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1 **Comparing the efficiency of hypoxia mitigation strategies in an urban, turbid tidal**
2 **river, using a coupled hydro sedimentary-biogeochemical model**

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23 **Highlights**

- 24 - A 3D model shows different efficiencies of management actions to limits hypoxia.
- 25 - Sewage overflow reduction improves DO levels only locally.
- 26 - Downstream relocation of wastewater discharges mitigates totally hypoxia.
- 27 - Support of river flow must be adapted depending of hydrological context
- 28 - The combination of different management actions improves DO levels.



29 **Abbreviations**

- 30 DO: dissolved oxygen
- 31 DOC: dissolved organic carbon
- 32 LTS: long-term support
- 33 NT: Neap tide
- 34 POC: particulate organic carbon
- 35 SO: sewage overflow
- 36 ST: Spring tide
- 37 STS: short-term support
- 38 TGR: Tidal Garonne River
- 39 TMZ: turbidity maximum zone
- 40 WS: watershed
- 41 WW: wastewater
- 42 WWTP: wastewater treatment plant
- 43



44 **Abstract**

45 In view of future coastal hypoxia widespreading, it is essential to define management
46 solutions to preserve a good quality of coastal ecosystems. The lower Tidal Garonne River
47 (TGR, SW France), characterized by the seasonal presence of a turbidity maximum zone and
48 urban water discharges, is subject to episodic hypoxia events during summer low river flow
49 periods. The future climatic conditions (higher temperature; summer droughts) but also an
50 increasing urbanization could enhance hypoxia risks near the city of Bordeaux in the next
51 decades. A 3D model of dissolved oxygen (DO), which couples hydrodynamics, sediment
52 transport and biogeochemical processes, is used to assess the efficiency of different
53 management solutions on TGR oxygenation during summer low-discharge periods. We have
54 runned different scenarios of reduction of urban sewage overflows, displacement of urban
55 discharges downstream from Bordeaux, and/or temporary river flow support during summer
56 period. The model shows that each option limits hypoxia, but with variable efficiency over
57 time and space. Sewage overflow reduction improves DO levels only locally near the city of
58 Bordeaux. Downstream relocation of wastewater discharges allows to reach better
59 oxygenation level in the lower TGR. The support of low river flow limits the upstream TMZ
60 propagation and dilutes TGR waters with well-oxygenated river waters. Scenarios combining
61 wastewater network management and low water replenishment indicate an improvement in
62 water quality over the entire TGR. These modelling outcomes constitute important tools for
63 local water authorities to develop the most appropriate strategies to limit hypoxia in TGR

64 **Keywords:** hypoxia, management, modeling, Garonne Tidal River, wastewater, water quality

65



66 1 Introduction

67 In view of the ongoing global change, it is essential to find management strategies for
68 hypoxia mitigation (dissolved oxygen (DO) concentration $< 2 \text{ mg.L}^{-1}$ or $< 30\%$ of saturation,
69 Rabalais et al. (2010)). Coastal hypoxia is a widespread phenomena since the middle of the
70 20th century due to the combined effect of the increase in temperature and anthropogenic
71 activities (Breitburg et al., 2018). Hypoxia is a major environmental issue, which stresses
72 marine organisms and perturbs the functioning of coastal ecosystem (Vaquer-Sunyer and
73 Duarte, 2008). Due to their strategic position for fish migration, a good oxygenation of
74 estuarine waters is crucial (Rabalais et al., 2010). Usually, coastal and transitional zones
75 receive increasing organic matter and nutrients inputs from watershed and urban effluents,
76 that lead to an extension of eutrophic and hypoxic areas (Diaz, 2001). In macrotidal estuaries,
77 the DO consumption by heterotroph processes is exacerbated by the presence of a turbidity
78 maximum zone (TMZ) which limits primary production (Goosen et al., 1999). Estuarine
79 deoxygenation is the result of the complex interaction of several environmental factors such
80 as temperature, river flow, the quantity of urban effluents discharged in the aquatic system,
81 high turbidity and sediment dynamics (Talke et al., 2009). For that reason, recovering or
82 maintaining a good ecological status for transitional waters is one of the objectives of the
83 European Water Framework Directive (Best et al., 2007).

84 In an urban tidal river, a first obvious action to mitigate hypoxia is to improve urban
85 wastewater network and treatment and to reduce the input of organic matter and nutrients to
86 the estuary. In several European estuaries undergoing urban inputs, water quality
87 improvement were achieved: in the Thames Estuary since the installation and renovation of a
88 wastewater treatment plant (WWTP) in 1980s (Andrews and Rickard, 1980; Tinsley, 1998),
89 in the Seine River since the construction of a WWTP in 1990s (Billen et al., 2001). In the



90 Scheldt Estuary, the sewage network was also improved and two WWTPs were implemented
91 for the city of Brussels since 2000 (Billen et al., 2005; Soetaert et al., 2006; Vanderborght et
92 al., 2007). Sewage network systems in Europe usually combine both the urban sewage and
93 stormwater collection. During heavy rain and storm events, the capacity of urban wastewater
94 network is generally insufficient to treat all effluents, inducing deoxygenation events due to
95 untreated wastewater release from sewage overflows (SO) (Even et al., 2007). In the 2000s,
96 the Environmental Protection Agency promoted a strategy to monitor urban drainage network
97 in real time to regulate flow and avoid overflow of untreated wastewater (EPA, 2006; Gonwa,
98 1993). This control was developed in several cities, such as Québec (Pleau et al., 2005) or
99 Tokyo (Maeda et al., 2002). An additional management solution was tested in the Thames
100 Estuary: the construction of a 24-km long outfall under the riverbed, which allows the transit
101 of urban wastewater to the WWTP located downstream (Thames Tideway Tunnel,
102 www.tideway.london). This type of solution is also ongoing in Stockholm
103 (www.stockholmvatten.se) and Helsinki (www.hsy.fi) metropolis.

104 In macrotidal estuaries, the lowest DO concentrations occur during the lowest river flow
105 (Lanoux et al., 2013; Talke et al., 2009; Zhang et al., 2015). A second possible action
106 therefore could be to modify the local residual circulation and to reduce water flushing time,
107 to promote the renewal of well-oxygenated waters, and/or the seaward dispersion of oxygen-
108 consuming material (Lajaunie-salla et al., 2018). This implies to provide water replenishment
109 above critical levels, by limiting water abstraction for irrigation in the watershed or by
110 modulating water release from dams, when hypoxia is present (Schmidt et al., 2017).

111 In order to optimize preventive management strategy, the efficiency of the potential solutions
112 needs to be evaluated. For that, numerical modelling is an efficient tool to assess
113 quantitatively hypoxia mitigation by management scenarios. Moreover, models allow to



114 provide guidelines for setting objectives to maintain a good water quality of coastal
115 environment (Kemp et al., 2009; Skerratt et al., 2013).

116 A recently developed 3D coupled hydro sedimentary-biogeochemical DO model simulated
117 possible scenarios for the coming decades suggesting a future spatial and temporal extension
118 of summer hypoxia in the Tidal Garonne River (TGR, S-W France), an urban, turbid tidal
119 river (Lajaunie-salla et al., 2018). Until now in the TGR, only few hypoxia events have been
120 reported, for example during summer 2006 (Lanoux et al., 2013). Previous work highlighted
121 that these low DO level are due to the combination of the presence of TMZ high water
122 temperature, drought periods and urban effluents inputs (Lajaunie-Salla et al., 2017; Lanoux
123 et al., 2013; Schmidt et al., 2017). Such a perspective of a permanent summer hypoxia in the
124 lower TGR implies to develop management strategies to protect the ecosystem. The aim of
125 the present work was to assess the efficiency of possible management solutions to limit future
126 hypoxia risk in the Tidal Garonne River. For this purpose, we applied the aforementioned DO
127 model in order to simulate scenarios based on two main management actions: optimization of
128 urban wastewater network and fresh water replenishment during low water periods.

129 **2 Materials and Methods**

130 **2.1 Study Area**

131 The Garonne River, located in Southwest of France, is the main tributary of the Gironde
132 Estuary, which is formed by its confluence with the Dordogne River and flows toward the
133 Atlantic Ocean (Fig.1). This macro-tidal fluvio-estuarine system is characterized by the
134 presence of a TMZ, where suspended sediment concentration in surface waters are $> 1 \text{ g.L}^{-1}$
135 (Allen, 1972). The position of the TMZ varies seasonally : during low river flow it is present
136 in the Tidal Garonne River, from PK25 to PK-70 (Fig.1). The rest of the year, the TMZ is



137 located around Pauillac (Fig.1) at downstream of the Gironde Estuary (Jalón-Rojas et al.,
138 2015)

139 The annual mean Garonne River flow is $680 \text{ m}^3 \text{ s}^{-1}$ for the period 1913-2018, with the highest
140 values in winter (mean of $720 \text{ m}^3 \text{ s}^{-1}$) and the lowest in summer and early autumn (mean of
141 $190 \text{ m}^3 \text{ s}^{-1}$) (<http://www.hydro.eaufrance.fr/indexd.php>). Since mid 80s, there has been an
142 increase in the number of days with a river flow below $110 \text{ m}^3 \text{ s}^{-1}$ (Etcheber et al., 2013). Such
143 a decrease in the Garonne flow limits the reoxygenation of TGR waters with well-oxygenated
144 freshwaters and favours the upstream advection and the concentration of TMZ (Lajaunie-
145 salla et al., 2018). Six water reservoirs are located in the upper Garonne River, which can
146 store a maximum water volume of 58 hm^3 : this volume corresponds to an equivalent river
147 flow of $95 \text{ m}^3 \text{ s}^{-1}$ during one week. This water storage is used to maintain the Garonne
148 discharge above the critical thresholds for the ecosystem during summer.

149 The large city of Bordeaux is located at the border of the Tidal Garonne River, 25 km
150 upstream of the confluence (Bec d'Ambès, Fig.1). The sewage systems of the metropolis
151 drains an urban area of 578 km^2 and serves a population estimated at 749 595 inhabitants in
152 2015. The part of the sewage system is composed of a combined sewer network: two
153 wastewater treatment plants (WWTP), Clos de Hilde and Louis Fargue, and nine sewage
154 overflows (SO). The continuous releases of treated and untreated wastewaters represent up to
155 1.5 % of the fluvial Garonne discharge (Lanoux et al., 2013).

156 Bordeaux Metropolis has already taken several actions to improve the urban wastewater
157 network. In 2011, the WWTP Louis Fargue was resized and upgraded to the treatment
158 effectiveness of the WWTP Clos de Hilde. In addition, since 2013 a real time control of
159 urban drainage network was developed in order to reduce urban effluents during rainy
160 weather (Andréa et al., 2013). This system had allowed to decrease the volume of untreated



161 wastewater released by 30% in 2013 and 40% in 2014 and 2015 (Robitaille et al., 2016),
162 improving the overall net epuration efficiency to > 95% for particulate organic carbon (POC),
163 >75% for dissolved organic carbon (DOC) and >30% for ammonia (Lanoux, 2013).

164 **2.2 Model description**

165 The SiAM-3D model, which couples hydrodynamics, suspended sediment transport and
166 biogeochemical processes (Lajaunie-Salla et al., 2017), was used to test the efficiency of
167 possible management solutions. The model and its avalidation is presented in detail in
168 Lajaunie-Salla et al. (2017). Briefly, the transport model solves the advection/dispersion
169 equations for dissolved and particulate variables, i.e. suspended sediment, salinity and
170 biogeochemical variables. The biogeochemical model includes all the processes that produce
171 and consume oxygen in the water column, taking into account different types of dissolved
172 and particulate organic matters: degradation of organic matter (mineralization of organic
173 carbon and ammonification using the C/N ratio), nitrification, photosynthesis, respiration and
174 mortality of phytoplankton, and DO gas exchange with the atmosphere. The model includes
175 11 state variables: dissolved oxygen (DO), ammonia (NH_4^+ , input from rivers and mainly
176 from urban effluents), nitrate (NO_3^-), POC and DOC from the watershed (POC from litter;
177 DOC from rivers), WWTPs, SOs, phytoplankton and detritus. At the open boundaries, the
178 hydrodynamic model is forced by astronomical tides at the shelf and by daily river flow of
179 the Garonne and Dordogne Rivers at the upstream limit (data from www.hydro.eaufrance.fr).
180 The biogeochemical model use measured water temperature (MAGEST network; Etcheber et
181 al. (2011), https://twitter.com/Gironde_Magest), wind and incident light intensity (Météo
182 France). Urban wastewater discharges are included in the model (Fig.1).

183 The reference simulation is based on the real conditions of year 2006, which was a critical
184 year from the point of view of river discharge, temperature and hypoxia. A 21-days heat



185 wave occurred and the summer water temperature reached a maximum of 29.5°C, with an
186 average of 24.6°C. The reference simulation considered a severe and constant low flow of 40
187 m³s⁻¹ from July 15 to September 30, which is different from the real river flow recorded, but
188 helps to visualize the impact of potential solutions on oxygenation (Fig.2a). However, we
189 used urban effluents time series of 2014, as the WWTP rehabilitation in 2011 permitted to
190 reduce the percentage of SO discharge (12% in 2014; 16% in 2006).

191 **2.3 The scenarios**

192 Several scenarios have been designed to assess the efficiency of the retained management
193 strategies to improve DO levels of the Tidal Garonne River (Tab.1): optimization of urban
194 wastewater network and water replenishment during low water periods.

195 Two main actions of wastewater management were simulated (Tab.2):

- 196 - the increase of wastewater storage during heavy rains. For this, a fraction of 10, 20,
197 30, 40 and 50%, of untreated wastewater SO was transferred to WWTP discharges;
- 198 - the implementation of an outfall, that releases urban effluents downstream. Two
199 wastewater discharge points were tested: at 11 km (PK15) and 21 km (PK25)
200 downstream Bordeaux (Fig.1). Although this solution seems difficult to implement
201 due to technical and financial constraints, it is interesting to investigate its potential
202 environmental benefits.

203 For the support of low river flow during the driest season, two actions were tested according
204 to the available volume of stored water (Tab.2):

- 205 - a low-intensity and long-term support (LTS) from 15th July, by 10, 20 and 30 m³s⁻¹
206 during 67, 33 and 22 days, respectively.



207 - an intense and short-term support (STS) as an emergency solution, by 100, 200 and
208 $400 \text{ m}^3 \text{ s}^{-1}$ at spring tide from July 27 to 29 (3 days), corresponding to a water volume
209 of 16, 41 and 93 hm^3 , respectively.

210 Finally, two scenarios which couple wastewater management actions and the support of low
211 river flow were simulated (Tab.2):

212 - a LTS of $10 \text{ m}^3 \text{ s}^{-1}$ during 67 days was combined to the reduction of 50% of untreated
213 wastewater SO which is transferred to WWTP discharges;

214 - a LTS of $10 \text{ m}^3 \text{ s}^{-1}$ during 67 days was combined to the reduction of 50% of untreated
215 wastewater SO which is transferred to WWTP discharges and to the relocation of
216 wastewater discharges at 11 km (PK15) downstream Bordeaux (Fig.1).

217 Each of the 16 scenarios were run over 10 months, from the January 1 to October 31. To
218 evaluate the improvement of DO level, three indicators were used: (1) the minimum DO
219 value (DO_{\min}); (2) the number of hypoxia days, i.e. $\text{DO} < 2 \text{ mg.L}^{-1}$; and (3) the summer-
220 averaged rates of biogeochemical processes consuming DO at Bordeaux and Portets. The grid
221 cells in front of Bordeaux and Portets were chosen because Bordeaux is directly under the
222 impact of urban effluents and Portets represents the presence of TMZ in the upper TGR.

223 **3 Results**

224 **3.1 Action 1: Wastewater management**

225 • **Action 1.1: Reduction of sewage overflows**

226 The simulations of sewage overflow reduction do not show an increase of DO_{\min} at Bordeaux
227 and Portets (Tab.2). However, some short but significant differences in modeled DO time
228 series in Bordeaux are noticeable during the largest sewage overflow flow events (Fig.2c).



229 For the scenario SO-50%, there is a slight increase of DO level by 6 and 2 %sat in late June
230 and mid-August, respectively (Fig.2c). The total DO consumption by biogeochemical
231 processes decreases up to 6% at Bordeaux (Tab.3). The rate of mineralization of urban
232 organic matter decreases considerably, by 31% and 33% with a reduction of 50% of SO flow
233 at Bordeaux and Portets, respectively (Tab.3). In fact, at Bordeaux the material brought by
234 the SO contributes to 7% of total DO consumption with the reduction of 50% against 13%
235 without reduction (Fig.2d). In addition, the contribution of WWTP matter degradation
236 represents 16% when untreated water discharge is reduced by 50%, against 14% without
237 reduction (Fig.2d). In contrast, the nitrification process is slightly increased by the reduction
238 of SO flow (Tab.3) because the wastewater removed from SOs is transferred to WWTPs,
239 which are enriched in ammonia compared to SOs (Lanoux, 2013).

240 In these simulations, sudden events of wastewater releases from SO (end-June) did not occur
241 simultaneously with the maximum of temperature (i.e. end-July). In such a case, a more
242 critical hypoxia event would have occurred. However, the modelling results show that
243 improvement of SO management contributes to improve DO level only locally and temporary
244 at the vicinity of the city of Bordeaux.

245 **• Action 1.2: Downstream relocation of wastewater discharges**

246 In the case of a relocation of urban effluents discharge at PK15, only 4 days of hypoxia are
247 simulated with a minimum of 1.8 mg.L^{-1} (Tab.2), which represents a reduction of 9 days in
248 comparison with the reference simulation. In case of a relocation of urban effluents discharge
249 more downstream at PK25, the model simulates no hypoxia and a minimum DO value of 2.1
250 mg.L^{-1} (Tab.2). According to the model, the displacement of the urban wastewater discharge
251 point downstream shows a significant improvement of oxygen levels in the TGR around
252 Bordeaux (Tab.2 & Fig.3) and appears to be an efficient action to mitigate hypoxia near
253 Bordeaux (Fig.3). Under these relocation scenarios, the amount of urban organic matter and



254 ammonia are lower at Bordeaux. Urban effluents are diluted by downstream estuarine waters
255 and exported toward the Gironde. In fact, urban matters reach the city of Pauillac, about 50
256 km downstream Bordeaux (Fig. 1) after 1 and 1.5 days when effluents are released at PK25
257 and PK15, respectively, against 2.5 days when they are discharged near Bordeaux. With the
258 relocation of urban discharge downstream, DO levels are strongly improved in the TGR,
259 without significantly altering the oxygenation condition downstream. This is due to shorter
260 residence times and larger dilution with oxygenated estuarine waters downstream.

261 A downstream relocation (PK15 or PK25) significantly decreases total DO consumption in
262 the lower TGR, by 33% and 47% respectively: the mineralization of urban matter is reduced
263 by 65% and 95%, and the nitrification by 47% and 69%, respectively (Tab.3). At Portets,
264 even if the total DO consumption decreases only by 8%, the degradation of urban matter
265 decreases strongly by 76% and 94% and the nitrification is reduced by 17% and 20% when
266 urban effluents are discharged in PK 15 and PK25, respectively (Tab.3). In fact the
267 mineralization of urban matter occurs downstream of TGR with little impact on DO due to
268 dilution effect with estuarine waters. Finally, at Bordeaux the contribution of urban effluents
269 on DO consumption decreases from 27% to 2% and nitrification from 20% to 10% (Fig. 3d).

270 The discharge of wastewater downstream city center improves considerably the water quality
271 in the vicinity of Bordeaux. However, hypoxia persists in Portets (30 hypoxic days, Tab.2 &
272 Fig.3), because in the upper TGR, hypoxia is mainly due to very high turbidities and low
273 water renewal.

274 **3.2 Action 2: Support of summer river discharge**

275 • **Action 2.1: Low intensity and long-term support of summer river discharge**

276 The simulations of low-intensity and long-term support (LTS) of water flow show an increase
277 of DO_{\min} not only at Portets, but also at Bordeaux (Tab.2). At Bordeaux, the DO_{\min} increases



278 only by $0.3 \text{ mg}\cdot\text{L}^{-1}$ and the number of simulated hypoxia days decreases only by 2 days for a
279 discharge increase of $30 \text{ m}^3\text{s}^{-1}$. However in Portets, oxygen levels are much more improved:
280 the additional flows reduce significantly the number of hypoxic days: it drops from 52 days
281 (reference simulation) to 29, 39 days or 40 days for a support of 10, 20 or $30 \text{ m}^3\text{s}^{-1}$
282 respectively (Tab2).

283 Significant effects of maintaining summer river discharge in the area of Bordeaux are the
284 decrease of nitrification processes and the increase of mineralization of matter coming from
285 the watershed (Tab.3). At Portets, nitrification and mineralization of organic matter are
286 decreased due to the reduced input of urban water upstream (Tab.3).

287 These simulations show that a low-intensity and long-term support of river flow reduces
288 considerably hypoxia events in the upper TGR, but not sufficiently to influence significantly
289 Bordeaux waters. The average time to renew half of the water volume in Bordeaux is 22 and
290 67 days in cases of river flows increased by 10 and $30 \text{ m}^3\text{s}^{-1}$, respectively. By comparison, at
291 Portets, the renewal times are only 3 and 11 days, respectively. The option of low-intensity
292 support needs to be sufficiently long to maintain good oxygen level during all summer in the
293 upper TGR. An additional river flow $> 10 \text{ m}^3\text{s}^{-1}$ during two months will be a feasibly solution
294 to avoid hypoxia events upstream Bordeaux, and freshwater storage should be optimized to
295 reach these objectives.

296 **• Action 2.2: Intense and Short-term support of low water discharges**

297 An intense and short-term support (STS) of freshwater induces a strong dilution of estuarine
298 water with well-oxygenated fluvial waters due to the large amount of water supply (100, 200
299 and $400 \text{ m}^3\text{s}^{-1}$) (Fig.4 & Fig.5). Model results show a decrease of the number of hypoxia days
300 in Bordeaux and Portets (Tab.2). Water half-renewal times are less than 1 day at Portets, and
301 decrease from 6.6 to 1.6 at Bordeaux with increasing discharge support from 100 to $400 \text{ m}^3\text{s}^{-1}$



302 ¹. During STS, DO concentrations increase faster at Portets than at Bordeaux (Fig.4 & Fig.5).
303 During a semi-diurnal tidal cycle, DO rises by 9 %sat at Bordeaux and by 56 %sat at Portets
304 with an input of 400 m³s⁻¹. Higher is the river flow support, faster waters of TGR are
305 reoxygenated.
306 The total oxygen consumption decreases only in Portets with STS (Tab.3). At Bordeaux, the
307 decrease of nitrification is counterbalanced with an increase of river organic matter
308 mineralization (Tab.3). The intense short-term support moves the TMZ downstream Portets,
309 reducing organic matter mineralization in the area of Portets (Tab.3 & Fig.4).
310 Intense STS (400m³s⁻¹) is not able to maintain good level of oxygen all summer long. After
311 the massive water input, DO level stays above the hypoxia threshold during one or two weeks
312 only and then decreases again (Fig.5). This type of management is very powerful as an urgent
313 remediation during a severe hypoxia to improve quickly the oxygenation levels of TGR
314 waters, more particularly in the upper section of the tidal river. For example, during the heat
315 wave of end-July 2006 (Fig.2c), STS would have avoided hypoxia. In the case of a late
316 hypoxia occurring at the end of the summer, STS may be efficient if the stored water volume
317 is sufficient.

318 **3.3 Synthesis of management actions efficiency**

319 These different simulated scenarii allow us to estimate quantitatively the efficiency of
320 different options of management to reduce hypoxia in the TGR. The two management
321 solutions have locally different impacts on DO (Tab.4): optimization of urban wastewater
322 network reduces hypoxia in the lower TGR, whereas the water replenishment during low
323 water periods enhances DO levels in the upper TGR. The improvement of wastewater
324 network by a reduction of labile organic matter input reduces oxygen consumption in
325 Bordeaux waters. The alternative, consisting in discharging urban effluents downstream the
326 lower TGR, has the advantage to dilute wastewater with the Gironde water and to favor their



327 dispersion downstream in the wider sections of the estuary. In addition, taking into account
328 the increasing gradient of temperature landward (Schmidt, personal data), wastewater
329 effluents would be discharged in cooler waters, about 1-2°C, than at Bordeaux. The water
330 replenishment during low water periods is also a powerful solution, which favors the
331 dilution of upper TGR waters with well oxygenated freshwater and limits the upstream TMZ
332 displacement. The scenario combining an increase of $10 \text{ m}^3 \text{ s}^{-1}$ of the Garonne River flow, a
333 reduction of 50% of SO releases and discharge of urban effluents at PK15 suggests an
334 improvement of water quality over the entire TGR (Fig.6): only 2 days below the hypoxia
335 threshold (Tab.2) and the oxygen consumption by urban matter degradation is totally reduced
336 (Tab.3).

337 Regarding the projected population growth of Bordeaux city (one millions inhabitants will be
338 reached in 2030) and the objectives of the European Water Framework Directive to maintain
339 a good water quality, the reduction of the impact of urban wastewater networks in urban areas
340 appears as a major challenge for the coming years. The construction of an outfall under the
341 river could be an efficient solution to mitigate total hypoxia at Bordeaux but this solution is
342 for instance an academic scenario considering its cost and technical constraints. Moreover the
343 environmental impact of such construction can hinder this solution. The support of summer
344 river flow could be certainly optimized by reducing water use for agricultural practice in the
345 watershed during summer and by improving the release of stored water as a function of
346 meteorological conditions. In the case of defavorable conditions (heat wave, drought) early
347 summer, LTS could be implemented. But if these conditions occur late summer, intense STS
348 could be considered. An alternative solution could be intermittent supports, with water
349 release of $100 \text{ m}^3 \text{ s}^{-1}$ during spring tide all summer long (July and August, i.e. 4 spring tides).
350 By continuing the improvement of urban wastewater network and by maintaining good river



351 flow level simultaneously, the both management options may improve oxygen level on the
352 TGR.

353 **4 Conclusion**

354 The 3D biogeochemical model for the Tidal Garonne River coupling hydrodynamics and
355 sediment transport was applied to assess the efficiency of different management solutions to
356 improve the DO level of waters. This study tested different scenarios of management
357 solutions that can be implemented by local water authorities to maintain the best water
358 quality as possible. Whereas a reduction of SO flows contributes only to improve locally and
359 temporary DO levels, the downstream relocation of WWTP outfalls totally mitigates hypoxia
360 in TGR and seems to be the most efficient management solution, despite being difficult to
361 implement in practice. The support of low river flow limits the propagation of TMZ upstream
362 of the TGR and dilutes estuarine waters with fresh oxygenated waters. A low-intensity
363 support over the summer maintains a good oxygen level of waters during all the drought
364 period and prevents hypoxia in the upper TGR. In contrast, an intense support of low water
365 flow during 3 days improves quickly and considerably oxygen levels along the entire TGR,
366 but only during few weeks. The improvement of urban effluents network and the support of
367 low river flow periods from dams, or irrigation reduction, are complementary. They
368 contribute to reoxygenate waters near the city of Bordeaux and upstream of Tidal Garonne
369 River, respectively. The biogeochemical numerical model turns out helpful to guide
370 management policy of urban effluents and watershed, in order to limit and mitigate hypoxia
371 events.

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475 **Table 1: Forcing of the different scenarios simulated with the model.**

Scenarios	River flow	Wastewater flow
Reference	$Q_{ref} = Q_{G/D} 2006 + Q_G = 40 \text{ m}^3 \text{ s}^{-1}$ from 15/07 to 30/09	$Q_{WW} 2006$
WW of 2014 (WWTP rehabilitated)	Qref	$Q_{WW} 2014$
SO -10%	Qref	$Q_{WW} 2014 - 10\%$ SO
SO -20%	Qref	$Q_{WW} 2014 - 20\%$ SO
SO -30%	Qref	$Q_{WW} 2014 - 30\%$ SO
SO -40%	Qref	$Q_{WW} 2014 - 40\%$ SO
SO -50%	Qref	$Q_{WW} 2014 - 50\%$ SO
Management of wastewater discharges		
Release moved to PK15	Qref	$Q_{WW} 2014$ at Parempuyre
Release moved to PK25	Qref	$Q_{WW} 2014$ at Bec d' Ambès
Support of low river flow		
+10 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G < 50 \text{ m}^3 \text{ s}^{-1}; Q_G + 10 \text{ m}^3 \text{ s}^{-1}$ over 67 days	$Q_{WW} 2006$
+20 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G < 50 \text{ m}^3 \text{ s}^{-1}; Q_G + 20 \text{ m}^3 \text{ s}^{-1}$ over 33 days	$Q_{WW} 2006$
+30 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G < 50 \text{ m}^3 \text{ s}^{-1}; Q_G + 30 \text{ m}^3 \text{ s}^{-1}$ over 22 days	$Q_{WW} 2006$
+100 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G + 100 \text{ m}^3 \text{ s}^{-1}$ over 3 days	$Q_{WW} 2006$
+200 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G + 200 \text{ m}^3 \text{ s}^{-1}$ over 3 days	$Q_{WW} 2006$
+400 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G + 400 \text{ m}^3 \text{ s}^{-1}$ over 3 days	$Q_{WW} 2006$
Combined options		
-50% +10 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G < 50 \text{ m}^3 \text{ s}^{-1}; Q_G + 10 \text{ m}^3 \text{ s}^{-1}$ over 67 days	$Q_{WW} 2014 - 50\%$ SO
-50% + PK15 +10 $\text{m}^3 \text{ s}^{-1}$	$Q_{ref}; Q_G < 50 \text{ m}^3 \text{ s}^{-1}; Q_G + 10 \text{ m}^3 \text{ s}^{-1}$ over 67 days	$Q_{WW} 2014 - 50\%$ SO at Parempuyre



476 **Table 2:** Minimum simulated DO (in % of saturation and in $\text{mg}\cdot\text{L}^{-1}$), the corresponding temperature and the number of hypoxia days in
 477 Bordeaux and Portets for each scenario.

Scenarios	Bordeaux				Portets			
	T (°C)	DO _{min} (%)	DO _{min} ($\text{mg}\cdot\text{L}^{-1}$)	Days of hypoxia	T (°C)	DO _{min} (%)	DO _{min} ($\text{mg}\cdot\text{L}^{-1}$)	Days of hypoxia
Reference	27.4	13.5	1.0	13	24.4	8	0.7	52
WW of 2014	27.3	16.4	1.3	17	24.4	8.5	0.7	39
-10%	27.3	16.5	1.3	16	24.4	8.6	0.7	38
-20%	27.3	16.5	1.3	16	24.4	8.6	0.7	38
-30%	27.3	16.5	1.3	16	24.4	8.6	0.7	38
-40%	27.3	16.6	1.3	14	24.4	8.6	0.7	37
-50%	27.3	16.6	1.3	13	24.4	8.6	0.7	37
Release moved to PK15	26.9	23.5	1.8	4	24.4	9.7	0.8	33
Realease moved to PK25	26.9	26.9	2.1	0	24.4	10	0.8	32
Support of low river flow								
+10 $\text{m}\cdot\text{s}^{-1}$	26.9	13.8	1.1	13	24.4	12.7	1.0	29
+20 $\text{m}\cdot\text{s}^{-1}$	26.8	15.3	1.2	11	24.4	8.3	0.7	39
+30 $\text{m}\cdot\text{s}^{-1}$	26.8	17	1.3	11	24.4	8.3	0.7	40
+100 $\text{m}\cdot\text{s}^{-1}$	26.9	12.3	1.0	12	24.4	8.4	0.7	48
+200 $\text{m}\cdot\text{s}^{-1}$	27.4	14.5	1.1	10	24.4	8.3	0.7	44
+400 $\text{m}\cdot\text{s}^{-1}$	27.7	16.7	1.3	5	24.4	9.1	0.7	37
Combined options								
-50% +10 $\text{m}\cdot\text{s}^{-1}$	26.9	14.5	2	14	24.4	12.5	1	26
-50% + PK15 +10 $\text{m}\cdot\text{s}^{-1}$	26.9	24.9	2	2	26.9	14.1	1.1	22



478 **Table 3:** Differences (in %) of biogeochemical process rates impacting DO between the scenarios and reference simulations during summer in
 479 Bordeaux

Scenarios	Bordeaux			Portets		
	total nitrification	mineralization TOC _{WS}	mineralization TOC _{WW}	total nitrification	mineralization TOC _{WS}	mineralization TOC _{WW}
WW of 2014	-1%	+11%	0	-1%	+4%	-16%
-10%	-2%	+12%	0	-1%	+4%	-16%
-20%	-3%	+13%	0	-1%	+6%	-23%
-30%	-4%	+13%	+1%	-1%	+6%	-26%
-40%	-5%	+14%	+1%	-1%	+6%	-29%
-50%	-6%	+14%	+1%	-1%	+6%	-33%
Release moved to PK15	-33%	-47%	+2%	-8%	-17%	-76%
Release moved to PK25	-47%	-66%	+3%	-8%	-20%	-94%
+10 m³ .s⁻¹	1%	-6%	+6%	-2%	-20%	-4%
+20 m³ .s⁻¹	0%	-6%	+5%	+1%	-14%	-2%
+30 m³ .s⁻¹	0%	-6%	+4%	-2%	-13%	-3%
+100 m³ .s⁻¹	0%	-2%	+2%	-5%	-4%	-3%
+200 m³ .s⁻¹	0%	-5%	+4%	-9%	-10%	-6%
+400 m³ .s⁻¹	0%	-11%	+9%	-13%	-14%	-8%
Combined options	-2%	+10%	+11%	+2%	+5%	-36%
-50% + PK15 + 10 m³ .s⁻¹	-46%	-70%	+14%	-2%	+6%	-100%



480 **Table 4: Summary of management solutions efficiency and recommendations**

Management Solutions	Efficiency to mitigate hypoxia		Recommendation
	Lower TGR	Upper TGR	
SO reduction: -50 %	++	+	Implementation of SOs
WW discharges at PK15	+++	+	WWTP outfall relocation
WW discharges at PK25	+++	+	WWTP outfall relocation
LTS	+	++	Preventive measures against hypoxia: reduction of freshwater substruction during summer
STS	++	+++	Curative measures at spring tide during severe drought
LTS - SO reduction -50 %	+	++	reduction of freshwater substruction during summer implementation of SOs
LTS - SO reduction: -50 % - WW discharges at PK15	+++	++	reduction of freshwater substruction during summer implementation of SOs WWTP outfall relocation



481 **Figure 1:** The Gironde-Garonne-Dordogne estuary including the Tidal Garonne River in the
482 southwestern France (Inset B). “PK” denotes the distances in km from the city center of
483 Bordeaux; the control grid cell at Bordeaux is at PK-4 and Portets is at PK-20. The insert A
484 precises the position of sewage overflows (purple triangles) and of the two wastewater
485 treatment plants (green squares). The area in orange represents the area of Bordeaux for
486 which the biogeochemical fluxes were calculated.

487

488 **Figure 2:** Time series of Garonne River (black) and Dordogne River (grey) flow of the
489 reference simulation (a, m^3s^{-1}), wastewater discharges (WWTP+SO) for year 2006 (green)
490 and 2014 (blue) (b, m^3s^{-1}). Comparison of simulated DO_{\min} evolution (over tidal cycle in
491 %sat) in Bordeaux with urban effluents of 2014 (blue) or a 50% reduction of SOs (red) (c).
492 The contribution on DO consumption (%) of degradation of watershed organic matter
493 (brown), WWTP (red), SO (green) and nitrification (blue) in Bordeaux (d). For nitrification
494 processes, ammonium is coming from watershed and wastewater.

495 **Figure 3:** Snapshot of the vertical transect of simulated DO saturation along the Garonne
496 tidal river for the scenarios with an urban effluents discharges points in Bordeaux (a), at
497 PK15 (b) and at PK25 (c). P1, P2 and P3 indicate the locations of Bec d’Ambès, Bordeaux
498 and Portets, respectively. The contribution on DO consumption (%) of degradation of
499 watershed (brown), WWTP (red), SO (green) and nitrification (blue) processes at Bordeaux
500 (d). For nitrification processes, ammonium is coming from watershed and wastewater.

501 **Figure 4:** Snapshot of the vertical transect of simulated DO concentration in %sat along the
502 Garonne tidal river for the scenarios of reference (a), short river flow increases by $100 \text{ m}^3\text{s}^{-1}$
503 (b), $200 \text{ m}^3\text{s}^{-1}$ (c) and $400 \text{ m}^3\text{s}^{-1}$ (d). P1, P2 and P3 indicate the locations of Bec d’Ambès,
504 Bordeaux and Portets, respectively.

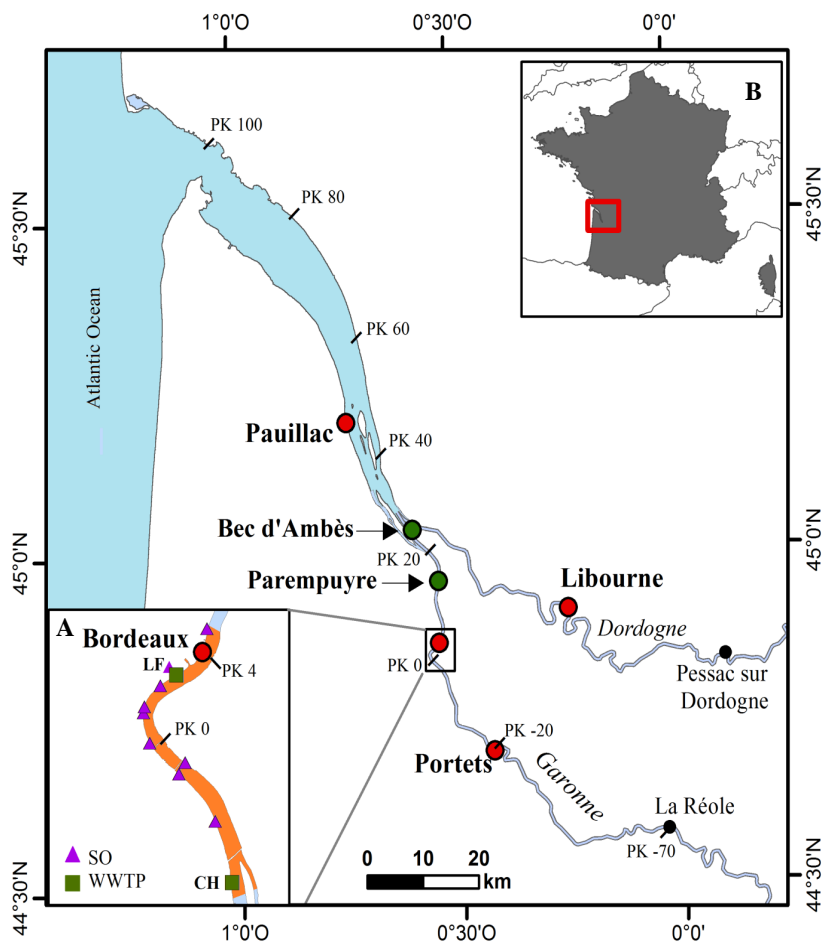
505 **Figure 5:** Time series of river flow (top, m^3s^{-1}), DO at Bordeaux (middle, %sat) and DO at
506 Portets (bottom, %sat) for the scenarios of short river flow increases by $100 \text{ m}^3\text{s}^{-1}$ (a, d and
507 g), $200 \text{ m}^3\text{s}^{-1}$ (b, e and h) and $400 \text{ m}^3\text{s}^{-1}$ (c, f and i). Blue line represents the simulation of
508 reference.

509 **Figure 6:** Spatiotemporal evolution of daily average surface DO (saturation in %) along the
510 Tidal Garonne River section for the scenarios of reference (a) combining $+10 \text{ m}^3\text{s}^{-1}$ of river
511 flow and reduction of 50% of SO releases (b), and $+10 \text{ m}^3\text{s}^{-1}$ of river flow, a reduction of 50%
512 of SO releases and urban effluents discharges at PK15 (c). The y-axis represents the
513 kilometric points, and the white lines represent Bordeaux and Portets.

514



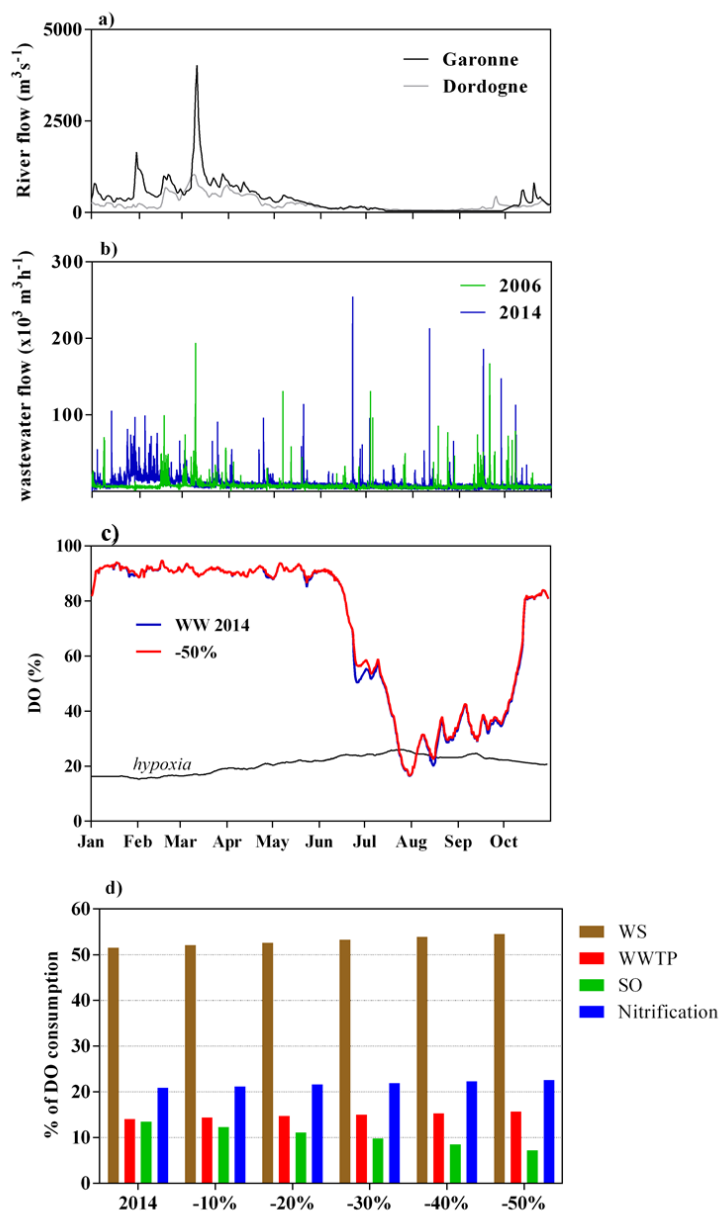
515 **Figure 1**



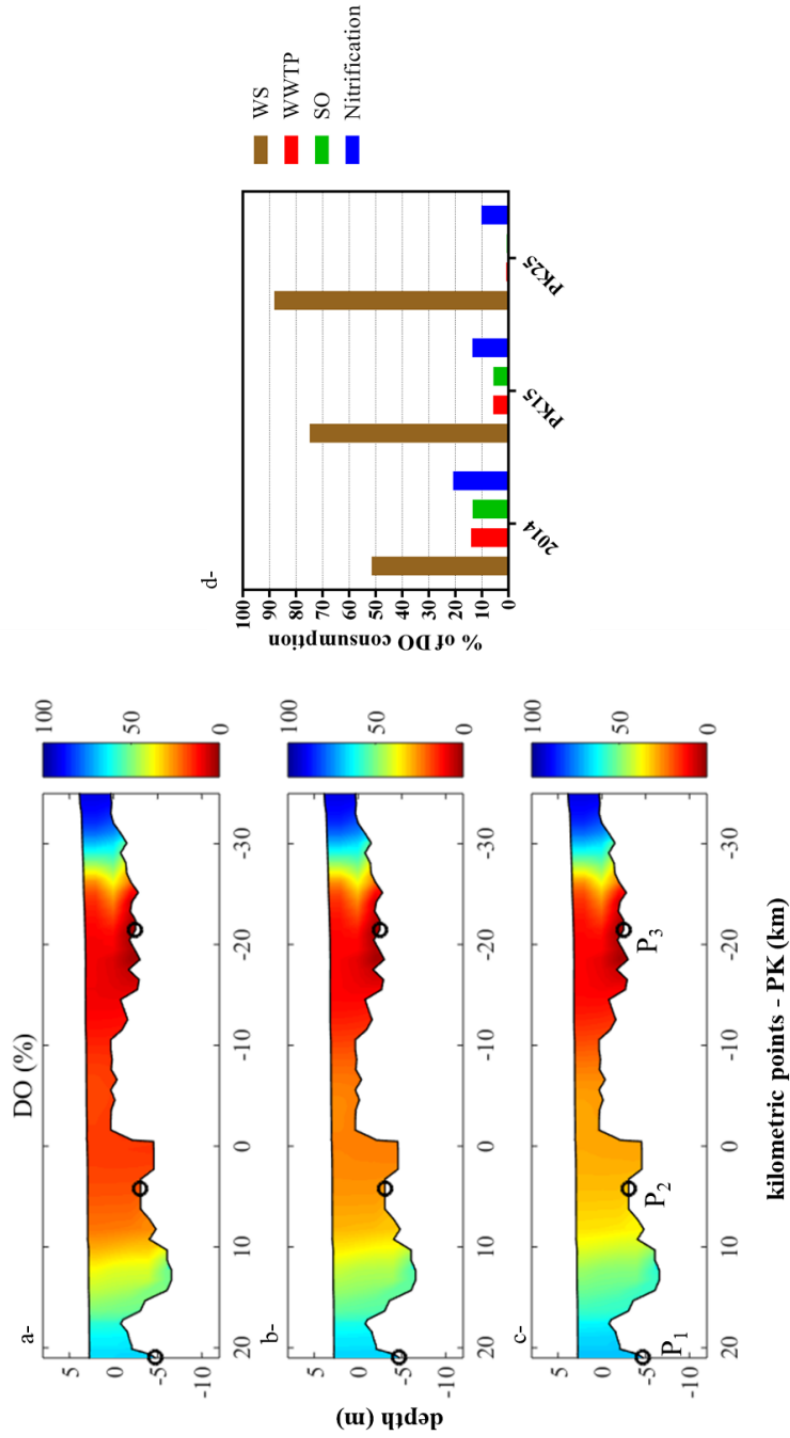
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517 **Figure 2**



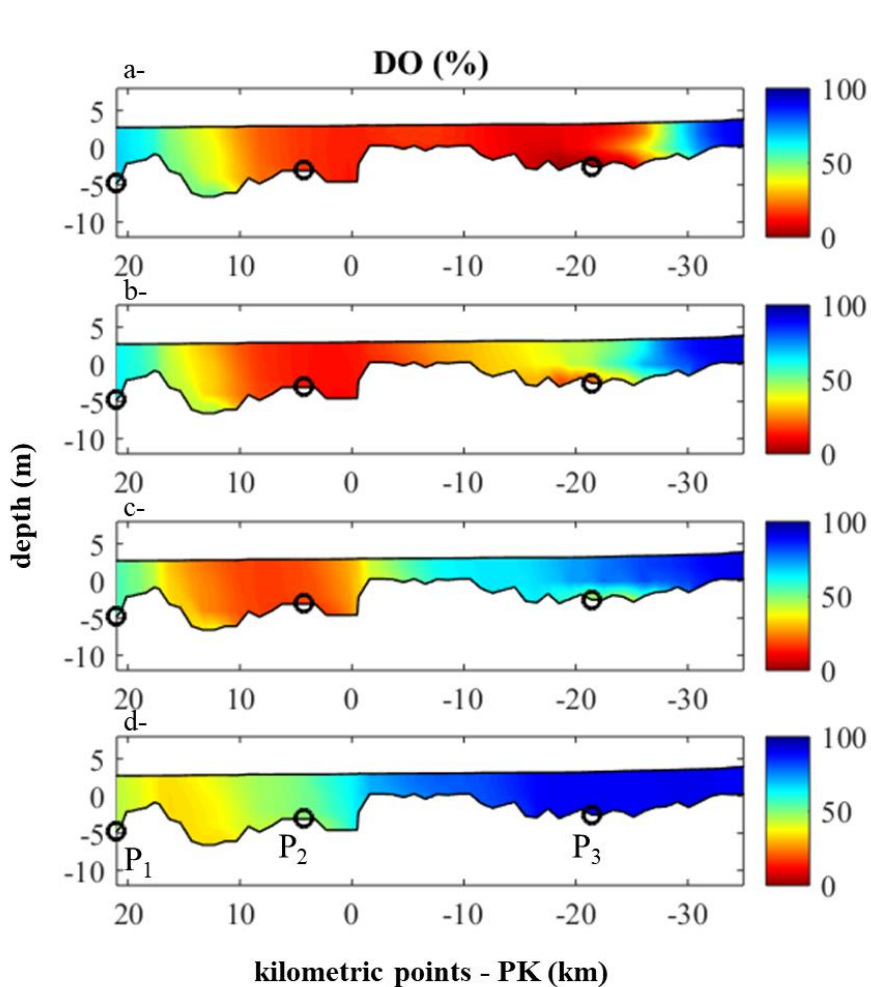
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519 **Figure 3**



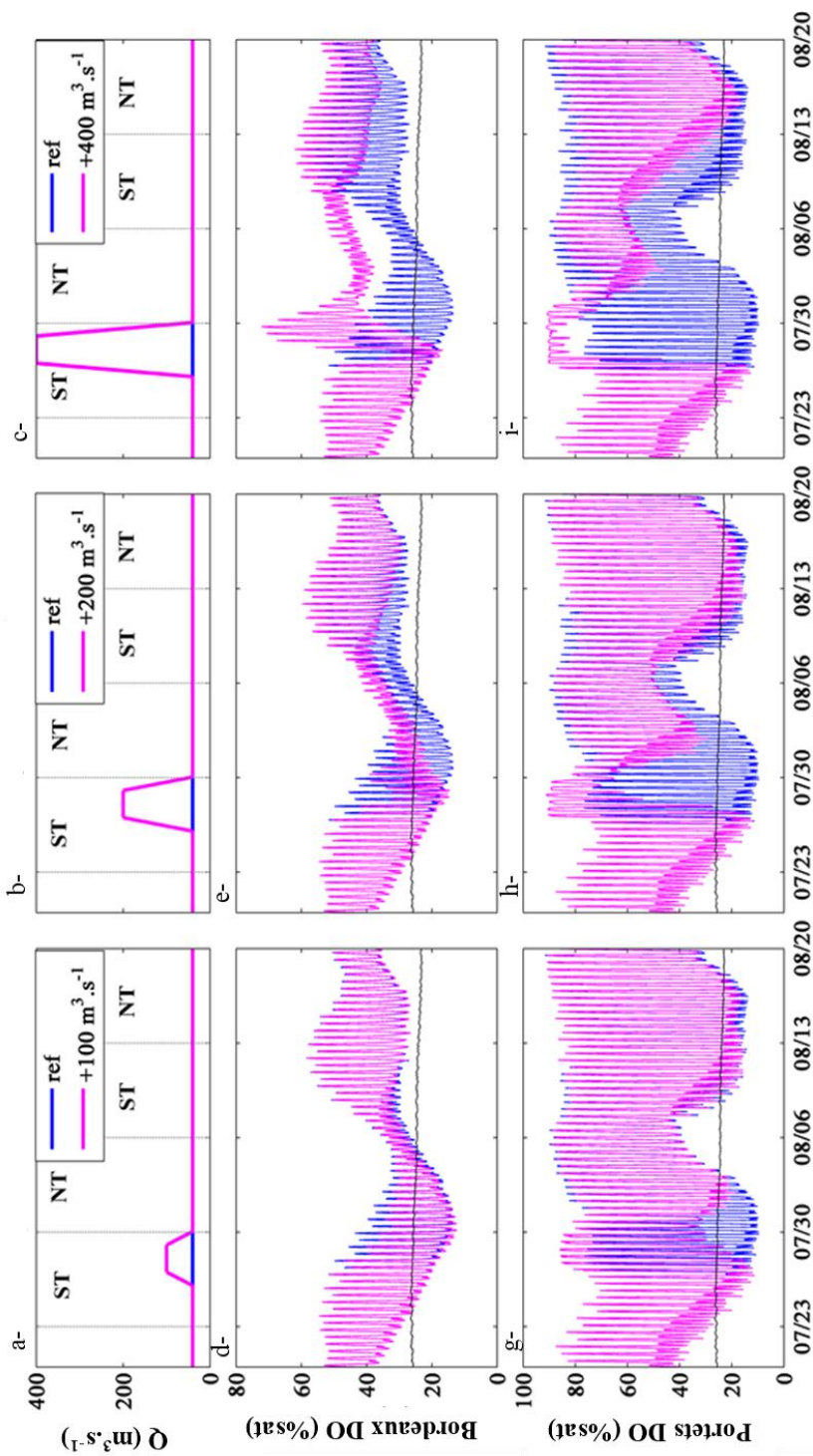
521 **Figure 4**



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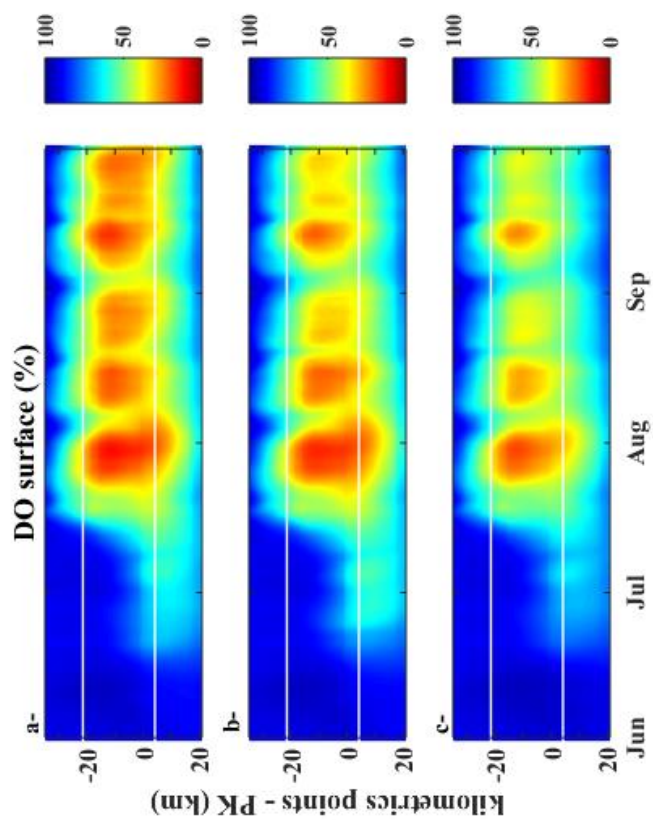
523 **Figure 5**



524



525 **Figure 6**



526