.1080/11956860.1997.11682371>
- Adite A., Sonon S. P., Gbedjissi G. L. (2013). Feeding ecology of the mangrove oyster, *Crassostrea gasar* (Dautzenberg, 1891) in traditional farming at the coastal zone of Benin, West Africa. *Natural Science*, 5(12), 1238-1248. <http://dx.doi.org/10.4236/ns.2013.512151>
- Adjahouinou D.C., Liady N. D., Fiogbe E. D. (2012). Diversité phytoplanctonique et niveau de pollution des eaux du collecteur de Dantokpa (Cotonou-Bénin). *International Journal of Biological and Chemical Sciences*, 6(5), 1938-1949. <http://dx.doi.org/10.4314/ijbcs.v6i5.4>
- Adjahouinou D.C., Yehouenou B., Liady M. N. D., Fiogbe E. D. (2014). Caractérisation bactériologique des eaux résiduaires brutes de la ville de Cotonou (Bénin). *Journal of Applied Biosciences*, 78, 6705-6713. <http://dx.doi.org/10.4314/jab.v78i1.13>
- Aina M.P., Djihouessi B., Vissin E.W., Kpondjo N.M., Gbèdo, V., Sohounhloué, K.C.D. (2012a). Characterization of the domestic wastewaters and dimensionality of a pilot treatment station by lagooning at Abomey Calavi city- Benin. *International Journal of Engineering Science*, 1(1), 45-50.
- Aina M. P., Degila H., Chikou A., Adjahatode F., Matejka, G. (2012b). Risk of intoxication by heavy metals (Pb, Cd, Cu, Hg) connected to the consumption of some halieutic species in lake Nokoué: case of the *Penaus schrimps* and the *Sarotherodon Melanoth*. *British Journal of Science*, 5(1), 104-118.
- Allersma E., Tilmans W.M.K. (1993). Coastal conditions in West Africa: a review. *Ocean & Coastal Management*, 19, 199-240. [https://doi.org/10.1016/0964-5691\(93\)90043-X](https://doi.org/10.1016/0964-5691(93)90043-X)
- Andréfouët S., Pagès J., Tartinville B. (2001). Water renewal time for classification of atoll lagoons in the Tuamotu Archipelago (French Polynesia). *Journal International Coral Reefs*, 9, 399-408. <https://link.springer.com/article/10.1007/s00338-001-0190-9>
- Arakawa A., Lamb V.R. (1977). Computational Design of the Basic Dynamical Process of the UCLA General Circulation Model. *Methods Computational Physics*, 17, 173-265. <http://dx.doi.org/10.1016/B978-0-12-460817-7.50009-4>

- Auclair F., Marsaleix P., Estournel C. (2001). Specification of the exchanges through the continental shelf break in high resolution coastal models: penetration of the LPC current over the Gulf of Lion (Mediterranean). *Oceanol. Acta* 24 (6), 529–544.
- Avigdor A., Denny M. (1997). Settlement of Marine Organisms in Flow. *Annual Review of Ecology and Systematics*, 28(1), 317-339. <https://doi.org/10.1146/annurev.ecolsys.28.1.317>
- Balotro R. S., Isabel A., Shimizu M. (2003). Seasonal Variability in Circulation Pattern and Residence Time of Suo-Nada. *Journal of Oceanography*, 259-277. <http://dx.doi.org/10.1023/A:1025555608384>
- Baohong C., Weidong J., Jinmin C., Cai L., Haining H., Yunlong H., Xianbiao J. (2013). Characteristics of nutrients in the Jiulong River and its impact on Xiamen water, China. *Chinese Journal of Oceanology and Limnology*, 31, 1055-1063. <http://dx.doi.org/10.1007/s00343-013-2263-3>
- Béjaoui B., Solidoro C., Harzallah A., Chevalier C., Chapelle A., Zaaboub N., Aleya L.. (2016). 3D modeling of phytoplankton seasonal variation and nutrient budget in a southern Mediterranean Lagoon. *Marine Pollution Bulletin*, 1-15. <http://dx.doi.org/10.1016/j.marpolbul.2016.11.001>
- Blumberg A. & Mellor G. (1987). A description of a three-dimensional coastal ocean circulation model, three-dimensional coastal ocean models. *Coastal Estuarine Sci.* <http://dx.doi.org/10.1029/CO004p0001>
- Bolin B. and Rodhe H.. (1973). A note on the concepts of age distribution and transit time in natural reservoirs. 25 (1), 58-62. <https://doi.org/10.1111/j.2153-3490.1973.tb01594.x>
- Bouchette F., Schuster M., Ghienne J-F., Denamiel C., Roquin C., Abderamane M., P. Marsaleix, P. Durringer P. (2010). Hydrodynamics in Holocene Lake Mega-Chad. *Quaternary Research*, 73(2), Pp. 226-236. <https://doi.org/10.1016/j.yqres.2009.10.010>
- Bretherton F. P., Russ E. D. And Fandry C. B.. (1976). A technique for objective analysis and design of oceanographic experiments applied to MODE-73. *Deep-Sea Research*, 23, 559-582. [https://doi.org/10.1016/0011-7471\(76\)90001-2](https://doi.org/10.1016/0011-7471(76)90001-2)
- Cerralbo P., Manuel Espino, Manel Grifoll. (2016). Modeling circulation patterns induced by spatial cross-shore wind variability in a small-size coastal embayment. *Ocean Modelling*, 104, 84-98. <http://dx.doi.org/10.1016/j.ocemod.2016.05.011>
- Chaigneau A., Ouinsou T. F., Akodogbo H. H., Dobigny G., Avocegan T. T., Dossou-Sognon F. U., Okpeitcha V O., Djihouessi M. B. and Azémar F. (2023). Physicochemical Drivers of Zooplankton Seasonal Variability in a West African Lagoon (Nokoué Lagoon, Benin). *Journal of Marine Science and Engineering*, 11(556), 1-24. <https://doi.org/10.3390/jmse11030556>

- Chaigneau A., Okpeitcha O. V., Morel Y., Stieglitz T, Assogba A., Benoist M., Allamel P., Honfo J., Sakpak D. A. T., Rétif F., Duhaut T., Peugeot C., Sohou Z. (2022). From seasonal flood pulse to seiche: Multi-frequency water-level fluctuations in a large shallow tropical lagoon (Nokoué Lagoon, Benin). *Estuarine, Coastal and Shelf Science*, 267 (107767),1-12. <https://doi.org/10.1016/j.ecss.2022.107767>
- Chaffra A.S., A.C. Agbon, E.A.M. Tchiboza (2020). Cartographie par télédétection des Acadjas, une technique de pêche illicite sur le lac Nokoué au Bénin. *Sci. Tech.*, 5, 11–29.
- Costa A., Doglioli A. M., Marsaleix P., Petrenko A. A. (2017). Comparison of in situ microstructure measurements to different turbulence closure schemes in a 3-D numerical ocean circulation model. *Ocean Modelling*, 1-17. <https://doi.org/10.1016/j.ocemod.2017.10.002>
- Cucco A., Umgiesser G. (2006). Modeling the Venice Lagoon residence time. *Ecological Modelling*, 193, 34-51. <https://doi.org/10.1016/j.ecolmodel.2005.07.043>
- Cucco A., Umgiesser G., Ferrarin C., Perilli A., Canu D. M., Solidoro C. (2009). Eulerian and lagrangian transport time scales of a tidal active coastal basin. *Ecological Modelling*, 220, 913-922. <https://doi.org/10.1016/j.ecolmodel.2009.01.008>
- Bernardi D., Caleffi V., Gasperini L., Schippa L., Valiani A. (2012). A Study of the Hydrodynamics of the Coastal Lagoon “Valli di Comacchio”. 3Rd Symp.int. on Shallow Flows, Iowa City, USA, 1-11.
- Delhez E. M., Heemink, A.W., Deleersnijder, E. (2004). Residence time in a semi-enclosed domain from the solution of an adjoint problem. *Estuarine, Coastal and Shelf Science* , 61, 691-702. <https://doi.org/10.1016/j.ecss.2004.07.013>
- Delhez E. M., de Brye B., de Brauwere A., Deleersnijder E.. (2014). Residence time vs influence time. *Journal of Marine Systems*, 132,185-195. <http://dx.doi.org/10.1016/j.jmarsys.2013.12.005>
- Djihouessi M. B., Djihouessi M. B., Aina M P. (2019). A review of habitat and biodiversity research in Lake Nokoué, Benin Republic : Current state of knowledge and prospects for further research. *Ecology & Hydrobiology*, 19, 131–145. <https://doi.org/10.1016/j.ecohyd.2018.04.003>
- Djihouessi M. B., Aina M. P. (2018). A review of hydrodynamics and water quality of Lake Nokoué : Current state of knowledge and prospects for further research. *Regional Studies in Marine Science*, 18, 57–67. <https://doi.org/10.1016/j.rsma.2018.01.002>
- Djihouessi M. B., Aina M.P., Kpanou B., Kpondjo N. (2017). Measuring the Total Economic Value of Traditional Sand Dredging in the Coastal Lagoon Complex of Grand-Nokoué (Benin). *Journal of Environmental Protection*, 8, 1605-1621. <https://doi.org/10.4236/jep.2017.813099>

- Dovonou F., Aina M., Boukari M. et Alassane A. (2011). Physico-chemical and bacteriological pollution of an aquatic ecosystem and its ecotoxicological risks: the case of Lake Nokoue in southern Benin. *International Journal of Biological and Chemical Sciences*, 5(4), 1590-1602. <http://dx.doi.org/10.4314/ijbcs.v5i4.23>
- Dyer, K. R. 1973. *Estuaries: A Physical Introduction*, 1st edition. John Wiley and Sons, London, U.K.
- Du J., Shen J. (2016). Water residence time in Chesapeake Bay for 1980–2012. *Journal of Marine Systems* 164, pp 101–11. <http://dx.doi.org/10.1016/j.jmarsys.2016.08.011>
- Duy T. T., Herrmann M., Estournel C., Marsaleix P., Duhaut P., Hong L.B., Bich N. T. (2022). The role of wind, mesoscale dynamics, and coastal circulation in the interannual variability of the South Vietnam Upwelling, South China Sea – answers from a high-resolution ocean model. *Ocean Sci.*, 18, 1131–1161. <https://doi.org/10.5194/os-18-1131-2022>
- Estournel C., Bosc E., Bocquet M., Ulses C., Marsaleix P., Winiarek V., Osvath I., Nguyen C., Duhaut T., Lyard F., Michaud H., and Auclair F. (2012). Assessment of the amount of cesium-137 released into the Pacific Ocean after the Fukushima accident and analysis of its dispersion in Japanese coastal waters. *Journal of Geophysical Research*, 117, C11014. <https://doi.org/10.1029/2012JC007933>
- Estournel C., Zervakis V., Marsaleix P., Papadopoulos A., Auclair F., Perivoliotis L., Tragou E (2005). Dense water formation and cascading in the Gulf of Thermaikos (North Aegean), from observations and modelling. *Continental Shelf Research*, 25, 2366-2386. <https://doi.org/10.1016/j.csr.2005.08.014>
- Estournel C., Durrieu de Madron X., Marsaleix P., Auclair F., Julliand C. and R. Vehil (2003). Observation and modeling of the winter coastal oceanic circulation in the Gulf of Lion under wind conditions influenced by the continental orography (FETCH experiment). *Journal of geophysical research*, 108 (C3). <https://doi.org/10.1029/2001JC000825>
- Estournel C., Broche P., Marsaleix P., Devenon J.L., Auclair F. and Vehil R. (2001). The Rhone River Plume in Unsteady Conditions: Numerical and Experimental Results. *Estuarine, Coastal and Shelf Science*, 53, 25-38. <https://doi.org/10.1006/ecss.2000.0685>
- Ferrarin C., Bergamasco A., Umgiesser G., Cucco A. (2013). Hydrodynamics and spatial zonation of the Capo Peloro coastal system (Sicily) through 3-D numerical modelling. *Journal of Marine Systems*, 1-49. doi:doi:10.1016/j.jmarsys.2013.02.005
- Geyer W. R. (1997). Influence of Wind on Dynamics and Flushing of Shallow Estuaries. *Estuarine, Coastal and Shelf Science*, 44(6), 713-722. <https://doi.org/10.1006/ecss.1996.0140>

- Geyer W. R., Morris J. T., Prahl F., G.; Jay D. A. (2000). Interaction entre les processus physiques et la structure de l'écosystème; Une approche comparative (eurekamag.com). In: Hobbie, J.E. (Ed.), Estuarine Science: a Synthetic Approach to Research and Practice. Island Press, Washington, DC., 177–206.
- Guèdjè K. F., Houeto A. V.V., Houngrinou B. E., Fink H. A. and Knippertz P. (2019). Climatology of coastal wind regimes in Benin. Meteorol. Z. (Contrib. Atm. Sci.), 28(1), 23–39. <http://dx.doi.org/10.1127/metz/2019/0930>
- Guragai B., Hashimoto T., Oguma K., Takizawa S. (2018). Data logger-based measurement of household water consumption and micro-component analysis of an intermittent water supply system. Journal of Cleaner Production, 197(1), 1159-1168. <https://doi.org/10.1016/j.jclepro.2018.06.198>
- Herbert G., Ayoub N., Marsaleix P. and Lyard F. (2011). Signature de la variabilité de la circulation côtière dans les données altimétriques dans le sud du golfe de Gascogne au cours de l'hiver et de l'automne 2004. Journal des systèmes marins, 88 (2), 139-158. <https://doi.org/10.1016/j.jmarsys.2011.03.004>
- Hu Z.Y., Doglioli A. M., Petrenko A. A., Marsaleix P., Dekeyser I. (2009). Numerical simulations of eddies in the Gulf of Lion. Ocean Modelling, Elsevier, 28 (4), 203-208. <https://doi.org/10.1016/j.ocemod.2009.02.004>
- Jouon A., Douillet P., Ouillon S., Fraunie P. (2006). Calculations of hydrodynamic time parameters in a semi-opened coastal zone using a 3D hydrodynamic model. Continental Shelf Research 26, 1395–1415. doi:10.1016/j.csr.2005.11.014
- Lerczak A. J., Geyer W. R. (2006). Mechanisms Driving the Time-Dependent Salt Flux in a Partially Stratified Estuary. Journal of Physical Oceanography, 36, 2296-2311. <https://doi.org/10.1175/JPO2959.1>
- Du J., Park K., Shen J., Zhang Y. J., Yu X., Ye F., Wang Z., Rabalais N. N. (2019). A hydrodynamic model for Galveston Bay and the shelf in the northern Gulf of Mexico. Ocean Science, 951–966. <https://doi.org/10.5194/os-15-951-2019>
- Kjerfve, B. (1994) Coastal Lagoons. In: Kjerfve, B., Ed., Coastal Lagoon Processes, Elsevier Oceanographic Series, Amsterdam, 1-8.
- Koutitonsky V. G., T. Guyondet, A. ST-Hilaire, S. C. Courtenay, A. Bohgen (2004). Water Renewal Estimates for Aquaculture Developments in the Richibucto Estuary, Canada. Estuaries, Vol. 27, No. 5, p. 839–850

- Lacy J. R., Stacey M. T., Bura J. R., Monismith S. G. (2003), Interaction of lateral baroclinic forcing and turbulence in an estuary, *J. Geophys. Res.*, 108, 3089, C3. <https://doi.org/10.1029/2002JC001392>
- Lalèyè, P., Philippart J.C., Poncin, P. (1995). Reproductive biology of two species of *Chrysichthys* (Siluriformes, Bagridae) from Lake Nokoué and the PortoNovo Lagoon in Benin. *Journal of African Zoology*, 109(3), 213-224.
- Lalèyè P., Niyonkuru C., Moreau J., Teugels G.G. (2003). Spatial and seasonal distribution of the ichthyofauna of lake Nokoué, Benin, West Africa. *African Journal of Aquatic Science*, 28(2), 151–161. <https://doi.org/10.2989/16085910309503779>
- Lalèyè P., Villanueva M.C., Entsua-Mensah M., Moreau J. (2007). A review of the aquatic living resources in Gulf of Guinea lagoons, with particular emphasis on fisheries management issues. *J. Afrotrop. Zool. Special issue* : 123-136. Belgium.
- Lane R. R., Madden C. J., Day J.W., Solet D. J. (2011). Hydrologic and nutrient dynamics of a coastal bay and wetland receiving discharge from the Atchafalaya River. *Hydrobiologia* 658, 55–66. <https://doi.org/10.1007/s10750-010-0468-4>
- Liu W.-C., Chen W-B., Hsu M-H.(2010). Using a three-dimensional particle-tracking model to estimate the residence time and age of water in a tidal estuary. *Computers & Geosciences*, 37, 1148–1161. <https://doi.org/10.1016/j.cageo.2010.07.007>
- Loisel H., Vantrepotte V., Ouillon S., Ngoc D.D., Marine H., Tran V., Mériaux X., Dessailly D., Jamet C., Duhaut T., Nguyen H.H., Van Nguyen T. (2017). Assessment and analysis of the chlorophyll-a concentration variability over the Vietnamese coastal waters from the MERIS ocean color sensor (2002–2012). *Remote Sensing of Environment*, 190, 217–232. <http://dx.doi.org/10.1016/j.rse.2016.12.016>
- Lovato T., Androsov A., Romanenkov D., Rubino A. (2010). The tidal and wind induced hydrodynamics of the composite system Adriatic Sea/Lagoon of Venice. *Continental Shelf Research*, 692-706. <https://doi.org/10.1016/j.csr.2010.01.005>
- Maier-Reimier. (1977). Residual circulation in the North Sea due to the M 2 tide and mean annual wind stress. *Deutsche Hydrographische Zeitschrift.*, 69-80. <https://doi.org/10.1007/BF02227045>
- Mama D., Deluchat V., Bowen J., Chouti W., Yao B., Gnon B., Baudu M. (2011). Caractérisation d'un Système Lagunaire en Zone Tropicale: Cas du lac Nokoué(Bénin). *European Journal of Scientific Research*, 56(4), 516-528.

- Maraldi C., Chanut J., Levier B., Ayoub N., De Mey P., Reffray G., Lyard F., Cailleau S., Drévillon M., Fanjul E. A., Sotillo M. G., Marsaleix P. (2013). NEMO on the shelf: assessment of the Iberia–Biscay–Ireland configuration. *Ocean Science*, 9, 745–771. <https://doi.org/10.5194/os-9-745-2013>
- Marine. J. H., Diaz F., Estournel C., Marsaleix P., Ulses C. (2013). Impact of atmospheric and oceanic interannual variability on the Northwestern Mediterranean Sea pelagic planktonic ecosystem and associated carbon cycle. *Journal Geophysical Research : Ocean*, 118, 5792–5813. <https://doi.org/10.1002/jgrc.20405>
- Marine. J. H., and Somot S. (2008). Relevance of ERA40 dynamical downscaling for modeling deep convection in the Mediterranean Sea. *Geophysical Research Letters*, 35 (L04607). <https://doi.org/10.1029/2007GL032442>
- Marsaleix P., Auclair F., Estournel C. (2006). Considerations on Open Boundary Conditions for Regional and Coastal Ocean Models. *Journal of Atmospheric and Oceanic Technology*, 23, 1604–1613. <https://doi.org/10.1175/JTECH1930.1>
- Marsaleix P., Auclair F., Floor J. W., Marine H. J., Estournel C., Pairaud I., Ulses C. (2008). Energy conservation issues in sigma-coordinate free-surface ocean models. *Ocean Modelling*, 20, 61–89. <https://doi.org/10.1016/j.ocemod.2007.07.005>
- McIntosh P. (1990). Oceanographic data interpolation: Objective analysis and splines. *Journal of Geophysical Research*, 95, 13529–13541. <https://doi.org/10.1029/JC095iC08p13529>
- Michaud H., Marsaleix P., Leredde Y., Estournel C., Bourrin F., Lyard F., Mayet C., Ardhuin F. (2012). Three-dimensional modelling of wave-induced current from the surf zone to the inner shelf. *Ocean Science*, 8, 657–681. <https://doi.org/10.5194/os-8-657-2012>
- Mohanty P. K. & Panda B. U. S. (2009). : Circulation and mixing processes in Chilika lagoon. *Indian Journal of Marine Sciences*, 205-214. <http://nopr.niscpr.res.in/handle/123456789/4671>
- Monsen N. E., Cloern E. J., Lucas V. L., Monismith G. S. (2002). A comment on the use of flushing time, residence time, and age as transport time scale. *American Society of Limnology and Oceanography*, 47 (5), 1545–1553. doi: <https://doi.org/10.4319/lo.2002.47.5.1545>
- Morales M., Aquije J., Carvalho L., Mejía A. (2020). Hydrodynamic Modelling of a Coastal Lagoon in México. *Revista de Investigación de Física*. <https://doi.org/10.15381/rif.v23i3.20301>
- Morel Y., Chaigneau A., Okpeitcha O. V., Stieglitz T., Rétif F., Duhaut T., Sohou Z. (2022). Terrestrial or oceanic forcing? Water level variations in coastal lagoons. *Advances in Water Resources*, 169 (104309). <https://doi.org/10.1016/j.advwatres.2022.104309>

- Mudge M. S., Glacé D. J., Newton A. (2008). Residence times in a hypersaline lagoon: Using salinity as a tracer. *Estuarine, Coastal and Shelf Science*, 77, 278-284. <https://doi.org/10.1016/j.ecss.2007.09.032>
- Newton A., Brito A.C., Icely J.D., Derolez V., Clara I., Angus S., Schernewski G., Inacio, M., Lillebø, A.I., Sousa, A.I., Béjaoui B., Solidoro C., Tosic M., Canedo-Argüelles M., Yamamuro M., Reizopoulou S., Tseng H.-C., Canu D., Roselli L., Maanan M., Cristina S., Ruiz-Fernandez, A.C., de Lima R.F., Kjerfve, B., Rubio-Cisneros, N., Pérez-Ruzafa A., Marcos C., Pastres R., Pranovi F., Snoussi M., Turpie J., Tuchkovenko Y., Dyack B. (2018). Assessing, quantifying and valuing the ecosystem services of coastal lagoons. *Journal for Nature Conservation*, 50-65. <https://doi.org/10.1016/j.jnc.2018.02.009>
- Niyonkuru C. & Lalèyè P.A. (2010). Impact of acadja fisheries on fish assemblages in Lake Nokoué, Benin, West Africa. *Knowledge and Management of Aquatic Ecosystems*, 399, 05 <https://doi.org/10.1051/kmae/2010033>.
- O’Callaghan J. and C. Stevens. (2011). Wind Stresses on Estuaries. *Estuarine and Coastal Science*, 151-166. <https://doi.org/10.1016/B978-0-12-374711-2.00211-4>
- O’Callaghan J., Pattiaratchi C., Hamilton D. (2007). The response of circulation and salinity in a micro-tidal estuary to sub-tidal oscillations in coastal sea surface elevation. *Continental Shelf Research*, 1947-1965. <https://doi.org/10.1016/j.csr.2007.04.004>
- Ogutu-Ohwayo R., Hecky E. R., Cohen S. A., Kaufman L. (1997). Human Impacts on the African Great Lakes. *Environmental Biology of Fishes*, 50(2), 117-131. <http://dx.doi.org/10.1023/A:1007320932349>
- Okpeitcha V., Chaigneau A., Morel Y., Stieglitz T., Pomalegni Y., Sohou Z., Mama D. (2022). Seasonal and interannual variability of salinity in a large West-African lagoon (Nokoué Lagoon, Benin). *Estuarine, Coastal and Shelf Science*, 264(107689),1-10. <https://doi.org/10.1016/j.ecss.2021.107689>
- Okpeitcha V., Chaigneau A., Morel Y., Duhaut T., Marsaleix P., Rétif F., Honfo J., Stieglitz T., Sintondji O. L., Sohou Z., Mama D. (2024). Modeling seasonal salinity variations in a large West African lagoon (Nokoué, Benin): Major drivers and mechanisms. *Regional Studies in Marine Science* 69 (2024) 103330. <https://doi.org/10.1016/j.rsma.2023.103330>
- Onguéné R.. Modélisation multi-échelle de la circulation océanique en Afrique centrale, de la plaine abyssale à l’estuaire du Cameroun. *Océanographie*. Université Paul Sabatier - Toulouse III, 2015. Français. fFNNT : 2015TOU30393ff. fftel-03657048ff

- Pairaud I. L., Lyard F., Auclair F., Letellier T., Marsaleix P. (2008). Dynamics of the semi-diurnal and quarter-diurnal internal tides in the Bay of Biscay. Part 1: Barotropic tides. *Continental Shelf Research*, 28, 1294–1315. <https://doi.org/10.1016/j.csr.2008.03.004>
- Panda U.S., Mahanty M. M., Rao R. V., Patra S. and Mishra P. (2015). Hydrodynamics and water quality in Chilika Lagoon-A modelling approach. *Procedia Engineering*, 639-646. <https://doi.org/10.1016/j.proeng.2015.08.337>
- Peng C., Wang A., Wu J., Lin Y., Chen J., Chen N. (2021). An assessment of residence and influence times in Xiamen Bay, China. *Estuarine, Coastal and Shelf Science*, 262(107595). <https://doi.org/10.1016/j.ecss.2021.107595>
- Pérez-Ruzafa A., Marcos C., Pérez-Ruzafa I. M. & Pérez-Marcos M. (2011). Coastal lagoons: “transitional ecosystems” between transitional and coastal waters. *Journal of Coastal Conservation*, 15(3), 369-392 (24 pages). <https://doi.org/10.1016/j.ecss.2007.04.030>
- Pérez-Ruzafa A., Pérez-Ruzafa I. M., Newton A., Marcos C. (2019). Coastal Lagoons: Environmental Variability, Ecosystem Complexity, and Goods and Services Uniformity. *Elsevier Coasts and Estuaries*, 253-276. <https://doi.org/10.1016/B978-0-12-814003-1.00015-0>
- Pritchard D. W. (1952). Salinity distribution and circulation in the Chesapeake Bay estuarine system. *Journal of Marine Research*, 106–123.
- Robinson I. S. (1981). Tidal vorticity and residual circulation. *Deep-Sea Research*, 28A(3), 195-212. [https://doi.org/10.1016/0198-0149\(81\)90062-5](https://doi.org/10.1016/0198-0149(81)90062-5)
- Rodhe H. (1992). *Modeling Biogeochemical Cycles*. Academic Press, pp. 55–71.
- Sale P.F., Feary D.A., Burt J.A. (2011). The Growing Need for Sustainable Ecological Management of Marine Communities of the Persian Gulf. *AMBIO* 40, 4–17. <https://doi.org/10.1007/s13280-010-0092-6>
- Sassi M. G. and Hoitink A. J. F. (2013). River flow controls on tides and tide-mean water level profiles in a tidal freshwater river. *Journal Of Geophysical Research: Oceans*, 118, 4139–4151. <https://doi.org/10.1002/jgrc.20297>
- Seyfried L., Marsaleix P., Richard E., and Estournel C. (2017). Modelling deep-water formation in the north-west Mediterranean Sea with a new air–sea coupled model: sensitivity to turbulent flux parameterizations. *Ocean Sci.*, 13, pp 1093–1112. <https://doi.org/10.5194/os-13-1093-2017>
- Swift S.A. and Bower A.S., (2013). Formation and circulation of dense water in the Persian/Arabian Gulf. *Journal of Geophysical Research*, 108(C1)(3004,). <https://doi.org/10.1029/2002JC001360>

- Sylaios G. K., Tsihrintzis V. A., Akratos C. and Haralambidou K. (2006). Quantification of water, salt and nutrient exchange processes at the mouth of a mediterranean coastal lagoon. *Environmental Monitoring and Assessment*, 275-301. <https://doi.org/10.1007/s10661-005-9026-3>
- Sylaios G., Tsihrintzis V.A., Akratos C., Tsikliras A., Haralambidou K. (2003). Residual currents and fluxes through the mouth of Vassova coastal lagoon. *Mediterranean Marine Science*, 39-52. <https://doi.org/10.12681/mms.227>
- Takeoka H. (1984). Fundamental concepts of exchange and transport time scales in a coastal sea. *Continental Shelf Research*, 3 (3), 311-326. [https://doi.org/10.1016/0278-4343\(84\)90014-1](https://doi.org/10.1016/0278-4343(84)90014-1)
- Texier H., Colleuil B., Profizi J-P., Dossou C. (1980). Le lac Nokoué, environnement du domaine margino-littoral sud-béninois : bathymétrie, lithofaciès, salinité, mollusque et peuplements végétaux. *Bull. Inst. Geol. Bassin Aquitaine*; ISSN 0524-0832; Fra(28), pp. 115-142.
- Torres-Bejarano F.M., Torregroza-Espinosa A.C., Martinez-Mera E, Castañeda-Valbuena D., Tejera-Gonzalez D. (2020). Hydrodynamics and water quality assessment of a coastal lagoon using environmental fluid dynamics code explorer modeling system. *Global Journal of Environmental Science and Management*, 289-308. <https://doi.org/10.22034/gjesm.2020.03.02>
- Nguyen-Duy T., Ayoub K. N., Marsaleix P., Toubanc F., De Mey-Frémaux P., Piton V., Marine H., Duhaut T., Tran C. M., Ngo-Duc T. (2021). Variability of the Red River Plume in the Gulf of Tonkin as Revealed by Numerical Modeling and Clustering Analysis. *Frontiers in Marine Science* , 8:772139. <https://doi.org/10.3389/fmars.2021.772139>
- Ulses C., Estournel C., Bonnin J., Durrieu de Madron X., Marsaleix P. (2008). Impact of storms and dense water cascading on shelf-slope exchanges Impact of storms and dense water cascading on shelf-slope exchanges. *Journal of Geophysical Research*, 113 (C02010). <https://doi.org/10.1029/2006JC003795>
- Umgiesser, G., C. Ferrarin, A. Cucco, F. De Pascalis, D. Bellafiore, M. Ghezzi, and M. Bajo (2014). Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling, *J. Geophys. Res. Oceans*, 119, 2212–2226, doi:10.1002/2013JC009512.
- Villanueva M.C., Lalèyè P., Albaret J.J., Laë R., Morais L. T., Moreau J. (2006). Comparative analysis of trophic structure and interactions of two tropical lagoons. *Ecological modelling*, 197, 461–477.
- Welcomme, R.L. (1972), An evaluation of the acadja method of fishing as practised in the coastal lagoons of Dahomey (West Africa). *Journal of Fish Biology*, 4: 39-55. <https://doi.org/10.1111/j.1095-8649.1972.tb05651.x>

- Wilson G.V., Rigby J.R., Ursic M., Dabney S.M., (2016). Soil pipe flow tracer experiments: 1. Connectivity and transport characteristics. *Hydrological Processes*, 30, 1265–1279. <https://doi.org/10.1002/hyp.10713>
- Wong A. P. S., Johnson C.G., Owens W. B. (2003). Delayed-Mode Calibration of Autonomous CTD Profiling Float Salinity Data by u-S Climatology. *Journal of atmospheric and Oceanic Technology*, 20, 308-318. [https://doi.org/10.1175/1520-0426\(2003\)020%3C0308:DMCOAC%3E2.0.CO;2](https://doi.org/10.1175/1520-0426(2003)020%3C0308:DMCOAC%3E2.0.CO;2)
- Yehouenou E.A.P., Adamou R., Azehoun P.J., Edorh P.A. and Ahoyo T. (2013, May). Monitoring of Heavy Metals in the complex "Nokoué lake - Cotonou and Porto-Novo lagoon " ecosystem during three years in the Republic of Benin. *Research Journal of Chemical Sciences*, 3(5).
- Zandagba J., Adandedji M. F., Mama D., Chabi A., Afouda A. (2016). Assessment of the Physico-Chemical Pollution of a Water Body in a Perspective of Integrated Water Resource Management: Case Study of Nokoué Lake. *Journal of Environmental Protection*, 7, 656-669. <http://dx.doi.org/10.4236/jep.2016.75059>
- Zimmerman J. T. F. (1988). Estuarine residence times. (H. o. In B. Kjerfve [ed.], Éd.) Consulté le 10 23, 2022. <https://doi.org/10.1201/9781351073257>