Hypoxia also occurs in small highly turbid estuaries: the example of the Charente (Bay of Biscay)

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Abstract. The French coast facing the Bay of Biscay (north-east Atlantic) is characterised by the presence of small macrotidal and turbid estuaries, including the Charente, geographically located between the two large estuaries of the Gironde and the Loire (south-west France). Multi-year, multi-site, high-frequency water quality surveys have shown that the Loire, and to a lesser extent the Gironde, suffer from summer hypoxia. These observations raised the question of the possible occurrence of hypoxia, particularly in one of these small estuaries, the Charente, which flows into the Bay of Marennes-Oléron, the first oyster-producing area in France. Unlike its two large neighbours, the Charente estuary is not continuously monitored, although it is subject to similar climatic changes and anthropogenic pressures, making it impossible to assess potential risks to the ecosystem. Here we present a first investigation of dissolved oxygen in the Charente estuary, based on a combination of longitudinal studies along the estuary axis and instrumented sites to determine the intensity and spatial extent of deoxygenation. Oxygen and salinity sensors were deployed at several sites during the summers of 2018, 2019 and 2020 to record temperature, salinity and dissolved oxygen every 15 minutes. This high-frequency dataset will be compared with a long-term low-frequency dataset (1975-2022) to determine whether or not there is a degradation of oxygenation in the Charente estuary. The high-frequency dataset shows a high variability of dissolved oxygen (DO), with a clear influence of tidal cycles. During summer, DO concentrations are often below 5 mg L^{-1}, and sometimes even below 2 mg L^{-1}, indicating the presence of a summer oxygen minimum zone with an extension of about 20-25 km. Temperature is the DO main controlling factor, limiting preventive management strategies and, in the context of global warming, raising questions about the long-term suitability of the estuarine conditions for community needs, in particular migratory fishes.

1 Introduction

Globally, there has been a decrease in dissolved oxygen in the oceans, which is more pronounced in coastal waters, resulting in more frequent hypoxia events (Diaz and Rosenberg, 2008; Zhang et al., 2010; Stramma et al., 2011; Gilbert et al., 2010). Dissolved oxygen (DO) is an important parameter for diagnosing of water quality. Dissolved oxygen is one of the key physico-chemical quality elements that the EU Water Framework Directive (WFD) requires to be considered in order to achieve "good ecological status" (Best et al., 2007). Essential for the survival of aquatic animals and plants, oxygen levels are the main factor determining the type and abundance of organisms that can live there (Breitburg, 2002; Sampaio et al., 2021). Dissolved oxygen comes from two natural processes: diffusion from the atmosphere and photosynthesis by aquatic plants. The mixing of surface waters by wind and waves increases the rate at which oxygen from the air can be dissolved or absorbed into the water. Conversely, bacteria and other decomposing organisms consume oxygen to break down organic matter. It is therefore common to observe deviations from the theoretical saturation value predicted by temperature and salinity. Dissolved oxygen depletion occurs when the measured dissolved oxygen concentration is below the theoretical saturation value. This can occur when large inputs of nutrients, usually from wastewater discharges, stimulate excessive growth of aquatic plants (eutrophication), whose decomposition can lead to oxygen depletion, even to hypoxia (< 2 mg L^{-1}) or anoxia (0 mg L^{-1}). Stratification of the water column can also lead to oxygen depletion in bottom waters. Conversely, supersaturation of dissolved oxygen can occur, usually

during the day, associated with the presence of aquatic plants. Given the variety of processes affecting DO, the variability of dissolved oxygen in coastal systems is still poorly documented, making it difficult to estimate its long-term evolution. In

60   particular, hypoxia in estuaries has received less the attention than in coastal waters.

Situated at the interface between the ocean and the continent, estuaries are dynamic natural collectors of liquid and solid inputs from watersheds, that are highly variable both spatially and seasonally. Downstream, the large volumes of seawater entering with each rising tide are progressively diluted, influencing the chemistry of estuarine waters. The physico-chemical quality of estuarine waters provides the necessary support for biological life and determines the distribution of species, on which many

65   ecosystem services (e.g. commercial or recreational fisheries) depend. Estuaries are habitats of great ecological interest for many biological groups, including fish, which use them as nurseries or spawning grounds (Delage et al., 2019). Understanding future changes in the quality of these transitional waters is therefore crucial, given their large impact on aquatic organisms. In macrotidal estuaries, where the tidal range is greater than 3 metres, the asymmetry of the tidal wave as it propagates upstream, creates a well-developed turbidity maximum zone (TMZ) with suspended particulate matter (SPM) loads from several hundred

70   milligrams to several grams of dry sediments per litre (Allen et al., 1980; Uncles et al., 2002). SPM limits light penetration and hence photosynthetic activity, and gas exchange with the atmosphere (Goosen et al., 1999). In addition, the degradation of the organic content of SPM consumes DO, all of which is likely to promote deoxygenation in macrotidal turbid estuaries (Talke et al., 2009).

Along the French coast facing the Bay of Biscay (north-east Atlantic), there are many small tidal and turbid estuaries,

75   geographically located between the two large estuaries of the Gironde and the Loire, which are natural corridors for migratory fish (Arevalo et al., 2023). The spatio-temporal DO dynamics of the two large systems are well described by long-term, high-frequency and multi-sites measurements of water quality. While episodic summer hypoxia events have been recorded in the fluvial Gironde estuary, the Loire estuary experiences permanent summer hypoxia in its lower reaches (Lanoux et al., 2013; Schmidt et al., 2019). These observations have raised the question of the possible occurrence of hypoxia in the small estuaries

80   that are located between them. Indeed, the question of the evolution of the quality and ecological status of estuarine waters will become increasingly critical in the face of rising temperatures and water levels, decreasing rainfall and runoff, and the population growth forecast for the south-west France by 2030. In addition to global warming, climate projections predict an increase in the number of summer heatwave days: these climatic extremes are particularly worrying in terms of the tolerance of biological communities such as fish, and the vulnerability of macrotidal estuaries to deoxygenation.

85   This paper presents a study of the present day dynamics of dissolved oxygen in one of the small estuaries of the Bay of Biscay: the Charente estuary. The objectives were to determine the occurrence and extent of a possible oxygen minimum zone and to determine whether hypoxia could be triggered there. We used a complementary strategy based on a combination of longitudinal studies along the estuary axis and a few instrumented sites to determine the intensity and spatial extent of potential deoxygenation. This work focused on the summer period when low discharge, the presence of the turbidity maximum zone

90   and summer heat are likely to promote low dissolved oxygen.

2 Material and method

2.1 The Charente estuary

Located on the French Atlantic coast, the Charente estuary is a small, shallow, macrotidal estuary with an average tidal range of 4.2 m, reaching up to 7 m during spring tides (Figure 1). The tidal influence is stopped 50 km upstream of the mouth by a

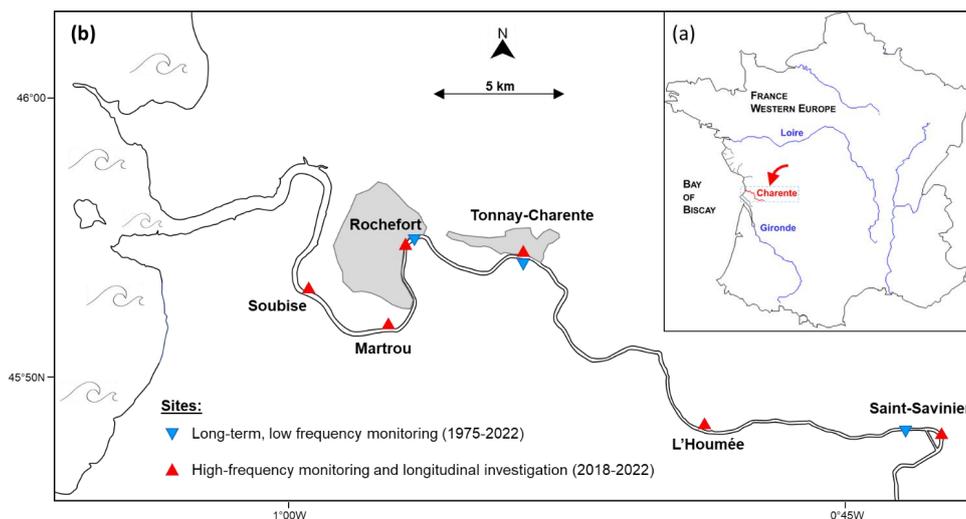
95   dam at Saint-Savinien, which is opened during spring tides to prevent flooding of downstream areas (Modéran et al., 2012). The high tidal range and upstream tidal asymmetry and subsequent tidal pumping promote a turbidity maximum zone (TMZ), as observed in two large estuaries, the Loire and the Gironde (Jalon-Rojas et al., 2017; Toublanc et al. 2016). High concentrations of suspended particulate matter (SPM) are typically several grams of dry sediment per litre (Auguet et al.,

2005). The position of the TMZ varies longitudinally between the river mouth and 30-40 km upstream, depending on river

100 discharge and tidal cycles.

The Charente River is 360 km long and its catchment area covers almost 10,549 km². The Charente river discharges through the Charente estuary (Figure 1) into the Bay of Marennes-Oléron, the first oyster-producing area in France (Goulletquer and Heral, 1997) and a major nursery ground for juveniles of the Bay of Biscay sole population (Le Pape et al., 2003; Modéran et al., 2012). There is a strong contrast between the densely populated coastal fringe (80 to 100 inhabitants km⁻²) and the rural

105 interior (40 to 60 inhabitants km⁻²). The largest town in the estuary is Rochefort, with an estimated urban population of over 63 000. The rest of the catchment area is largely agricultural (75% of the surface area): vineyards, maize, mixed farming and livestock. For the period 2006-2022, the minimum, average and maximum daily flows of the Charente are 6.5, 65.2 and 584 m³ s⁻¹ respectively (Table A1). The target low flow, defined as "the reference flow which allows good water status to be achieved and above which all uses are satisfied on average 8 years out of 10", is 15 m³ s⁻¹. In fact, flows below this threshold

110 are recorded almost every year, demonstrating that the Charente has experienced severe low flows in recent decades, making this estuary particularly sensitive to water quality problems. Managing water during these critical periods to meet socio-economic needs while maintaining good water status is therefore a major challenge (EPTB Charente, 2023).

115 **Figure1: (a) The Charente estuary between the Loire and Gironde in the West France. (b) Location of the different instrumented sites along the Charente estuary**

2.2 Data sources

The study of dissolved oxygen variability in the Charente estuary is based on three different datasets (Table 1). The first two

120 dataset were acquired between 2018 and 2020, based on a strategy developed in the Loire and Gironde estuaries (Schmidt et al., 2019). The principle is to combine instrumented sites and longitudinal investigations. In the course of this work, we discovered the existence of an institutional long-term low frequency monitoring of water quality, started in 1975, whose data were also used.

2.2.1 High-frequency summer monitoring of the Charente estuary

125 In order to better document the DO variability during the summer, the selection of a site to monitor was based on the experience gained in the Loire and Gironde estuaries (Schmidt et al., 2019), with the hypothesis that a minimum oxygen zone might develop in the inner estuary, just upstream of the urban area of Rochefort. The first site was therefore located in Tonnay-

Charente, 6.1 km upsteam of Rochefort and 26 km (PK26) from the estuary mouth (in the following, the kilometre distance from the estuary mouth is indicated as PK followed by the value). HOBO oxygen (optode) and conductivity sensors with

130 antifouling protection were used for a period of three weeks in summer 2018 to record temperature, salinity and dissolved oxygen every 15 minutes. The sensors were deployed on a floating pontoon at a depth of approximately 50 cm below the surface. Sensor calibration was checked immediately before and after deployment. In summer 2019, Tonnay-Charente was instrumented again, complemented by a site further upstream at L'Houmée (PK37). In summer 2020, the downstream sector was instrumented with the same sensors at two sites, Rochefort (PK20) and Martrou (PK16). In addition, to test the possibility

135 of making it a permanent site, Tonnay-Charente was equipped with a multi-parameter sensor (SAMBAT, NKE Instrumentation) from the end of April to November 2020. As part of a preliminary study, the advantage of placing the sensors on floating pontoons is to limit the cost of the study, as they are accessible without nautical equipment. However, in the case of macrotidal rivers such as the Charente, when the pontoons are not far from the shore, they tend to be grounded at low tide, especially during spring tides; this was the case at the L'Houmée, Rochefort and Matrou sites. This explains the gaps in the

140 time series at these three sites.

Table 1 Detail of the available data: site name, distance from the mouth (PK, in km), type of dataset, measurement period and link to the data repository. Sites are listed from upstream to downstream. The measured parameter are salinity, temperature and dissolved oxygen. PK: distance in km from the mouth of the considered site. LF: low-frequency (6 – 12 measures per year); HF:

145 **high-frequency (1 measure every 10 to 20 minutes); LS: longitudinal survey. * SPM avalaible.**

Site	PK km	Type	Measurement periods	Data repository
Saint-Savinien	47.6	LF	2011-2022	https://adour-garonne.eaufrance.fr/ station 05006860
L'Houmée	37.0	HF	June, 29 to Sept 7 2019	doi.org/10.17882/95886
Tonnay-Charente	25.9	LF	2011-2022	https://adour-garonne.eaufrance.fr/ station 05002350
		HF	July, 19 to Aug. 9 2018; June, 29 to Sept 7 2019; April, 24 to Nov 16 2020*	doi.org/10.17882/95886
Rochefort	19.8	LF	1975-2022	https://adour-garonne.eaufrance.fr/ station 05001500
		HF	Summer 2020	doi.org/10.17882/95886
Martrou	16.1	HF	Summer 2020	doi.org/10.17882/95886
Saint-Savinien to Soubise	12.1	LS	August 9 2018	doi.org/10.17882/95886
Tonnay-Charente to Soubise		LS	August 8 2019	doi.org/10.17882/95886

2.2.2. Longitudinal investigation of the Charente estuary

A complementary approach was to carry out longitudinal studies. In 2018, this was done on 7 August 2018 between Soubise (PK12) and Saint-Savinien (PK47) from the pontoons. This first survey took advantage of the return to the Charente estuary

150 to remove the sensors that had been installed for 3 weeks in the Tonnay-Charente. At each station, the sensors were placed about 50 cm below the surface for about 15 minutes to ensure that the sensors were in equilibrium with the water. In 2019, this approach was repeated, for the first time on 23 and 24 July, allowing us to measure dissolved oxygen at low and high tide at L'Hounée. On the 7th of August, the transit between Soubise and Tonnay-Charente was made by sea with a multi-parameter probe (SAMBAT, NKE Instrumentation) permanently submerged at a depth of 0.5 metres below the surface and recording

155 data every 2 minutes. The 2018 transect covered the longest distance along the estuary, approximately 35 km from Soubise,

near the mouth, to Saint-Savinien; the 2019 transects were reduced in upstream extension in light of the observations obtained in 2018.

2.2.3 Low-frequency dataset

160   Dissolved oxygen data collected from 2018 to 2020 revealed hypoxic situations, which was surprising as the Charente estuary was not known to have such a problem, unlike the Loire and Charente estuaries. We therefore searched for historical data, which enabled us to discover the existence of a long-term, low-frequency monitoring of water quality, carried out by the French Water Agency, in particular to assess the ecological status of transitional waters. This monitoring is part of the water quality assessment carried out by the French Water Agency, in accordance with the guidelines of the European Water Framework Directive, which includes the measurement of a number of chemical species such as organic and metallic pollutants, as well

165   as temperature, salinity and dissolved oxygen. All data are freely available on a dedicated website (SIE Adour Garonne, 2023). There are three water quality stations in the Charente estuary. Rochefort (station number 5001500) has been monitored since 1975, initially with 8 visits per year, then from 1982 with 10 to 12. The extension of the monitoring to Tonnay-Charente (station number 5002350) and Saint-Savinien (station number 5006860) is more recent, in 2011, with a lower frequency (6 times per year).

170   2.2.4 Water quality criteria by DO values

The Water Framework Directive (WFD, 2000/60/EC) aims to achieve 'good status' for all ground and surface waters (rivers, lakes, transitional waters and coastal waters) in the European Union. The Directive identifies dissolved oxygen (DO) as one of the "five general chemical and physico-chemical elements supporting the biological elements". In this paper, we use the classification proposed by Best et al (2007) for water status according to DO levels: bad below 2 mg L^{-1}, poor to moderate

175   between 2 and 5 mg L^{-1}, good above 5 mg L^{-1}. Such management issues in estuaries that justify the use of the unit in mg L^{-1}. The correspondence between mg L^{-1} and µmol L^{-1} is as follow: 1 mg L^{-1} corresponds to 31.3 µmol L^{-1}; 2 mg L^{-1} to 62.5 µmol L^{-1} and 5 to 156.3 µmol L^{-1}.

3. Results and discussion

3.1 Long-term, low-frequency monitoring of dissolved oxygen

180   The low-frequency dataset acquired at Rochefort covers 48 years, corresponding to very contrasting hydrological and climatic conditions. During this period, river discharges varies between 7.3 and 479 m^3 s^{-1}, covering the whole range of the Charente discharge. As river discharge decreases, salinity increases, ranging from 0.25 to 17.8 (**Figures 2 & 3; Table A2**). The highest salinities are usually observed in summer and autumn, during the low water period of the Charente river. It is also during this period that the water temperature is the highest, typically between 20.5 and 27.0°C, while in winter it ranges between 3 and

185   10.2°C. On the basis of the high summer salinity and temperature, it was already possible to speculate that these conditions were not favourable for good oxygenation of the Rochefort waters, since solubility decreases as these parameters increase. An additional parameter in this highly turbid estuary is the occurrence of TMZ: SPM, also monitored, confirms the presence of TMZ at Rochefort when the Charente discharge is less than 70 m^3 s^{-1}, which is usually the case in summer and early autumn (data not shown). Indeed, DO concentration and saturation show a strong seasonal signal. The highest values are observed in

190   winter and early spring when water temperature is the lowest and salinity negligible, with concentrations and saturation usually higher than 10 mg L^{-1} and 90 %. There are even a few occasions in spring when there are strong oversaturation, up to 154 %, which may be associated with spring bloom, as already reported in turbid estuaries (Goosen et al, 1999). Then, from June to October, the estuarine waters of Rochefort are always undersaturated, the lowest value recorded being 15%. August is the month of consistently low dissolved oxygen, with saturations and maximum concentrations of 82% and 2.2 mg L^{-1},

195   respectively, due to the warmest and saltiest waters. However, critical DO levels were also observed in July, the lowest value measured by the low frequency survey being 1.3 mg L^{-1} (15% of saturation) on 23 July 1990. As the water cools in autumn,

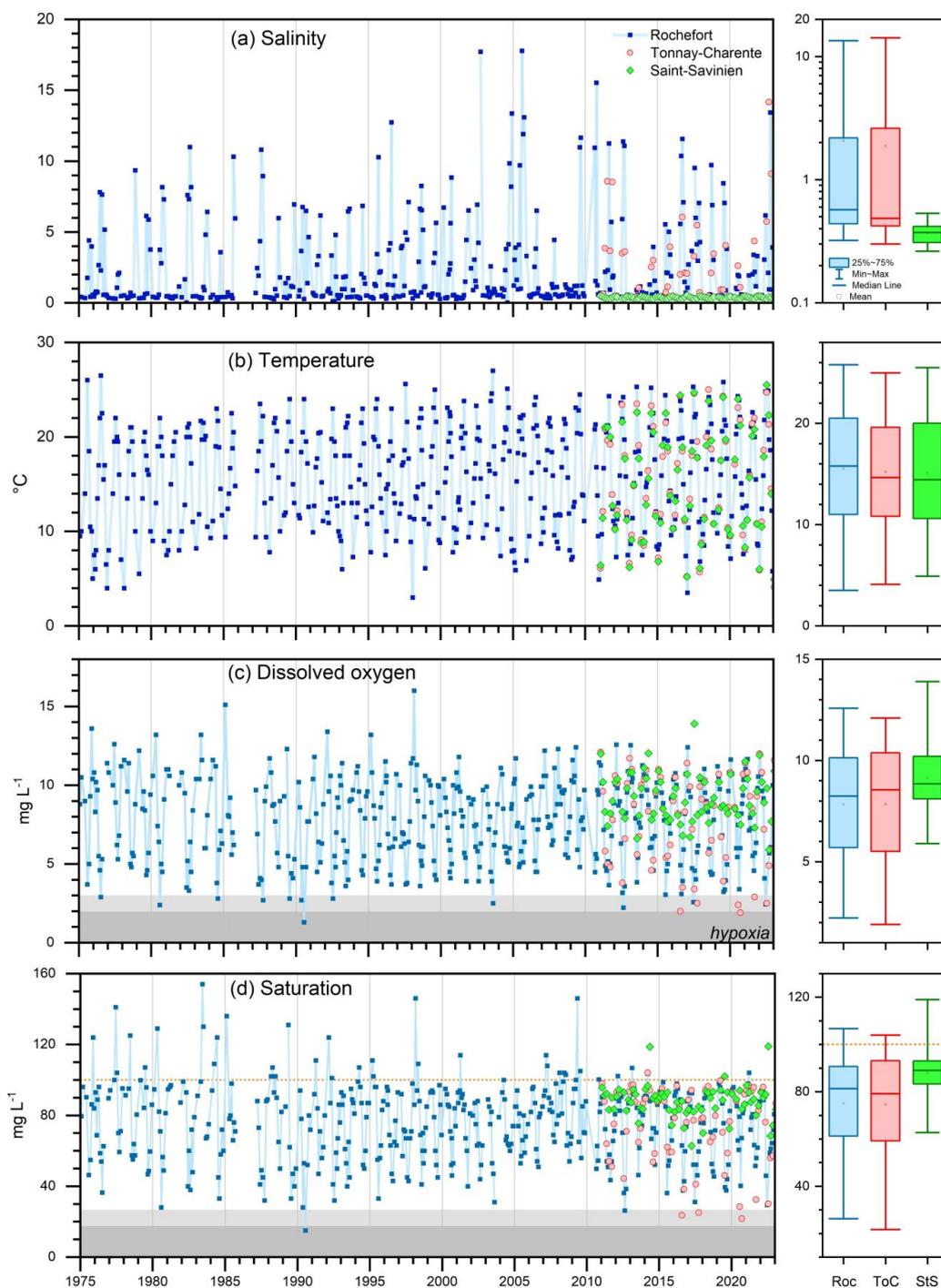
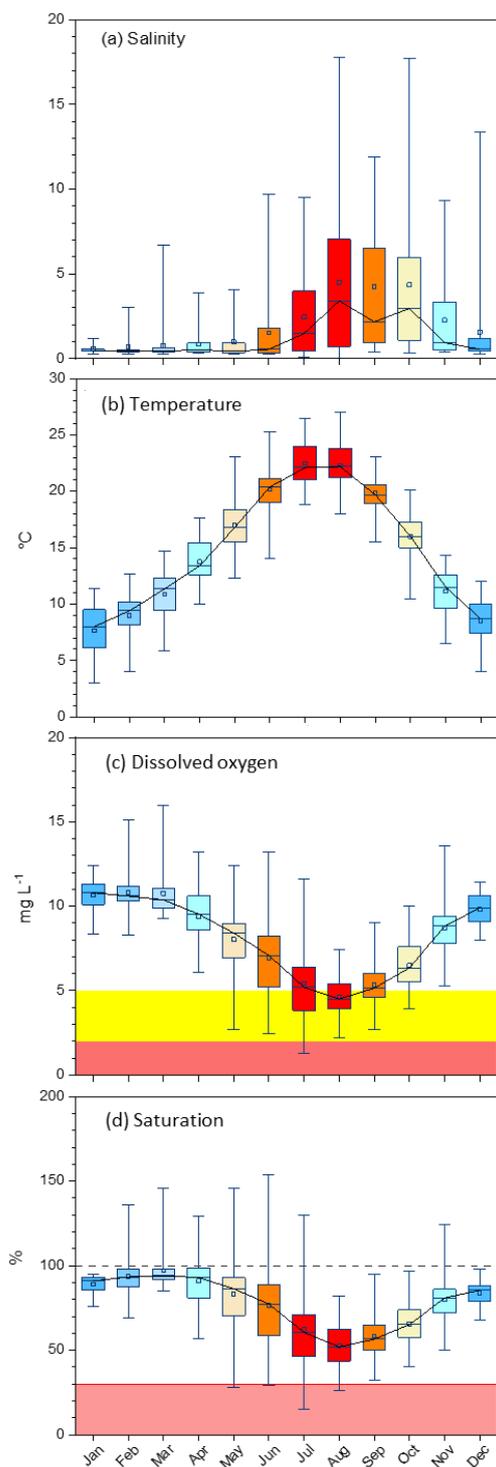
the oxygenation gradually improves, DO reaching values > 5 mg L^{-1} from October onwards and returning to a situation close to saturation.

200 **Figure 2: Low frequency records of (a) salinity, (b) temperature and dissolved oxygen (c) concentration and (d) saturation at Rochefort for the period 1975-2022 and at Tonnay-Charente and Matrou for the period 2011-2022. The panel on the right shows the box plot (min, max, median, mean, 25%-75%) of each parameter per station (Roc: Rochefort; ToC: Tonnay-Charente; StS: Saint-Savinien) for the period 2011-2022.**

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Figure 3: Monthly box plot of (a) salinity, (b) temperature and dissolved oxygen (c) concentration and (d) saturation based on the long-term low-frequency monitoring at Tonnay-Charente for the period 1975-2022.

About 6 km upstream, at Tonnay-Charente, the water quality station was added much later, starting in 2011 (Figure 2 ; Table A2). Not surprisingly, the salinity range is slightly lower than in Rochefort, from 0.3 to 14.2. Saline intrusion (salinity > 1) is

210 usually observed in summer and autumn. Temperatures are rather similar, with a general monthly mean temperature difference of less than 0.5°C between Tonnay-Charente and Rochefort. Dissolved oxygen concentrations are also the highest in winter and spring, ranging from 8.3 to 12.4 mg L^{-1} and close to saturation equilibrium (95-104%). Spring is a transitional period, after which there is a strong deterioration of water oxygenation. In July and September, the average DO for the period 2011-2022 is 4.4 and 4.7 mg L^{-1}, with extremes ranging from 1.9 to 5.1 mg L^{-1}. In November, DO concentrations return to good levels,

215 with values above 5.9 mg L^{-1}, although undersaturation remains (57-93%), as the Charente discharge increases and the water is cooler. There is a striking feature in the DO minimum in the Tonnay-Charente record (Figure 2): whereas the lowest value (3.8 mg L^{-1}) during the period 2011-2015 was observed on 27 July 2012, since 2016 there is a tendency to reach even concentrations below 3.5 mg L^{-1} almost every year. Unfortunately, the small number of measurements (6 per year) does not allow to draw conclusions on this possible trend.

220 The seasonal pattern of DO variability is rather similar between the stations of Rochefort and Tonnay-Charente, 6 km apart, both located in the turbidity maximum zone from spring to autumn. On the other hand, at Saint-Savinien, which is located at about 28 and 22 km away from the two other stations, the low-frequency survey shows large difference in salinity and dissolved oxygen (Figure 2; Table A2). This water quality station is located in the fluvial Charente estuary, which means that salinity is negligible throughout the year (< 0.53). The main difference concerns DO concentrations, which range from 5.9 mg L^{-1} to 13.9

225 mg L^{-1} (saturation between 63 and 168 %), indicating good conditions regarding this criteria.
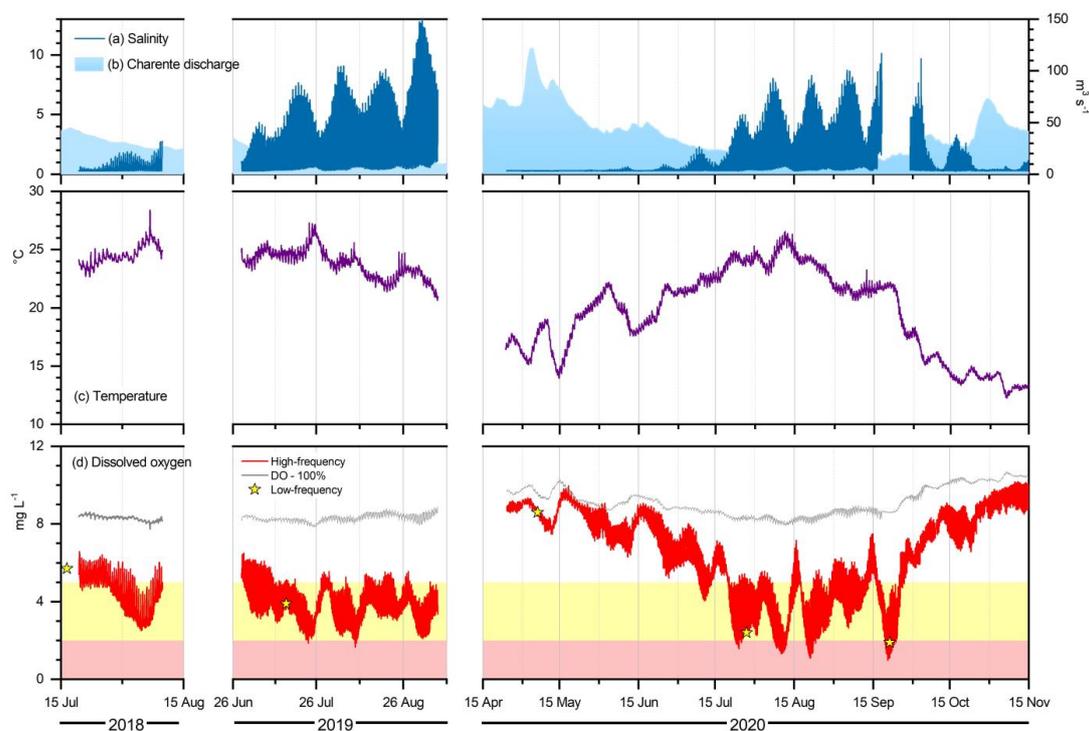
Figure 4: High-frequency record of (a) salinity, (c) temperature and (d) dissolved oxygen in surface waters of Tonnay-Charente during summers 2018 and 2019, and from spring to autumn 2020. Details on instrumented periods are given Table 1. The blue curve
230 **corresponds to the (b) fluvial Charente discharge and the grey line to the theoretical dissolved oxygen concentration at saturation, calculated from temperature and salinity.**

Long-term, low frequency monitoring highlights that severe summer deoxygenation occurs in the inner Charente estuary, near and upstream of the town of Rochefort. Values below 3 mg L^{-1} were measured several times from 1975 to 2022, without a clear trend over decades. Given the low number of measurements (6 to 12 per year, depending on the water quality station concerned), it is not possible to estimate whether the lowest values have been reported and the duration of potential hypoxic events.

3.2 High-frequency monitoring of dissolved oxygen

3.2.1 DO dynamic at Tonnay-Charente

The first high-frequency record at Tonnay-Charente covers three weeks from 17 July to 9 August 2018, when the Charente River entered a low-water period, with a decrease in discharge from 45 to 23 m^3 s^{-1} and the presence of a moderate TMZ (Figure 4). At the same time, a short heatwave occurred at the beginning of August, causing a rapid increase in temperature, with a maximum of 28.4°C, and highlighting the high variability of dissolved oxygen. In this context, it can be seen that dissolved oxygen is already highly undersaturated at the end of July, with the difference between measured and theoretical DO being around 2.3 and 3.8 mg L^{-1} depending on the tidal moment. Then, coinciding with the rise in temperature, which peaked on 6 August, there was a rapid decrease in dissolved oxygen, with daily concentrations falling from 5.4 to 3.1 mg L^{-1} (63.3% to 37.9%) in a few days. The DO deficit reached up to 5.7 mg L^{-1}, indicating an increase in DO consumption. Then, there is a restoration of DO with the decrease in temperature to reach almost 5 mg L^{-1} at the end of the summer 2018 observation. The minimum DO reached at the beginning of August 2018 is 2.5 mg L^{-1}, just above the hypoxic level. However, if we considering the threshold of 5 mg L^{-1} for daily mean DO as good for the ecosystem (Best et al, 2007), 13 of the 22 days observed were below this criterion.

In 2019, the instrumentation period will be 70 days, with an early implementation date of 29 June 2019 due to a first heatwave at the end of June. The low water period was particularly severe in the summer of 2019, with a mean river discharge of 12 m^3 s^{-1} (July to September) compared to 25 and 17 m^3 s^{-1} in 2019 and 2020 (Figure 3). These very low flows of the Charente in 2019 are reflected in much higher salinities in 2019 compared to 2018. Semi-diurnal tidal and spring/neap cycles are clearly visible in the salinity signal. Temperature variations, on the other hand, are influenced by the different warm periods and heat waves. DO concentration is also highly variable, influenced by the tidal cycle, which is outweighed by the effect of warm periods, during which minima, as low as 1.65 mg L^{-1}, are measured. From 11 July 2019, dissolved oxygen will be below 5 mg L^{-1} most of the time. On 23 July and 9 August 2019, the concentration even reaches very critical levels, below the hypoxic threshold (2 mg L^{-1}) and an oxygen deficit higher than 6 mg L^{-1}. 69 of the 71 days observed were below below 5 mg L^{-1}, but always higher than 2.

In 2020, still at Tonnay-Charente, monitoring started at the end of April, when the Charente discharge decreased to levels that allowed TMZ to develop and persist until the autumn floods (Fig. 4). SPM concentrations varied between 0.1 and up to 8 g L^{-1} during the summer (data not shown). The extended monitoring period supports the observations from the low-frequency monitoring, with DO concentrations approaching equilibrium in spring and autumn and hypoxic events in summer. From June to September 2020, representing a total of 92 days, there were 74 and 2 days during which the daily mean DO was below the threshold of 5 and 2 mg L^{-1}, respectively. The autumn cooling in 2020 is accompanied by a rapid recovery of the oxygenation to higher levels (i.e., > 5 mg L^{-1}), although the suspended matter load is still high (> 1 g L^{-1}).

The periods during which hypoxia levels are measured are usually short, typically between 3 and 6 days, which calls into question the frequency of measurements to be able to capture them. The low frequency measurements have been plotted along the high-frequency records (Fig. 4). A first comment is the good agreement between the two datasets, which came as a pleasant surprise. Indeed, one might have expected a problem with the quality of the low-frequency monitoring data, which is carried out by operators rather than scientific teams. This validates the use of these data, which are often discarded by research teams. However, the main problem is the inability to capture large variations in DO. This is not surprising with only two measurements

in summer at the water quality station of Tonnay-Charente (July, September). On the basis of low-frequency monitoring, water

275 quality in 2018 and 2019 would be described as relatively good in terms of dissolved oxygen. In 2020, as it happens, both measurements were taken when the dissolved oxygen was at hypoxic levels. But these comparisons illustrate, if proof were needed, that high-frequency monitoring is essential in macrotidal estuaries. However, the comparison with the long-term, low-frequency AEAG survey does not allow us to determine whether these severe deoxygenations have changed significantly since 1975.

280 **3.2.2 DO dynamic apart Tonnay-Charente**

A second site was instrumented in 2019 at L'Houmée (PK37), roughly halfway between Tonnay-Charente (PK25.9) and Saint-Savinien (PK47.6). The data show the same trends as for Tonnay-Charente, but attenuated in the case of salinity due to a more upstream location (data not shown): salinity never exceeds 2. Dissolved oxygen also shows a temporal variability similar to that of Tonnay-Charente, but with a slightly wider range of values (Figure 5). During the tidal cycle, minimum values, typically

285 between 2.1 and 2.4 mg L^{-1} (24.4-30.4%), are always observed at high tide, indicating the advection of oxygen-poor water from downstream. As a result, the minimum DO is always equal to or higher than the values recorded at Tonnay-Charente. Conversely, at low tide, the river water, which tends to be more oxygenated, as shown for Saint-Savinien, influences the site: the DO range is then much higher between 4.7 and 7.9 mg L^{-1} (58-92%). As a result, the daily mean DO in L'Houmée is higher than in Tonnay-Charente, with only half of the observation days having a daily mean of less than 5 mg L^{-1} (most of them in

290 Tonnay-Charente).
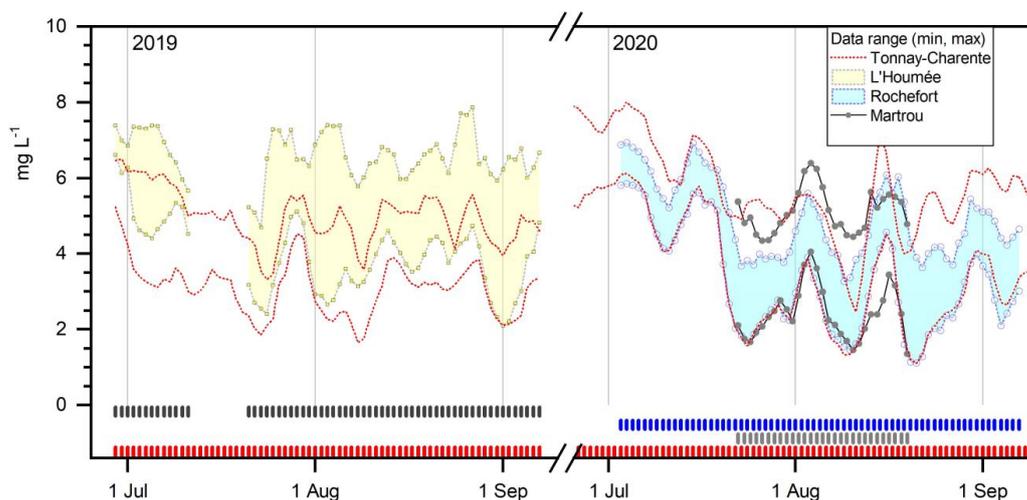
Figure 5: Comparison of summer DO range (minimum, mean, maximal) at Martrou, Rochefort, Tonnay-Charente and L'Houmée during summer 2019 and 2020

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In 2020, two stations were instrumented in the downstream sector between Soubise (KP12.2) and Tonnay-Charente (KP25.9) at Matrou (KP16.1) and Rochefort (KP19.8). Matrou has a slightly higher salinity than Rochefort due to its position further upstream and closer to the mouth, but both are higher than Tonnay-Charente: maximum salinities are 15.0, 14.4 and 7.7 respectively. The DO concentration in Rochefort and Tonnay-Charente shows limited differences (Fig. 5). In summer, the

300 minimum DO values are usually the same, but in September, when the maximum DO values are higher in Tonnay-Charente, Rochefort appears as the station with the lowest DO. Martrou was monitored for a shorter period, and its minimum values are similar to those of the other stations. Only briefly, during high tide, DO could be 1 to 2 mg L^{-1} higher than at the other two stations due to the advection of more oxygenated seawater. In short, the waters of Rochefort always showed the lower

maximum values, which could be explained by the fact that this station is surrounded by oxygen-poor waters, whereas Tonnay-

305 Charente and Martrou could benefit from the advection of marine or fluvial waters with higher DO concentration, depending on the Charente discharge and the tidal range.
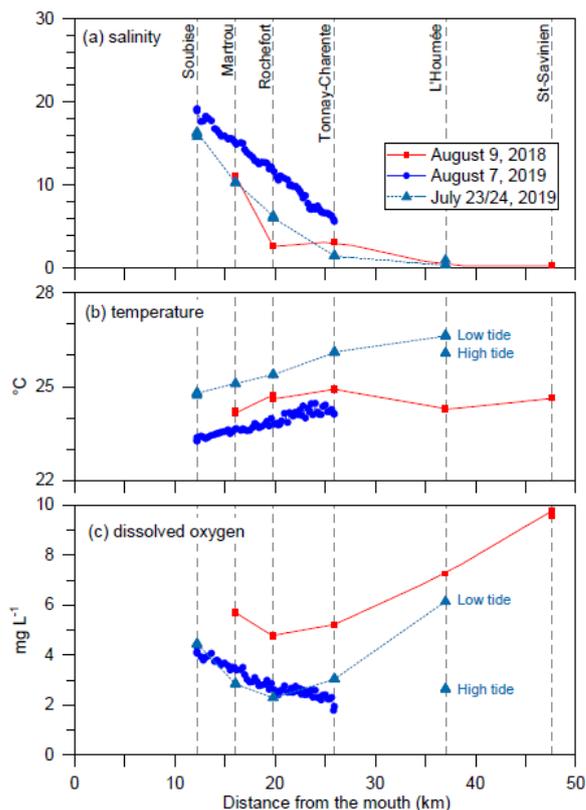
Figure 6: Longitudinal distributions of (a) salinity, (b) temperature and (c) dissolved oxygen in surface water according distance from the mouth. The position of the instrumented sites is indicated by the dashed lines

310 **3.3 Localisation of the Oxygen minimum zone**

The identification of hypoxia in the Charente estuary then required an assessment of the area of the oxygen minimum zone, based on several approaches. Firstly, the low-frequency data set has already been used to define the maximum extent of the OMZ. For the period 2011-2022, the mean DO at Saint-Savinien is 9.1 ± 1.5 mg L^{-1} (87.9 ± 9.1%) and the lowest value recorded, in September 2022, is 5.9 mg L^{-1} (62.7%) (Table A2; Fig. 2). Thus, although there is evidence of summer

315 deoxygenation, it remains well above the hypoxic threshold (< 30%). At Saint-Savinien, in the fluvial estuary about 48 km from the mouth of the Charente, the oxygenation of the water seems to be good. On the other hand, the two water quality stations in the inner estuary (Rochefort and Tonnay-Charente) are clearly located in an area where severe deoxygenation has already been observed in summer and early autumn. In Tonnay-Charente, the 2018-2020 high-frequency monitoring confirms the decreasing trend in summer DO detected by the low-frequency monitoring. At this stage, this already places an OMZ in a

320 sector between 19.8 and 25.9 km from the mouth, with an upstream extension below 47.6 km.

More recent instrumentation of sites upstream and downstream of Tonnay-Charente may provide additional clues. Firstly, the high-frequency records confirm that the presence of the OMZ is in this sector, with strong deoxygenations and more frequent summer hypoxia than suggested by the low-frequency monitoring. Secondly, the low DO recorded at L'Houmée (PK37) shows that the upstream extent of the OMZ is not very far from Saint Savinien (PK47.6). In the lower reaches, the occurrence of

325 severe deoxygenation at Martrou (PK16.1) reveals that the OMZ extends toward downstream.

To determine the spatial extension of deoxygenation, a complementary strategy based on longitudinal surveys along the estuary axis was applied, as developed in the Gironde estuary (Schmidt et al., 2019) (Figure 6). The three longitudinal transects show a concave profile, with minimum values in a sector between 16 and 37 km from the mouth, which corresponds to a larger area than that estimated on the basis of monitoring. On 23/24 July, L'Houmée (PK37) was visited twice, at low and high tide. At

330   low tide, DO was 6.14 mg L^{-1}, a high level explained by the arrival of oxygenated river water, such as that observed at Saint-Savinien, 10.5 km further upstream. At high tide, however, DO drops to 2.65 mg L^{-1}, indicating the advection of DO-depleted estuarine water. This site must therefore be close to the maximum upstream extension of the oxygen minimum zone. DO values are higher, typically > 4-5 mg L^{-1}, at low tide at L'Houmée and at high tide at Matrou, due to the downward and upstream migration of well oxygenated fluvial and marine waters respectively. We can therefore assume that the boundaries of the OMZ

335   are close to these two sites. The OMZ thus appears to be anchored around Rochefort, with an extension of several tens of km upstream and less than 10 km downstream of the town. It should be noted that measurements were taken in surface water, and that values close to anoxia are to be expected at the bottom of the water column. The spatial extension of the deoxygenated zone is critical for benthic species and fish, especially for migratory species (Hugman et al, 1984; Alabaster and Gough, 1986; Vaquer-Sunyer and Duarte, 2011; Woodland et al., 2009).

340
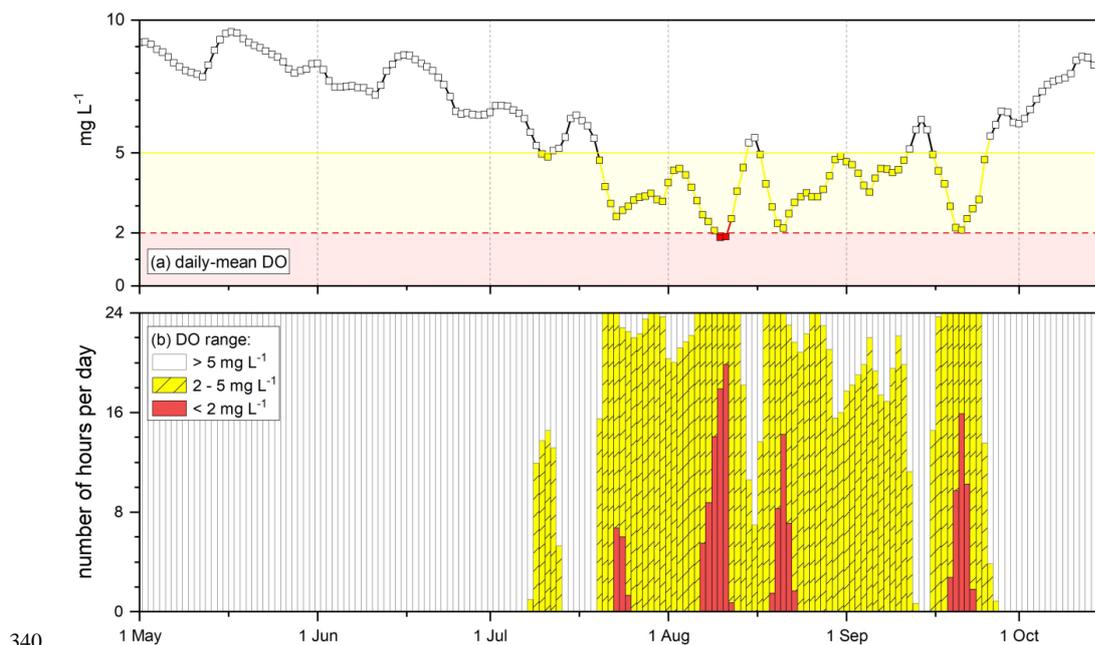
Figure 7: (a) daily-mean DO and (b) number of hours per day during which dissolved oxygen concentration of surface water in Tonnay-Charente is within the range of: < 2, 2-5, and >5 mg L^{-1}, from May, 1 to October, 15 2020.

3.4 Duration of hypoxic periods

All the data presented in this work show that the Charente estuary has a summer minimum oxygen zone with DO below 5 mg

345   L^{-1}, with a spatial extent of about 25 km under current discharge and temperature conditions. Estuarine waters in this OMZ could reach borderline or even hypoxic, levels during tidal cycles (Figures 4 & 5). Depending on species and stage of development, fish can tolerate hypoxic conditions for short periods (Curran and Henderson, 1988). Therefore, in addition to estimating the extent of the OMZ, it is necessary to evaluate the duration of hypoxia to assess whether an estuary is of sufficient quality to maintain healthy conditions, particularly for migratory species (Hugman et al, 1984). For this evaluation, we have

350   calculated the number of hours per day during which the DO concentration of the surface water in Tonnay-Charente was in the range of: < 2, 3-5, >5-7 mg L^{-1} in 2020, based on the high frequency monitoring, which has the interest to cover a large

temporal period from spring to autumn. As described in section 3.2.1, DO levels are higher than 5 mg L^{-1} until the beginning of July and after the end of September. During the summer, the daily average is usually comprised between 2 and 5 mg L^{-1}, only two days present hypoxic conditions the 10th and 11th of August. In the nearby Gironde estuary, water managers have

355 defined a target of a minimum daily average DO target of 5 mg L^{-1} to significantly improve water quality for the ecosystems and for downstream migration of juvenile fish (Schmidt et al., 2017). In the light of these quality criteria, summer levels in Tonnay-Charente can already be considered insufficient. In addition, there are several periods where the daily mean DO is higher than 2 mg L^{-1} but the measured DO is below the hypoxic threshold for 0.7 to 15.9 hours a day (Figure 7). As a result, fish in the Charente estuary can be exposed to hypoxic conditions for several hours a day or over several tens of kilometres in

360 summer. The synthesis by Breitburg et al (2002) provides a comprehensive inventory of the effects of hypoxia on fish, which can lead to large reductions in the abundance, diversity, and yield of fish in affected waters. Hypoxia and warming may also act synergistically, as hypoxia tolerance is generally lower in warmer waters, especially for larger fish (Sampaio et al., 2021; Verberk et al., 2022). Based on a review of the literature focusing on temperate estuaries, Arevalo et al. (2023) concluded that periods of low DO are generally episodic and do not necessarily pose a serious threat to estuarine organisms if they occur for

365 very short periods and do not recur. However, it is clear that the number of studies is limited and rather dated. There is therefore a need for a better understanding of the thresholds required by biological organisms in estuarine waters.
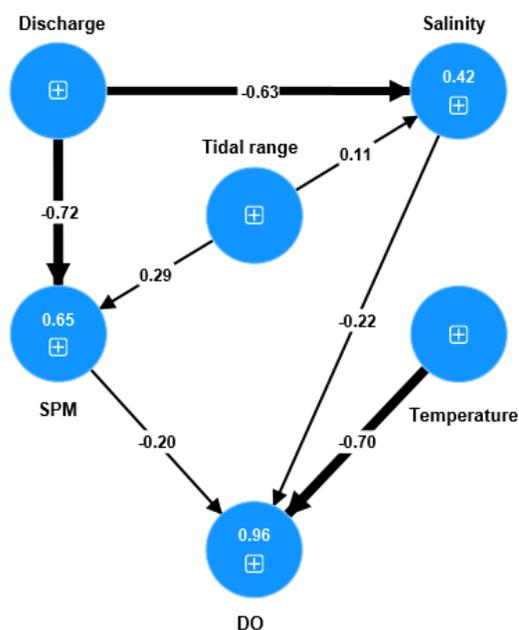
Figure 8: Path-analysis to define the relative importance of the factors controlling the temporal variability of dissolved oxygen, based
370 **on the 2020 dataset of Tonnay-Charente. The path analysis was performed using the SmartPLS4 software (Ringle et al., 2023) using**
the following parameters: discharge, tidal range, salinity, temperature, suspended particulate matter and dissolved oxygen

3.5 Hierarchy in forcing factors

The restoration of good ecological status for transitional waters is an objective of the European Water Framework Directive (Best et al., 2007). Various measures could be implemented to mitigate hypoxia, and there are examples of improvements in

375 European estuaries achieved by the installation or renovation of a wastewater treatment plant to reduce organic matter and nutrient inputs (Lajaunie-Salla et al, 2019). To optimise management strategies, modelling is an efficient tool to quantitatively test the potential solutions to mitigate hypoxia and to provide guidance for setting targets to maintain good water quality in estuaries (Kemp et al., 2009; Lajaunie-Salla et al, 2019). However, such an exercise requires a good knowledge of the DO dynamics in the system under consideration, as estuarine deoxygenation is the result of a complex interaction of environmental

380 factors. The time series recorded in the Charente estuary show the high variability of DO and the occurrence of short and recurrent hypoxia in summer. For a first estimation of the controlling factor of the DO variability using a path-analysis, we used the 2020 dataset, which has the interest to include also the concentrations of suspended particulate particles (Schmidt and Diallo, 2023). It also covers a temporal period from April to November, which encompasses the deficit DO period and then the temporal variability of the quality parameters in different hydrological and meteorological contexts. First, the regression

385 of the environmental parameters, i.e. discharge, tidal range, salinity, temperature, suspended particulate matter, with DO allowed to distinguish two groups according to their influence on DO variability. River discharge and tidal range have little direct influence, but act indirectly by affecting the variability of salinity and SPM (Fig. 8). The resulting model show that temperature, salinity and SPM account for 96% of the variability of DO. The main parameter controlling DO variability is undoubtedly temperature. This is explained by the decrease in oxygen solubility (Conley et al., 2009) and the acceleration of

390 DO consuming biogeochemical processes with increasing water temperature (Goosen et al., 1999). For the period 2018-2020, DO is always higher than 5 mg L^{-1} when the water temperature was below 18°C, even when TMZ is still present. To date, the water temperature at Rochefort and Tonnay-Charente is always below this threshold from October to April. Given the expected temperature rise in the south-west France, which could be as high as +4°C by 2100, the question arises as to the evolution of the timing of the onset of unfavourable temperatures. The Charente estuary is a corridor for migratory species such as allis

395 chad, salmon and eel. The downstream migration of juvenile fish is most frequent in the autumn, when the current conditions are favourable for entering the estuary (EPTB, 2013). Just to the south, in the Gironde-Garonne-Dordogne estuary continuum, it has been shown that there is a limited period of favourable temperature and dissolved oxygen conditions for the European sturgeon breeding season (Delage et al., 2019). The ongoing increase in temperature and the associated deoxygenation are expected to reduce their survival periods even further, leading to a possible shift of their repartition northwards in the long

400 term (Lassalle et al, 2010; Arevalo et al, 2023).

4. Concluding remarks

In short, the combination of historical low-frequency data and newly acquired high-frequency data has made it possible to highlight the occurrence of severe summer oxygen deficiency, even hypoxia, in the Charente estuary. The oxygen minimum zone is located in the inner estuary, in the vicinity of Rochefort and Tonnay-Charente, and has an extension of 20-30 km. This

405 work has demonstrated the need to monitor this small estuary as well as those of the Loire and the Gironde, which will be effective from 2021 through the extension of a regional monitoring network that was initially developed in the Gironde estuary since 2004 (Etcheber et al, 2011). Globally, there has been a decrease in dissolved oxygen in the oceans, which is more pronounced in coastal waters, leading to more frequent hypoxia events. However, hypoxia in estuaries receive less the attention than in coastal waters. Transferred to the macrotidal and highly turbid estuaries facing the Bay of Biscay, this led to the study

410 of DO dynamics in the Charente estuary, one of the small estuaries between the large Loire and Gironde estuaries. The evidence of summer hypoxia in the Charente estuary urges the need to investigate all small estuaries facing the Bay of Biscay.

In any case, this highlights the need to focus on small estuaries in order to understand and predict future changes in the face of anthropogenic and climatic pressures. A better understanding of the thresholds required by biological organisms in estuarine

415 waters is also needed to develop appropriate monitoring, remediation and mitigation strategies. Temperature is a key parameter in macrotidal estuaries, which often have a turbidity maximum zone: such a feature promotes the occurrence of severe deoxygenation up to hypoxia. At the scale of an estuary and its catchment, there are almost no levers to limit water temperature increases. Supporting low summer flows with water stored in reservoirs can limit water warming, reduce the residence time of estuarine water, increase the inflow of more oxygenated river water, and limit the TMZ concentration and hence the oxygen

420 consumption associated with bacterial degradation.

5. Appendice A

Table A1 Annual range (minimum, mean, maximum) of the Charente discharge for the period 2006-2022. Data are from
https://hydro.eaufrance.fr/sitehydro/R4230010/fiche corresponding to station Chaniers [Beillant].

Year	minimum	mean	maximum
2006	9.8	65.3	380
2007	14.4	75.2	584
2008	15.5	68.1	227
2009	8.4	48.6	425
2010	9.1	53.7	184
2011	6.7	33.1	294
2012	6.5	63.4	414
2013	17.5	99.4	464
2014	18.3	99.1	453
2015	14.7	52.5	200
2016	12.5	80.2	507
2017	8.5	31.0	181
2018	13.8	101.4	508
2019	7.4	69.1	321
2020	11.2	65.5	263
2021	14.9	71.4	485
2022	7.3	32.0	148

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Table A1 Range of salinity, temperature (°C), dissolved oxygen, in concentration (mg L⁻¹) and saturation (%) for each water quality station whose data series is plotted in Figure 2. For Rochefort, calculations have been made for the whole dataset (1975-2022) and for the period 2011-2022 to allow comparison with the other two other stations which only cover the period 2011-2022. Bold and underlined numbers correspond to concentrations and saturation less than 3 mg L⁻¹ or 35% and greater than 10 mg L⁻¹ or 100% respectively.

Site	Years	Month	N	Salinity			Temperature (°C)			DO (mg L⁻¹)			Saturation (%)		
				mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.
Rochefort	1975-2022	Jan	23	0.6	0.3	1.2	7.6	3.0	11.4	10.7	8.3	12.4	89	76	95
Rochefort	2011-2022	Jan	13	0.5	0.4	1.1	7.3	3.5	11.3	10.9	8.3	12.4	89	76	95
Tonnay-Ch.	2011-2022	Jan	11	0.6	0.4	2.1	7.9	5.2	10.3	10.9	9.0	12.1	90	78	98
St-SAvinien	2011-2022	Jan	12	0.5	0.4	0.5	7.6	4.9	10.3	10.7	8.3	12.0	88	70	97
Rochefort	1975-2022	Feb	31	0.7	0.3	3.0	9.0	4.0	12.7	10.8	8.3	15.1	94	69	136
Rochefort	2011-2022	Feb	13	0.6	0.4	2.7	10.0	7.3	12.7	10.8	9.6	12.6	94	85	107
Rochefort	1975-2022	Mar	38	0.8	0.3	6.7	10.9	5.9	14.7	10.8	9.3	16.0	97	85	146
Rochefort	2011-2022	Mar	12	0.5	0.4	0.7	11.6	8.5	14.7	10.4	9.6	11.7	94	88	104
Tonnay-Ch.	2011-2022	Mar	11	0.4	0.4	0.6	11.9	9.6	13.5	10.5	9.6	11.0	96	88	104
St-SAvinien	2011-2022	Mar	11	0.4	0.4	0.4	11.6	9.1	13.2	10.0	6.7	10.8	90	63	97
Rochefort	1975-2022	Apr	44	0.8	0.3	3.9	13.7	10.0	17.6	9.4	6.1	13.2	91	57	129
Rochefort	2011-2022	Apr	12	0.6	0.3	1.9	14.7	11.4	16.7	9.1	7.1	10.5	90	72	99
Rochefort	1975-2022	May	41	1.0	0.3	4.1	17.0	12.3	23.1	8.0	**2.7**	12.4	83	**28**	146
Rochefort	2011-2022	May	12	1.0	0.4	3.7	17.4	15.1	21.8	7.6	4.1	9.0	78	46	92
Tonnay-Ch.	2011-2022	May	11	0.7	0.3	3.8	17.7	14.8	20.8	7.9	5.8	9.3	84	64	96
St-SAvinien	2011-2022	May	11	0.3	0.3	0.4	17.6	14.9	21.0	8.8	7.7	12.0	92	82	119
Rochefort	1975-2022	Jun	48	1.5	0.3	9.7	20.1	14.0	25.3	6.9	**2.4**	13.2	77	**29**	154
Rochefort	2011-2022	Jun	12	1.1	0.3	6.2	21.3	18.4	25.3	6.1	**2.4**	8.3	68	**29**	92
Rochefort	1975-2022	Jul	44	2.6	0.3	9.5	22.4	18.8	26.5	5.4	**1.3**	11.6	62	**15**	130
Rochefort	2011-2022	Jul	11	3.9	0.3	9.5	23.7	21.2	25.8	4.8	3.1	7.5	56	36	79
Tonnay-Ch.	2011-2022	Jul	11	2.6	0.3	8.6	23.2	19.6	25.0	4.4	**2.0**	8.5	50	**24**	96
St-SAvinien	2011-2022	Jul	12	0.3	0.3	0.3	23.1	20.1	25.5	8.5	6.6	13.9	99	76	168
Rochefort	1975-2022	Aug	42	4.7	0.3	17.8	22.3	18.0	27.0	4.6	**2.2**	7.4	53	**26**	82
Rochefort	2011-2022	Aug	12	4.8	0.5	11.4	22.8	20.2	24.9	4.2	**2.2**	6.6	48	**26**	73
Rochefort	1975-2022	Sep	47	4.2	0.4	11.9	19.8	15.5	23.1	5.3	**2.7**	9.0	58	**32**	95
Rochefort	2011-2022	Sep	12	4.1	0.4	11.6	20.2	17.9	22.5	5.1	3.6	7.6	55	**39**	82
Tonnay-Ch.	2011-2022	Sep	12	4.1	1.0	14.2	19.8	18.0	22.0	4.7	**1.9**	6.7	51	**22**	73
St-SAvinien	2011-2022	Sep	12	0.3	0.3	0.4	19.6	17.7	22.3	7.7	5.9	8.8	84	68	93
Rochefort	1975-2022	Oct	45	4.4	0.3	17.7	16.0	10.5	20.1	6.5	3.9	10.0	66	40	97
Rochefort	2011-2022	Oct	12	4.1	0.4	13.4	16.2	13.2	18.6	6.6	4.4	8.2	66	46	83
Rochefort	1975-2022	Nov	40	2.3	0.4	9.3	11.1	6.5	14.3	8.7	5.3	13.6	80	50	124
Rochefort	2011-2022	Nov	13	1.8	0.5	7.0	11.5	8.4	14.3	8.6	6.9	9.8	78	66	87
Tonnay-Ch.	2011-2022	Nov	11	2.7	0.4	9.1	11.7	9.1	14.5	8.6	5.9	10.7	79	57	93
St-SAvinien	2011-2022	Nov	11	0.4	0.4	0.5	11.4	8.8	14.0	9.0	7.7	9.8	82	73	89
Rochefort	1975-2022	Dec	35	1.6	0.3	13.4	8.5	4.0	12.0	9.8	8.0	11.4	84	68	98
Rochefort	2011-2022	Dec	11	1.5	0.5	4.3	8.2	5.8	11.1	10.3	8.9	11.3	86	78	93

6. Data Availability

435 Data are available on data repositories as detailed in Table 1

7. Author contribution

SS: Conceptualization, Methodology, Investigation, Data Curation, Date analysis; I.I.D. Investigation, Resources, Project administration. SS prepared the manuscript with contributions from the co-author.

8 Competing interest

440 The authors declare that they have no conflict of interest

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10. Special issue statement

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