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

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Comment and replies to the reviewer 1

We thank the reviewer for the positive evaluation of our work and for the detailed and useful comments that contributed to improve the manuscript. All the modifications proposed will be made and will send the article for correction for English before submitting the revised MS.

Comment 1: L 17,......Lajaunie-Salla and supported...[This is an example of how to reduce words without losing meaning.]

Reply 1: We modified the sentence in the revised MS as suggested in L17.

Comment 2: L 24,...to limit hypoxia

Reply 2: We corrected the sentence in the revised MS as suggested L24.

Comment 3: L 25,......improves DO levels but only locally

Reply 3: We added "but" in the revised MS as suggested L26.

Comment 4: L 26,....discharges mitigates totally hypoxia low dissolved oxygen conditions

Reply 4: In this sentence "hypoxia" means "low dissolved oxygen conditions". Because the Highlights section is limited in size and number of characters we have kept the sentence as is.

Comment 5: L 27,....Support of river flow.... Is not clear.

Reply 5: We modified this highlight by "Water replenishment improves DO in the upper estuary." L27.

Comment 6:L 28,.....combination of different management actions.... Be more specific.

Reply 6: Again, because the Highlights section is limited in size and number of characters, we cannot give many details here; we decide to remove this highlight as it was not essential for the main message of the paper.

Comment 7: L 32 and 37, I do not see the need for this abbreviation. The impact will be greater in the text if the words were used in the text. Also WS: watershed and WW: wastewater, why not just spell them out. I am predicting that I will see a manuscript full of abbreviations that would be better expressed with words.

Reply 7: Abbreviations that were not necessary were removed from the MS: NT (neap tide) and ST (spring tide), WW (wastewater) and WS (watershed), and we spell them out throughout the text.

Comment 8: L 45-56, In view of future coastal hypoxia widespreading, it is essential to define management solutions to preserve a good quality of coastal ecosystems. These two sentences are awkward in English. Suggest: Coastal water hypoxia is increasing globally, and the need to define management solutions to support improved water quality of coastal ecosystems is necessary......

Reply 8: As suggested by the reviewer we modified this sentence in the revised MS L39-41 as following:
"Coastal water hypoxia is increasing globally due to global warming and urbanization, and the need to define management solutions to improve the water quality of coastal ecosystems has become important."

Comment 9: This manuscript has much to offer and will advance the study of mitigation of sources that may lead to the decline of dissolved oxygen in estuaries. The current text does not meet the standards of an appropriate translation to English to make it understandable, succinct, and to the point. I recommend that an additional person help with the English translation. This translation and re-writing will not be by this reviewer.

Reply 9: As suggested by the reviewer, we sent the MS for English corrections before resubmission.

Comment and replies to the reviewer 2

1. **General comments**

This study by Lajaunie-Salla et al., presents the potential efficiency of several mitigation measures to limit hypoxia in estuarine zones based on a 3D biogeochemical modelling approach.

I found this study interesting, appropriate for NHESS, even if very site-centred and essentially descriptive. My general position is that the authors did not take advantage of the powerful tool they have developed. I listed several issues that must be addressed before further consideration. In particular,

-> many hypotheses for the different scenarios are unjustified, such as using WWTP point sources time series of two different years without changing time series for other parameters (e.g. river flow), or such as considering point sources chemical composition during storm events (overflow reduction) being similar to the one observed the rest of time (would WWTP efficiency remain stable?). These issues are maybe correctly considered, but are not clearly explained in the text.

-> No information on upstream C, N, P loads forcing while they could be absolutely crucial in this study.

-> discussion of the results is almost absent from the manuscript, with a poor analysis of the processes involved. On the other hand, the results from the different scenarios should help stakeholders decide what are the best options to determine cost-effective measures and mitigate hypoxia in tidal zones. Therefore, I recommend major revision of this manuscript before it can be considered for final publication in NHESS.

Reply: We thank the reviewer for the positive evaluation of our work and for the detailed and useful comments that contributed to greatly improve the manuscript. We took into account the reviewer's comments in order to better justify our hypotheses for the different scenarios (see also responses to comments 17 to 20). The upstream river matter loads are taken into account in our model: nitrates, ammonia, particulate organic carbon from litter and phytoplankton and dissolved organic carbon. Before answering to the specific comments by the reviewer, we would like to make it very clear that our model deals specifically with hypoxia and not eutrophication; indeed, the processes that are simulated are those who contribute directly to oxygen consumption (and supply) in macrotidal, heterotrophic estuaries: this include degradation of dissolved and particulate organic matter from various origins (freshwater phytoplankton, soil and litter material from the watershed, and treated waste water from treatment plants and untreated urban waters from sewage overflow), and nitrification of ammonia coming from urban waters as well as ammonia resulting from degradation of organic matter (using a well constrained C/N ratio for the different type or organic matter). Phytoplanktonic primary production is also simulated in the model, as a source of oxygen and biodegradable organic matter; however, because turbidity (and not nutrients) is always the limiting factor for phytoplankton growth in low salinity regions of estuaries, the model does not simulate the P cycle, and the N cycle is simulated only in terms oxygen consumption by nitrification. Finally, oxygen supply by aeration is also simulated, as well as the hydro-sedimentary processes of particulate matter (deposition, resuspension and associated oxygen consumption), one of the originality of our work compared to other estuarine biogeochemical models. In order to make this clearer for readers, we provided more details of the model description in the revised version of the MS. We also added more discussion about the results of different scenarios that should help stakeholders to choose the best options to mitigate hypoxia zones. The article was sent for correction for English before submitting the revised MS.

2. **Major and technical comments**

Comment 1 - Lines 24-28: please consider a different order for the paper highlights, going from highest level of importance to lower levels. For instance, I'd rearrange bullet points 1-3-2-4

Reply 1: We changed the order of highlights as suggested by the reviewer; L24-27.

Comment 2 - Lines 30-42: My opinion is that there is an optimum in the number of abbreviations used to maximise clarity in the text, and this optimum is outreached with the use of abbreviations for words such as WS for "watershed", ST for "spring tide", WW for "wastewater",...I recommend to remove abbreviations for the following: neap tide, spring tide, watershed, wastewater which, in the end, are not so much used throughout the text.

Reply 2: As was suggested by both reviewers, we removed the abbreviations NT (neap tide) and ST (spring tide). We will also remove the abbreviations WW (wastewater) and WS (watershed).

Comment 3 - Line 45: please, include in this sentence why we should expect rising hypoxia in coastal areas, supported by references to previous studies.

Reply 3: For the interest of brevity, we avoided citing a reference in the abstract, but we mention below the reasons why hypoxia will most probably rise in the future in Garonne tidal river:

- an increase in temperature decreases oxygen solubility in surface water and favors thermal stratification of the water column, which limits reaeration (Conley et al., 2009; Lehmann et al., 2014). Water warming also accelerates biogeochemical processes that consume DO (Goosen et al., 1999).
- a decrease of river flow, due to a combination of climatic (lower precipitation) and anthropogenic factors (hydroelectric power dams and irrigation within watersheds) (Boé and Habets, 2014), modifies coastal estuarine circulation, sediment transport, and the transit (and then mineralization) of terrestrial organic material in estuaries (Abril et al. 1999; Howarth et al. 2000).
- an increase of population and human activities enriches coastal waters with nutrients and labile organic matter from urban effluents, possibly leading to eutrophication problems (Billen et al., 2001).

In the revised MS we modified this sentence as following (see also comment 8 of reviewer #1), L39-41:

"Coastal water hypoxia is increasing globally due to global warming and urbanization, and the need to define management solutions to improve the water quality of coastal ecosystems has become important."

Comment 4 - Lines 49-51: same as above, please, mention rising temperatures, lower summer low flows in temperate watersheds and higher nutrient loads near coastal areas due to urbanization to explain why we should expect rising hypoxia. It is good to also explain in plain language why does hypoxia occur, it makes things clear for everyone, and explains why a complex model is needed to investigate the response to different management scenarios.

Reply 4: Because the Abstract section is limited in size and number of characters, we kept the abstract as is. However more explanation and references about the future hypoxia rising due to temperature, river flows decreasing or by higher organic matter and nutrient loads from urbanized area were detailed in the Introduction section L69-81, as following:

"Estuarine deoxygenation is the result of a complex interaction of environmental factors. First, an increase in temperature decreases the oxygen solubility of the water, favors thermal stratification of the water column, limiting reaeration (Conley et al., 2009; Lehmann et al., 2014), and accelerates DO-consuming biogeochemical processes (Goosen et al., 1999). Second, a decrease in river flow modifies estuarine residual circulation, sediment transport, and the transit and mineralization of terrestrial organic material in estuaries (Abril et al., 1999; Howarth et al., 2000). In addition, an increase in population and human activities enriches coastal waters with nutrients and labile organic matter from urban effluents, possibly leading to eutrophication problems (Billen et al., 2001). Finally, in macrotidal estuaries, DO consumption by heterotrophic organisms is exacerbated by the presence of a turbidity maximum zone (TMZ), which favors the growth of particle-attached bacteria and, in contrast, limits phytoplankton primary production (Diaz, 2001; Goosen et al., 1999; Talke et al., 2009)."

Comment 5 - Lines 67-83: First paragraph of Introduction should be reorganized with first the broader messages (e.g. "Hypoxia is a major environmental issue,...etc") narrowed down with more specific messages (e.g. "In macrotidal estuaries, the DO consumption by heterotroph processes is exacerbated by...etc"). I also think it could be more synthetic by merging several sentences together.

Reply 5: We reorganized the first paragraph of Introduction L62-84 as follows:

"Hypoxia (dissolved oxygen (DO) concentration < 2 mg.L-1 or < 30% of saturation) is a major environmental issue, as it stresses marine organisms and disturbs the function of marine ecosystem (Rabalais et al., 2010; Vaquer-Sunyer and Duarte, 2008). Coastal hypoxia is a widespread phenomenon that has increased since the middle of the 20th century due to the combined effects of climate change and local anthropic activities (land and water uses) (Breitburg et al., 2018). Good oxygenation of estuarine waters is crucial in order to maintain ecological and economical services within the whole watershed because of the strategic position of estuaries for migratory fishes (Rabalais et al., 2010). Estuarine deoxygenation is the result of a complex interaction of environmental factors. First, an increase in temperature decreases the oxygen solubility of the water, favors thermal stratification of the water column, limiting reaeration (Conley et al., 2009; Lehmann et al., 2014), and accelerates DO-consuming biogeochemical processes (Goosen et al., 1999). Second, a decrease in river flow modifies estuarine residual circulation, sediment transport, and the transit and mineralization of terrestrial organic material in estuaries (Abril et al., 1999; Howarth et al., 2000). In addition, an increase in population and human activities enriches coastal waters with nutrients and labile organic matter from urban effluents, possibly leading to eutrophication problems (Billen et al., 2001). Finally, in macrotidal estuaries, DO consumption by heterotrophic organisms is exacerbated by the presence of a turbidity maximum zone (TMZ), which favors the growth of particle-attached bacteria and, in contrast, limits phytoplankton primary production (Diaz, 2001; Goosen et al., 1999; Talke et al., 2009). In view of the ongoing global changes, it is now essential to find management strategies for hypoxia mitigation. To recover or maintain a good ecological status for transitional waters is one of the objectives of the European Water Framework Directive (Best et al., 2007)."

Comment 6 - Line 80: Why don't you also mention diffuse nutrient loads and primary producers biomass developed in the upstream network?

Reply 6: As suggested by the reviewer we added this in the Introduction of the revised MS L75-78, as following (see also the comment above):

"In addition, an increase in population and human activities enriches coastal waters with nutrients and labile organic matter from urban effluents, possibly leading to eutrophication problems (Billen et al., 2001)."

Comment 7 - Line 81: What does "For that reason,..." refer to? Please, revise and be more specific.

Reply 7: As suggested we modified the sentence (see comment 5), L81-84:

"In view of the ongoing global changes, it is now essential to find management strategies for hypoxia mitigation. To recover or maintain a good ecological status for transitional waters is one of the objectives of the European Water Framework Directive (Best et al., 2007)."

Comment 8- Lines 87-92: It would be much clearer to give percentages of N and P load reduction due to these WWTP improvements or implementations. I believe this information appears in the cited papers.

Reply 8: For the whole Scheldt estuary N, P and Si loads were reduced by 5.4%, 1.3% and 1% respectively. We provided this information in the revised MS L90-93:

"In the Scheldt Estuary, sewage network improvement reduced N, P and Si loads by 5.4%, 1.3% and 1%, respectively, and two WWTPs have been implemented for the city of Brussels since 2000 (Billen et al., 2005; Soetaert et al., 2006; Vanderborght et al., 2007)."

Comment 9 - Line 141-142: The increased by how much? Why did Etcheber et al. took 110 $m^3.s^{-1}$ as a threshold?

Reply 9: The threshold of 110 m3 s^{-1} is the present-day low-water target flow for the lower Garonne, below which there is water replenishment. However, this target flow has rarely been reached in the past decades. We added details in the revised MS in L144-146:

"The threshold of 110 m3.s-1 is the present-day low water target flow for the lower Garonne, below which there is water replenishment for the period from June 1 to October 31."

Comment 10 - Line 148: which value of discharge is used as a critical threshold? This is too vague.

Reply 10: This value is explicated is the revised MS L153. See also reply of comment 9.

Comment 11 - Line 154: are these releases so "continuous"? Is there any kind of seasonality or other temporal cycles in these point sources?

Reply 11: The urban water releases from WWTP are continuous whereas sewage overflow are punctual event depending on pluviometry and the management of the sewerage network. In order to avoid ambiguities in the revised MS, we deleted the term "continuous".

Comment 12 - Lines 154-155: is this 1.5% reached during low-flow condition? How does C, N and P point sources from Bordeaux area compare to upstream loads? This seems like a crucial information to give.

Reply 12: "1.5%" represents the percentage of urban effluents discharged at Bordeaux during all the year. Total N and P loads are not crucial because they do not directly impact oxygen in the estuarine turbidity maximum where these nutrients are not limiting for primary production (controlled by light).

Comment 13 - Line 167: Even if description and validation of the model are extensively described in another publication, a brief description on how it performs has to be given. This would provide trust on the results for the reader's point of view. This has to be done for the reference simulation and placed at the beginning of the Results section.

Reply 13: In the revised MS, we added brief descriptions on how model performs have been given. This paragraph is included at the "Model description" section L201-206, as following:

"The model was compared with data available for the TGR and tested on the basis of three criteria: (i) the ability to reproduce the observed DO variability at a seasonal scale, (ii) the ability to reproduce the spring-neap tidal cycle, and (iii) a statistical evaluation based on the Willmott skill score (WSS, Willmott (1982)). In brief, the model performed well (WSS > 0.7) in the lower TGR around Bordeaux and is less accurate in the upper section (WSS < 0.5); the model and its validation were presented in detail by Lajaunie-Salla et al. (2017)."

Comment 14 - Line 175: how are temporally distributed the C, N and P inputs from upstream river network? Some strong hypotheses must have been done on this part, and they have to be clarified.

Reply 14: Total N and P loads from river are not crucial because they do not directly impact oxygen in the estuarine turbidity maximum where these nutrients are not limiting for primary production (controlled by light). Watershed sources include POC from litter, DOC from rivers, ammonia and nitrates (data from Etcheber et al. (2007) and Veyssy (1998)). The model also considers POC from freshwater phytoplankton and detritus (produced upstream of the turbidity maximum), for which data are from Etcheber et al. (2007), Lemaire (2002) and Lemaire et al. (2002). The temporal variability of these variables at boundary conditions (upstream) is given in table 1 of Lajaunie-Salla et al. (2017). We added this information in the revised MS L194-197 as following:

"The boundary conditions of biogeochemical variables were detailed by Lajaunie-Salla et al. (2017), and the data of organic matter and nutrients were retrieved from the works of Etcheber et al. (2007), Lemaire (2002), Lemaire et al. (2002) and Veyssy (1998)."

Comment 15 - Line 182: where did the point sources fluxes data originate from? What is the temporal frequency of this data? Which hypotheses were formulated to compute them?

Reply 15: The point sources fluxes were calculated from the discharge flows and the concentration of POC, DOC and NH_4 measured at different point sources. Concentrations were measured previously by Lanoux (2013): measurements were done in different points sources during dry and wet weathers. The discharge flows of points sources are recorded flow every 5 minutes by *SUEZ environment the WWPT manager*. We added this information in the revised MS L197-200:

"Urban wastewater discharges are included in the model with biodegradable POC and DOC and NH4 loads representative of water flowing from WWTP and from SO (every 5 minutes; concentration data are from Lanoux (2013), and the flow data are from the SUEZ environment; Fig. 1)."

Comment 16 - Line 187: what was the level of Q recorded then?

Reply 16: The mean summer Garonne River flow recorder in 2006 was 145 $m^3.s^{-1}$ (minimum of 54 $m^3.s^{-1}$) with 60 continuous days of river flow below 110 $m^3.s^{-1}$. In the revised MS we added this information in L212-215:

"The reference simulation considered a severe and constant low flow of 40 m3.s-1 from July 15 to September 30, which is different from the real river flow recorded (60 continuous days of river flow below 110 m3.s-1) but helps to visualize the impact of potential solutions on oxygenation (Fig. 2a)."

Comment 17 - Line 189: is it safe to use WWTP data of another year than the one simulated in the reference with no change in other parameters like river discharge? We should expect temporal dynamics during storm events to be unrelated to discharge variations in the estuarine zone. Please, develop this aspect to justify your choice since it seems not appropriate to me.

Reply 17: In fact in this scenario, we used temperature and river flow data from 2006 (with constant value between July 15 and September 30), whereas we used urban water releases data from 2014. As we mentioned, the year 2006 was a critical year from the point of view of temperature and river discharge (21-days of heat wave occurred and 60 continuous days of river flow below 110 $m^3.s^{-1}$). In this article, we want to demonstrate the advantage and/or effectiveness of urban water network and treatment processes improvement on hypoxia events during critical conditions. The sewage network of Bordeaux Metropolis was improved since 2011, and then we used data post-2011.We had to adjust this scenario in the model in order to account for the improvements made in the sewage network and load reduction rates, in order to reach our objectives that are to find managements solutions to mitigate hypoxia events.

In the revised MS we added this information in L215-218:

"The sewage network of the Bordeaux metropolis was improved in 2011, after which we used a time series of 2014 to reach our objectives to find management solutions to mitigate hypoxia events. The SO discharges constituted 16% in 2006 and 12% in 2014."

Comment 18 - Line 190: was it then considered that these fractions were fully treated by WWTPS? I think I understand that the volume of waste water from these wastewater SO were simply transferred to the volume of WWTP inputs into the river. Loads and volumes are very different quantities...This has to be clarified and justified: could the WWTPs absorb and treat up to 50% of these overflow volumes during storm events with the same efficiency as non-storm days?

Reply 18: The aim of these scenarios was to simulate an improvement of wastewater network by a reduction of 10 to 50% of the overflows of untreated water volumes in Bordeaux waters. Consequently, we add these overflows water volume as WWTP discharges of treated water, applying the respective POC and DOC and NH_4 concentrations, because this water volume is considered as treated. In order to make this point clear, we will make the following changes in the revised MS:

- in the section of model description L197-200:

"Urban wastewater discharges are included in the model with biodegradable POC and DOC and NH4 loads representative of water flowing from WWTP and from SO (every 5 minutes; concentration data are from Lanoux (2013), and the flow data are from the SUEZ environment; Fig. 1)."

- in the section of scenarios description L224-226:

"the increase in wastewater storage during storms. For this, fractions of 10, 20, 30, 40 and 50% of untreated wastewater SO was transferred to WWTP discharges (taking into account the organic matter and nutrient loads of WWTP)."

Comment 19 - Line 199: why were these two locations chosen specifically? It is certainly interesting to study, but it has to be explained why and what can be expected from such a measure.

Reply 19: We have chosen these two locations based on other studies, as for the Thames Estuary, where a 24-km long sewer network was constructed under the riverbed, which allows the transit of urban wastewater to the WWTP located downstream. We thus hypothesis an outfall of: (1) 21-km long (same length as in the Thames Estuary) corresponding to the position KP25 (Fig.1) where the currents are higher and could disperse urban effluents faster and (2) 11-km long corresponding to the KP15 as an alternative and less expensive solution.

We added this information in the revised MS L230-233:

"(1) at 21 km (same distance as in the Thames Estuary) corresponding to position KP25 (Fig. 1), where the currents are relatively high and could disperse urban effluents relatively quickly, and (2) at 11 km, corresponding to KP15 as an alternative and less expensive solution (Fig. 1)."

Comment 20 - Lines 205-206: again, these choices have to be justified. What is the basis of such scenarios? Same applies for other scenarios listed.

Reply 20: We justified these scenarios in the revised MS. Our calculations are based on the maximum stored water volume in dams of the upper Garonne River, which is 58 hm^3. The three scenarios simulate variable intensities of water replenishment during the driest season, according to:

- a support of 10 m^3s^{-1} during 67 days represents a volume of water input of 58 hm^3
- a support of 20 m^3s^{-1} during 33 days represents a volume of water input of 58 hm^3
- a support of 30 m^3s^{-1} during 22 days represents a volume of water input of 58 hm^3

We added this information in the revised MS L236-238:
"For the support of low river flow during the driest season, two actions were tested according to the maximum stored water volume in the dams (58 hm3) of the upper Garonne River (Tab. 2)"

Comment 21 - Line 220: how was this rate computed given all the different processes included?
Please, detail this point, especially since this metric is then used as a key indicator to assess mitigation measures.

Reply 21: The summer average rates of biogeochemical processes impacting DO (as mineralization of organic matter and nitrification) were calculated over the area of 6.6 km², including the WWTP and the SO sites of Bordeaux (as shown in Lajaunie-Salla et al. (2017): Figure 1, orange area in lower panel) and over the area of 1.2 km² around Portets. We added this information in the revised MS L253-255:

"and (iii) the summer-averaged rates of biogeochemical processes consuming DO in the Bordeaux and Portets areas (6.6 and 1.2 km², respectively)."

Comment 22 - Lines 220-221: even if you refer to another publication describing extensively the model, the reader might appreciate more information on the model. This sentence mentions the concept of grid cells ("in front of Bordeaux"), but this was not mentioned before. Please, specify size of grid cells in model description, as well as time resolution. Also, it would be helpful to clearly associate Kilometric Points in the text for the river stretches chosen for further analysis. How many grid cells were used?

Reply 22: As you suggested we added more information about the model in the revised MS L173-179, as following:

"The model was implemented for the Gironde Estuary from the 200 m isobath on the continental shelf to the upstream limits of the tidal propagation on both rivers (Sottolichio et al., 2000). The mesh of the model is an irregular grid, with finer resolution in the estuary (200 m x 1 km) and coarser resolution on the shelf. The tidal rivers are represented by one cell in width. The vertical grid uses real depth coordinates and is split into 12 layers. The model uses a finite difference numerical scheme with a transport time step of 35 s."

Comment 23 - Line 225 and following paragraph: In the end, these simulations show that waste water overflow discharged during storm events have a minor impact on the estuarine hypoxia. In the data used, what is the temporal variability of the overflow versus total point sources load ratio? What is the summer average of this ratio? This would help characterize these episodic events and might show right away the priorities to stake-holders.

Reply 23: The temporal variability of the overflow and treatment plants discharges and the ratio of water overflow over total point sources are represented on the Figure below. The annual and summer averages of this ratio are 12% and 11%, respectively. During storm events of few hours, the untreated water overflows can represent up to 98% of urban effluents. This information was added in the revised MS L263-265, as following:

"In fact, wastewater overflows represent, on average, 12% of the urban effluents but could represent up to 98% during storm events."

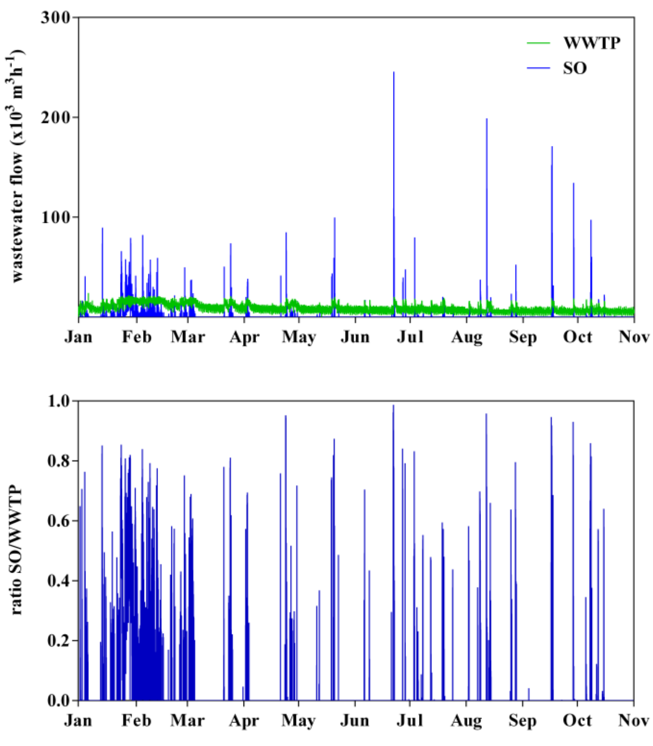

Figure 1: Time series of wastewater discharges in m^3s^{-1} from WWTP (green) and from SO (blue) for year 2006 (top). The ratio of SO flows over total wastewater discharges (bottom).

Comment 24 - Line 238: Again, is it safe to consider loads during storm events coming out of WWTPS to have similar characteristics as the rest of the time (such as "enriched in ammonia")?This is a critical assumption that needs solid clarification.

Reply 24:

The aim of these scenarios was to simulate an improvement of wastewater network by a reduction of 10 to 50% of the overflows of untreated water volumes in Bordeaux waters. Consequently, we add these overflows water volume as WWTP discharges of treated water, applying the respective POC and DOC and NH_4 concentrations, because this water volume is considered as treated. In order to make this point clear, we will make the following changes in the revised MS:

For these scenarios, the aim was to simulate an improvement of wastewater network by a reduction of 10 to 50% of the overflows of untreated water volumes in Bordeaux waters. We then add the overflows water volume as WWTP discharges, applying the different POC, DOC and NH_4 concentration, because this water volume is considered as treated. As mentioned by Lanoux e (2013), the WWTP releases treated water that contains mainly ammonia, whereas sewage overflows discharges untreated water mainly consisting of POC. Then the nitrification process will be higher for these scenarios, as more ammonia is discharged.

The transfer of 50% of SO water to WWTP, would correspond to a volume of 62.4 10^6 m^3 of WW, with a POC concentration of 584 instead of 6333 µmol L^{-1}, a DOC concentration of 734 instead of 1250 µmol L^{-1} and an NH_4 concentration of 1512 instead of 214 µmol L^{-1} (Lajaunie-Salla et al., 2017; Lanoux, 2013). In comparison with the reference simulation, this improvement in WW treatment corresponds to a reduction of 26% of POC, 3% of DOC and increase 6% of NH_4 loads.

We modified the sentence in the revised MS L271-274 as following:

"In contrast, the nitrification process and degradation of treated urban effluents were slightly increased by the reduction in SO flow (Fig. 2d & Tab. 3) because the wastewater removed from SOs is transferred to WWTPs, which include ammonia at the difference of SOs (Lanoux, 2013)."

In the revised MS we also added this information in the revised MS L226-228 as following:

"In comparison with the reference simulation, an improvement of 50% in WW treatment corresponds to a reduction of 26% of POC, 3% of DOC and an increase of 6% of NH4 loads."

Comment 25 - Line 245 and following paragraph: Can we consider that, if relocating point sources further downstream could help solve hypoxia in the estuarine zone it would significantly increase coastal eutrophication? This point is, to my view, absolutely crucial: are we not simply moving the problem to a different place and environment? Please, address this point in the Discussion based on available literature.

Reply 25: The reviewer is right when she/he asks if coastal eutrophication could be favored by relocating urban discharge downstream; in other terms, if solving the problem of hypoxia could create another problem by increasing the load of nutrient (specifically nitrogen) to the coastal zone; however, this question is relatively complex, because it depends on the overall capacity of the urban and estuarine system to remove nitrogen by denitrification, and this capacity is not necessarily linked to the place where wastewater is released more or less downstream. Indeed, as clearly exemplified with the case of the Scheldt estuary (Billen et al., 2005; Soetaert et al., 2006), hypoxic conditions in the water column will potentially promote anoxic conditions and denitrification in the surface sediment (and fluid mud; Abril et al. 2000). This means that resolving the question of hypoxia with any of the solutions tested in this work (not necessarily relocating the point source downstream, but all management that limits hypoxia like maintaining freshwater discharge or treating larger volumes of urban WW), with in theory increase the total N load (mainly as NO_3) to the coastal zone. This has been clearly shown for the Scheldt estuary since the pioneer work of (Billen et al., 1985). In fact, the solution to mitigate estuarine hypoxia and coastal eutrophication at the same time consists in realizing denitrification in WWTP, which is not the case in Bordeaux at the moment.

Comment 26 - Line 274 and following paragraph: Is there a big difference if we release the water from the upstream depending on the tidal variations? Do we want to flush the water (when tidal current goes downstream) or dilute estuarine zone (when tidal current goes upstream)? Would this make any difference?

Reply 26: We tested simulation with water release during neap tides and spring tides. Water release during neap tides is not significant, because hypoxia occurs during spring tides as highlighted by Etcheber et al. (2011); Lajaunie-Salla et al. (2017); Lanoux et al. (2013). This information was added at the end of the section 3.2 of the revised MS L359-361, as follows:

"Other scenarios of short term supports were made during neap tides (not shown) but were not very relevant because hypoxia events occur during spring tides (Etcheber et al. 2011, Lanoux et al. 2013, Lajaunie-Salla et al. 2017)."

Comment 27 - Line 296 and following paragraph: Generating such an event would increase water velocity and would likely erode river bed sediment, remobilizing nutrients and generating more turbidity. Does the model take this into account? I see nothing on the water-sediment processes in the study. Please, clarify this aspect and justify your choices.

Reply 27: Erosion of river bank is not an issue here in the Garonne tidal river, because tidal current are naturally very strong (up to 2.5 m s^{-1} during maximum flood) and changing the river discharge will not impact these maximum values.

A certain amount of the deposited particulate organic matter can be resuspended when the bottom shear stress exceeds the erosion threshold. However, not all the organic matter is always resuspended, this depends if the erosion rates is sufficiently high. When all the OM stored in the deposited mud has been eroded, bed stress cannot resuspend more material. On a neap-spring time scale however, all of the deposited material is eroded and no long-term burial occurs in the model.

The model considers a constant seabed oxygen consumption that is based on POC degradation rate, 10 times slower than in the water column. Moreover, $NO3^-$or $NH4^+$ benthic fluxes are not computed in the model.

This model result is consistent with earlier field and experimental work (Abril et al., 1999, 2000, 2010). In fact, the seabed in the Gironde turbidity maximum is composed of a layer of fine sediment (fluid mud) of variable height that is regularly resuspended depending to the tidal amplitude and water currents, as described by the model. Below this layer, consolidated sediments have larger grain size and lower organic carbon content and likely contribute very little to the total oxygen consumption. Concerning the fluid mud layer, which is suboxic and where denitrification and Mn reduction are the major respiratory pathways, experimental work (Abril et al., 2010) have shown that anaerobic carbon remineralisation rates are slow (in the range of 0.5-5 µmol L^{-1} h^{-1}), even if the sediment concentration exceeds 100 g L^{-1} (Abril et al. 2010). Reduced species (mainly $NH4^+$ and Mn(II)) build up in the fluid mud, but reaching relatively modest concentrations (respectively 30 and 10 µmol L^{-1}). Owing to the height of the fluid mud layer (max 10% of the water column), the modest surface of the estuary occupied by the fluid mud pools, it was concluded that the oxidation of inorganic reduced species during resuspension events had a negligible effect on the water column oxygenation even at spring tide (Abril et al. 1999).

Comment 28 - Line 344: If we expect lower low flows with longer summer droughts, can we really hope to "reduce water use for agricultural practice"?

Reply 28: This is a political choice to be made, we can only suggest it to stakeholders.

Comment 29 - Line 349: Do we actually know enough to determine which one of the proposed management decisions would be the best? Could your whole approach be transformed into a simple decision-tree to help local stakeholders take actions? This relates to the pre-diction capacity of the model used. A model can sometimes show good reproducible results (strong validation) but low prediction capacity under clearly different conditions. This has, to my view, to be discussed.

Reply 29: Our approach does not include cost, nor political choices such as agriculture versus urban investments.

Comment 30 - Line 351: In the end, would this combined approach have the best efficiency to effective cost ratio?

Reply 30: As we said previously our approach does not include cost, and then we are not able to assess the best efficiency to effective cost solution.

3. Minor comments

Line 24: "limit" instead of "limits"

Reply: We corrected as suggested L24.

Line 49: "Future climate conditions..." instead of "The future climatic conditions..."

Reply: We corrected as suggested L44.

Line 81: remove space before comma

Reply: We will correct as suggested.

Line 86: "suffering from" instead of "undergoing"?

Reply: We corrected as suggested L87.

Line 88: "...in the 1980s" instead of "in 1980s"

Reply: We corrected as suggested L89.

Line 89: same for "in 1990s"

Reply: We corrected as suggested L90.

Line 96: EPA also exists in the US and other countries. It is confusing since cases in Europe are presented just above, but examples in Canada and Japan are mentioned afterwards...Please be more specific.

Reply: In the revised MS L100-101 we added information about cases in US:

"This control was developed in several cities in the USA (Gonwa, 1993), Québec (Pleau et al., 2005) and Tokyo (Maeda et al., 2002)."

Line 100: "sewer network" instead of "outfall"?

Reply: We corrected as suggested L102.

Line 136: what is "PK"? Non-French speakers might not know it refers to "Point Kilo-métrique". Please, use a different term such as KP for Kilometric Point.

Reply: As suggested, we changed this annotation for "KP" to mean "Kilometric Points"

Line 137: please, include Pauillac position in the river reach to compare with "from PK25 to PK-70" in the previous sentence, even if it is clear on Fig. 1.

Reply: During low river flow, the TMZ is located between the KP25 and the KP-70, or from Bec d'Ambes to La Reole city, i.e. upstream of Pauillac. We added this information as follows in L138-139:

"The position of the TMZ varies seasonally: during low river flow, it is present in the Tidal Garonne River from KP25 to KP-70, i.e., upstream of Pauillac (Fig. 1)."

Line 137: "around Pauillac (Fig.1) downstream the Gironde Estuary" instead of "around Pauillac (Fig.1) at downstream of the Gironde Estuary"

Reply: We corrected as follows in L140: "the TMZ is located near Pauillac, in the Gironde Estuary"

Line 141: "Since the mid-80s," instead of "Since mid 80s,"

Reply: We corrected as follows in L146: "Since the mid 1980s".

Line 143: "Such a decrease" while you mention an increase just above...

Reply: In this sentence, we mention that the river flow decreases, whereas in the sentence before we mention that the numbers of days with a river flow below 110 m^3s^{-1} increases. We modified the sentence in the revised MS L148-150 as following:

"A decrease in the Garonne flow limits the reoxygenation of the TGR waters with well-oxygenated freshwater and favors upstream advection and the concentration of the TMZ (Lajaunie-salla et al., 2018)."

Line 152: "Part of the sewage system" instead of "The part of the sewage system"

Reply: We corrected as suggested L158.

Line 167: "validation" instead of "avalidation"

Reply: We corrected as suggested L206.

Line 170: "The biogeochemical model resolves extensively the processes that..." in-stead of "The biogeochemical model includes all the processes that..."

Reply: We corrected as suggested L182.

Line 180: "uses" instead of "use"

Reply: We corrected as suggested L192.

Line 181: where were the meteorological data measured?

Reply: The meteorological data were measured in Pauillac station and temperature data from Bordeaux station. We added this information L191-194 as following:

"The biogeochemical model uses measured water temperature from Bordeaux station (MAGEST network; Etcheber et al. (2011), http://magest.oasu.u-bordeaux.fr/) and wind and incident light intensity from Pauillac station (Météo France)."

Line 217: please correct English in this sentence.

Reply: We modified the sentence L251 as following: "The 16 scenarios were run over 10 months, from the January 1 to October 31."

Line 228: "the largest storm events" or "the largest sewage overflow events" instead of "the largest sewage overflow flow events"

Reply: We modified the sentence as suggested L263.

Line 235 and elsewhere in the text: "the contribution of WWTP matter degradation...".It brings confusion to refer to WWTPs outlets when mentioning WWTPs only. Please**,** revise throughout the manuscript.

Reply: We modified as suggested.

Line 236: this sentence is unclear. Please, clarify.

Reply: We agree with the reviewer, and will take into account this comment to improve the MS. We modified the sentence in the revised MS 271-274 as following:
"In contrast, the nitrification process and degradation of treated urban effluents were slightly increased by the reduction in SO flow (Fig. 2d & Tab. 3) because the wastewater removed from SOs is transferred to WWTPs, which include ammonia at the difference of SOs (Lanoux, 2013)."

Line 255: please, find a more explicit name for "urban matters".

Reply: We modified "urban matters" by "urban effluents" L292.

Line 259: clarify the changes in the downstream section under such condition.

Reply: We clarified this sentence as following L295-297:

"With the downstream relocation of urban discharge, DO levels are strongly improved in the TGR, without significantly altering the oxygenation condition downstream of Bordeaux."

Line 286: "diluted" instead of "reduced"

Reply: We corrected as suggested in the revised MS L325.

Line 301: Please, clarify what decreases by specifying the units after "6.6 to 1.6"

Reply: The water half-renewal times is expressed in days. We modified the sentence in the revised MS L343 as following:

"The water half-renewal times are less than 1 day at Portets and decrease from 6.6 to 1.6 days at Bordeaux ..."

Line 311: is it one or two weeks then? Accurate numbers would help.

Reply: Here, an intense STS of 400 m^3s^{-1} is not able to maintain good level of oxygen all summer long in Portets. After the massive water input, DO level stays above the hypoxia threshold during 17 days only and then decreases again (Fig.5i). In the revised MS L352-354 we added this information as following:

"Intense short-term support of freshwater (400 m3.s-1) is not able to maintain a good oxygen level all summer in Portets. After the massive water input, the DO level stayed above the hypoxia threshold for 17 days but then decreased again (Fig. 5i)."

Line 335: "threshold" instead of "thereshold", "degradation is" instead of "degradationis"

Reply: We corrected as suggested in the revised MS L382.

Line 338: add a reference to this expected population growth

Reply: We added the reference about the expected population growth in the revised MS L385

Line 342: could you provide an estimate of such a cost? Or give examples considering what is done for the Thames estuary?

Reply: We asked an estimation of such cost at the company of wastewater management, but they could not give us estimation.

Line 343: what can of environmental impact are you mentioning? Please, clarify.

Reply: Here, we wanted to mention the impact of outfall construction on the ecosystem. We modified the sentence in the revised MS L390-391 as following:

"Moreover, the environmental impact on the ecosystem of such construction can hinder this solution."

Line 344: "purposes" instead of "practice"

Reply: We corrected as suggested in the revised MS L392.

Line 357: Please remove "to maintain the best water quality as possible"

Reply: We removed as suggested in the revised MS.

Line 368: "the river water" instead of "waters"

Reply: We corrected as suggested in the revised MS L416.

4. **Specific comments on Tables on Figures**

Table1: abbreviations in the Table must be defined (as a footnote or in Table caption)

Reply: As suggested we defined abbreviations as following:

"Qref: river flow of 2006; $Q_{G/D:}$river flow of Garonne and Dordogne; Q_{WW}: wastewater flow; SO: sewage overflow"

Figure 2: Presenting 2a and 2b with log axis would help the reader. With the current graph, it is nearly impossible to identify river discharge values during summer, and compare point sources for the two years of data presented. I would not mix different x-axis in one figure.

Reply: In order to identify better the river discharges and point sources values during summer, we added a graph for summer period, as following in the below figure.

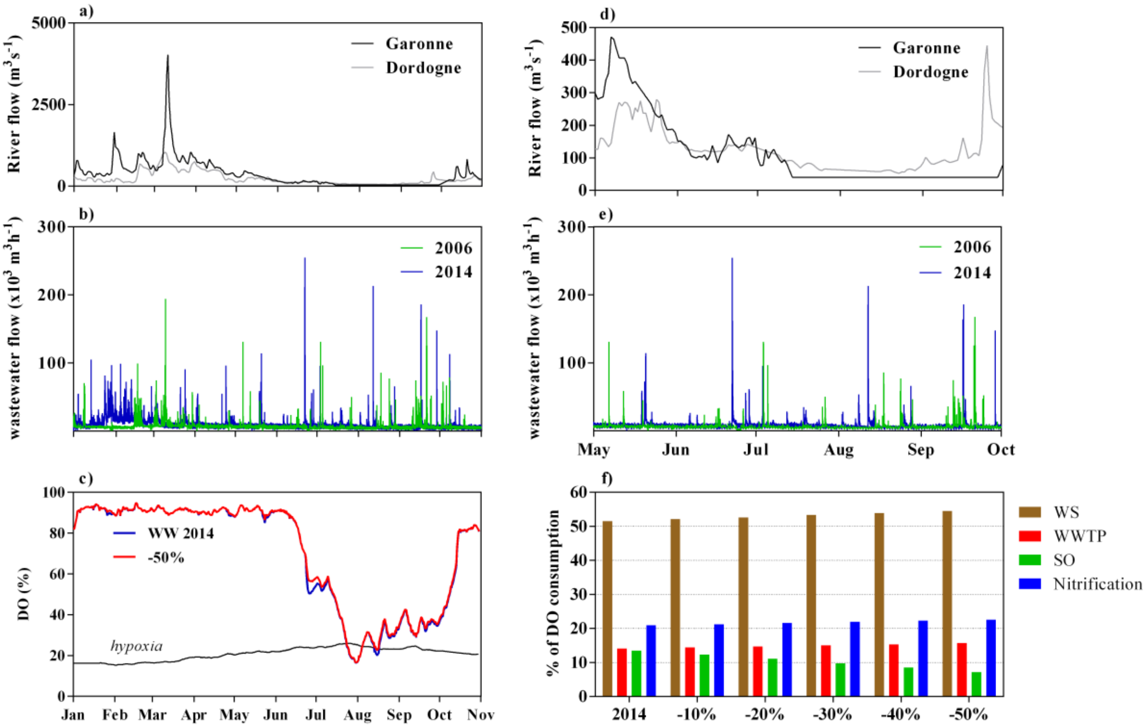

Figure 2: Time series of Garonne River (black) and Dordogne River (grey) flow of the reference simulation (a & d, m^{3}s^{-1}), wastewater discharges (WWTP+SO) for year 2006 (green) and 2014 (blue) (b & e, m^{3}s^{-1}). Comparison of simulated DOmin evolution (over tidal cycle in %sat) in Bordeaux with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

Figure 2d should be a different figure. I strongly recommend to add a figure presenting upstream C, N, P river loads and how they compare with point sources from Bordeaux metropolitan point sources.

Reply: Total N and P loads from river are not crucial because they do not directly impact oxygen in the estuarine turbidity maximum where these nutrient are not limiting for primary production (controlled by light). In our biogeochemical model, we did not represent the P cycle. In this work, the most important parameter is the load of compounds that will contribute to oxygen demand in the estuary at short time scale (biodegradable POC and DOC, as well as NH_4), and not the loads of total N and P. We can add as supplementary information the following figure to indicate the contribution of C (POC and DOC) and N (NH_4) loads from urban effluents compared to rivers.

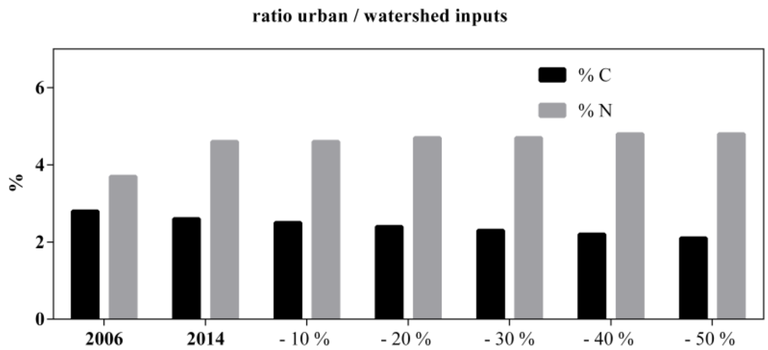

Figure 3: ratio of urban to watershed inputs of carbon and nitrogen in % for different scenarios.

Figure 3&4: Almost no use is made of the spatial distributions of DO in the text. It is apity since they show very clear differences between scenarios, and show the interest of using a complex modelling approach. These figures could get much clearer if each individual transect had an informative label, if P1, P2, P3 appeared on Figure 1, and also if it was mentioned the time associated with these longitudinal transects. Is it an average across the summer period? This has to be clarified. Other comments on these figures: vertical distribution seems quite homogeneous. what is the interest of 3D modelling in this case? Couldn't you simplify a lot the simulations with a 2D approach? Only one colorbar in these graphs is sufficient since they all have the same scale.

Reply: As suggested by the reviewer, more discussion was added in the revised MS

- L286-290:

"According to the model, figure 3 highlights that the displacement of the urban wastewater discharge point downstream significantly improves the oxygen levels in the TGR around Bordeaux and appears to be an efficient action to mitigate hypoxia near Bordeaux (Fig. 3). Moreover, the DO concentration does not change downstream of Bordeaux, maintaining a value of over 50% saturation."

- L336-341:

"An intense and short-term support of freshwater allows low-oxygenated water to be pushed downstream and induces a strong dilution of estuarine water with well-oxygenated fluvial waters due to the large amount of water supply (100, 200 and 400 m3.s-1) (Fig. 4 & Fig. 5). Figure 4 highlights this phenomenon and the improvement of oxygen level along the TGR, reaching saturation level around Portets and higher than 50% of saturation around Bordeaux (Fig. 4)."

The point P1, P2 and P3 referred to Bec d'Ambès, Bordeaux and Portets, respectively. This information is given at the legend of the Figure 3 and 4, and these cities are located in Figure 1. We think that is not necessary to add "P1, P2 and P3" in figure 1. The snapshot represents the period of minimum of DO simulated at Bordeaux that occurs the 30th July. The interest of the 3D model is to represent the turbidity maximum zone that impacts the DO. In fact the organic matter is trapped on suspended sediment which consumes oxygen. We can see this phenomenon around Portets (P3). We prefer to keep the three colorbas for cause of esthetic of the figure.

Figure 5: What is the interest of showing diel cycles? Wouldn't it be more instructive to extract from these time series daily amplitudes and averages for each scenario? It would be nicer to have this figure in a portrait layout.

Reply: As recommended by the reviewer, we modified the figure to show the simulated DOmin over the tidal cycle at Bordeaux and Portets.

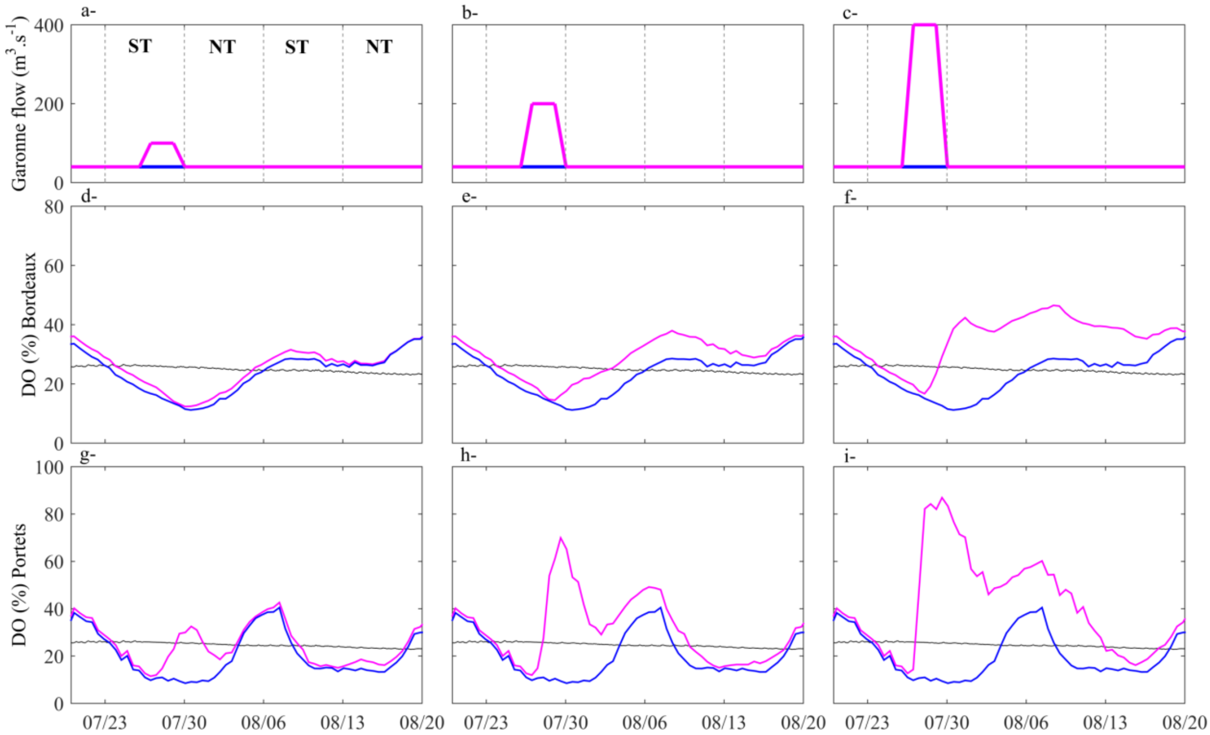

Figure 4: Time series of river flow (top, m^3s^{-1}), DOmin (over tidal cycle) at Bordeaux (middle, %sat) and DO at Portets (bottom, %sat) for the scenarios of short river flow increases by 100 m^3s^{-1} (a, d and g), 200 m^3s^{-1} (b, e and h) and 400 m^3s^{-1} (c, f and i). Blue line represents the simulation of reference.

Figure 6: Almost no use of this figure is made in the text. I recommend extracting metrics that are more informative such as daily averages and amplitudes. Amplitudes are also crucial in a river metabolism point of view. In any case, only one colorbar in these graphs is sufficient since they all have the same scale. Each individual panel should have an informative label. I also recommend to have this figure in a portrait layout, with enlarged width (along the spatial scale) to identify more clearly the temporal patterns.

Reply: As suggested by the reviewer, in order to highlights that hypoxia events are reduced temporally and also that the extension of hypoxia zone is reduces more discussion was added in the revised MS L376-379, as following:

"Combining these two management solutions can improve the oxygen level both in the upper TGR and around Bordeaux. Figure 6 reveals a reduction in hypoxia event frequency from 6 to 2 events in the TGR. Moreover, the extension of hypoxia is significantly reduced between KP0 and KP-20."

We prefer to keep the three colorbas for cause of esthetic of the figure.

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

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Highlights

- A 3D model shows different efficiencies of management actions to limit hypoxia.
- Downstream relocation of wastewater discharge totally mitigates hypoxia
- Sewage overflow reduction improves DO levels, but only locally.
- Water replenishment improves DO in the upper estuary.

Abbreviations

DO: dissolved oxygen

DOC: dissolved organic carbon

LTS: long-term support

POC: particulate organic carbon

SO: sewage overflow

STS: short-term support

TGR: Tidal Garonne River

TMZ: turbidity maximum zone

WWTP: wastewater treatment plant

Abstract

Coastal water hypoxia is increasing globally due to global warming and urbanization, and the need to define management solutions to improve the water quality of coastal ecosystems has become important. The lower Tidal Garonne River (TGR, southwestern France), characterized by the seasonal presence of a turbidity maximum zone (TMZ) and urban water discharge, is subject to episodic hypoxia events during low river flow periods in the summer. Future climatic conditions (higher temperature, summer droughts) and increasing urbanization could enhance hypoxia risks near the city of Bordeaux in the coming decades. A 3D model of dissolved oxygen (DO) that couples hydrodynamics, sediment transport and biogeochemical processes was used to assess the efficiency of different management solutions for oxygenation of the TGR during summer low-discharge periods. We ran different scenarios of reductions in urban sewage overflows, displacement of urban discharges downstream from Bordeaux, and/or temporary river flow support during the summer period. The model shows that each option mitigates hypoxia but with variable efficiency over time and space. Sewage overflow reduction improves DO levels only locally near the city of Bordeaux. Downstream relocation of wastewater discharges allows for better oxygenation levels in the lower TGR. The support of low river flow limits the upstream TMZ propagation and dilutes the TGR waters with well-oxygenated river water. Scenarios combining wastewater network management and low water replenishment indicate an improvement in water quality over the entire TGR. These modeling outcomes constitute important tools for local water authorities to develop the most appropriate strategies to limit hypoxia in the TGR

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

1 Introduction

Hypoxia (dissolved oxygen (DO) concentration < 2 mg.L^{-1} or < 30% of saturation) is a major environmental issue, as it stresses marine organisms and disturbs the function of marine ecosystem (Rabalais et al., 2010; Vaquer-Sunyer and Duarte, 2008). Coastal hypoxia is a widespread phenomenon that has increased since the middle of the 20th century due to the combined effects of climate change and local anthropic activities (land and water uses) (Breitburg et al., 2018). Good oxygenation of estuarine waters is crucial in order to maintain ecological and economical services within the whole watershed because of the strategic position of estuaries for migratory fishes (Rabalais et al., 2010). Estuarine deoxygenation is the result of a complex interaction of environmental factors. First, an increase in temperature decreases the oxygen solubility of the water, favors thermal stratification of the water column, limiting reaeration (Conley et al., 2009; Lehmann et al., 2014), and accelerates DO-consuming biogeochemical processes (Goosen et al., 1999). Second, a decrease in river flow modifies estuarine residual circulation, sediment transport, and the transit and mineralization of terrestrial organic material in estuaries (Abril et al., 1999; Howarth et al., 2000). In addition, an increase in population and human activities enriches coastal waters with nutrients and labile organic matter from urban effluents, possibly leading to eutrophication problems (Billen et al., 2001). Finally, in macrotidal estuaries, DO consumption by heterotrophic organisms is exacerbated by the presence of a turbidity maximum zone (TMZ), which favors the growth of particle-attached bacteria and, in contrast, limits phytoplankton primary production (Diaz, 2001; Goosen et al., 1999; Talke et al., 2009). In view of the ongoing global changes, it is now essential to find management strategies for hypoxia mitigation. To recover or maintain a good ecological status for transitional waters is one of the objectives of the European Water Framework Directive (Best et al., 2007).

In an urban tidal river, the first obvious action to mitigate hypoxia is to improve the urban wastewater network and treatment and to reduce the input of organic matter and nutrients to the estuary. In several European estuaries suffering from urban inputs, water quality improvement was achieved by the installation and renovation of a wastewater treatment plant (WWTP) in the Thames Estuary in the 1980s (Andrews and Rickard, 1980; Tinsley, 1998) and the construction of a WWTP in the Seine River in the 1990s (Billen et al., 2001). In the Scheldt Estuary, sewage network improvement reduced N, P and Si loads by 5.4%, 1.3% and 1%, respectively, and two WWTPs have been implemented for the city of Brussels since 2000 (Billen et al., 2005; Soetaert et al., 2006; Vanderborght et al., 2007). Sewage network systems in Europe usually combine both urban sewage and stormwater collection. During heavy rain and storm events, the capacity of the urban wastewater network is generally insufficient to treat all effluents, inducing deoxygenation events due to untreated wastewater release from sewage overflows (SO) (Even et al., 2007). In the 2000s, the Environmental Protection Agency promoted a strategy to monitor urban drainage networks in real time to regulate flow and avoid the overflow of untreated wastewater (EPA, 2006; Gonwa, 1993). This control was developed in several cities in the USA (Gonwa, 1993), Québec (Pleau et al., 2005) and Tokyo (Maeda et al., 2002). An additional management solution was tested in the Thames Estuary: the construction of a 24-km-long sewer network under the riverbed that allows the transit of urban wastewater to the WWTP located downstream (Thames Tideway Tunnel, www.tideway.london). This type of solution is also ongoing in Stockholm (www.stockholmvatten.se) and in the Helsinki (www.hsy.fi) metropolis.

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

To optimize preventive management strategy, the efficiency of the potential solutions needs to be evaluated. Therefore, numerical modeling is an efficient tool to quantitatively assess hypoxia mitigation by management scenarios. Moreover, models provide guidelines for setting objectives to maintain good water quality in coastal environments (Kemp et al., 2009; Skerratt et al., 2013).

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

2 Materials and Methods

2.1 Study Area

The Garonne River, located in southwestern France, is the main tributary of the Gironde Estuary, which is formed by its confluence with the Dordogne River and flows toward the Atlantic Ocean (Fig. 1). This macrotidal fluvio-estuarine system is characterized by the presence of a TMZ, where suspended sediment concentrations in surface waters are > 1 $g.L^{-1}$ (Allen, 1972). The position of the TMZ varies seasonally: during low river flow, it is present in the Tidal Garonne River from KP25 to KP70, i.e., upstream of Pauillac (Fig. 1). The rest of the year, the TMZ is located near Pauillac (Fig. 1), in the Gironde Estuary (Jalón-Rojas et al., 2015).

The annual mean Garonne River flow is 680 $m^3.s^{-1}$ for the period 1913-2018, with the highest flows in winter (mean of 720 $m^3.s^{-1}$) and the lowest flows in summer and early autumn (mean of 190 $m^3.s^{-1}$) (http://www.hydro.eaufrance.fr/indexd.php). The threshold of 110 $m^3.s^{-1}$ is the present-day low water target flow for the lower Garonne, below which there is water replenishment for the period from June 1 to October 31. Since the mid 1980s, there has been an increase in the number of days with a river flow below 110 $m^3.s^{-1}$ (http://www.hydro.eaufrance.fr/indexd.php). A decrease in the Garonne flow limits the reoxygenation of the TGR waters with well-oxygenated freshwater and favors upstream advection and the concentration of the TMZ (Lajaunie-salla et al., 2018). Six water reservoirs that can store a maximum water volume of 58 hm^3 are located in the upper Garonne River, corresponding to an equivalent river flow of 95 $m^3.s^{-1}$ during a single week. This water storage is used to maintain the Garonne discharge above the critical (>110 $m^3.s^{-1}$) for the ecosystem during the summer.

The large city of Bordeaux is located at the border of the Tidal Garonne River, 25 km upstream of the confluence (Bec d'Ambès, Fig. 1). The sewage systems of the metropolis drain an urban area of 578 km² and serve a population estimated at 749 595 inhabitants in 2015. Part of the sewage system is composed of a combined sewer network: two wastewater treatment plants, Clos de Hilde and Louis Fargue, and nine sewage overflows. The releases of treated and untreated wastewaters represent up to 1.5% of the fluvial Garonne discharge (Lanoux et al., 2013).

The Bordeaux metropolis has already taken several actions to improve the urban wastewater network. In 2011, the WWTP Louis Fargue was resized and upgraded to the treatment effectiveness of the WWTP Clos de Hilde. In addition, since 2013, real-time control of the urban drainage network was developed to reduce urban effluents during rainy weather (Andréa et al., 2013). This system decreased the volume of untreated wastewater released by 30% in 2013 and by 40% in 2014 and 2015 (Robitaille et al., 2016), improving the overall net purification efficiency to > 95% for particulate organic carbon (POC), >75% for dissolved organic carbon (DOC) and >30% for ammonia (Lanoux, 2013).

2.2 Model description

The SiAM-3D model, which couples hydrodynamics, suspended sediment transport and biogeochemical processes (Lajaunie-Salla et al., 2017), was used to test the efficiency of possible management solutions. The model was implemented for the Gironde Estuary from the 200 m isobath on the continental shelf to the upstream limits of the tidal propagation on both rivers (Sottolichio et al., 2000). The mesh of the model is an irregular grid, with finer resolution in the estuary (200 m x 1 km) and coarser resolution on the shelf. The tidal rivers are represented by one cell in width. The vertical grid uses real depth coordinates and is split into 12 layers. The model uses a finite difference numerical scheme with a transport time step of 35 s.

The transport model solves the advection/dispersion equations for dissolved and particulate variables, i.e., suspended sediment, salinity and biogeochemical variables. The biogeochemical model extensively resolves the processes that produce and consume oxygen in the water column, taking into account different types of dissolved and particulate organic matter: degradation of organic matter (mineralization of organic carbon and ammonification using the C/N ratio); nitrification; photosynthesis, respiration and mortality of phytoplankton; and DO gas exchange with the atmosphere. The model includes 11 state variables: dissolved oxygen (DO), ammonia (NH_4^+, input from rivers and mainly from urban effluents), nitrate (NO_3^-), POC and DOC from the watershed (POC from litter; DOC from rivers), WWTPs, SOs, phytoplankton and detritus. At the open boundaries, the hydrodynamic model is forced by astronomical tides at the shelf and by daily river flow of the Garonne and Dordogne Rivers at the upstream limit (data from www.hydro.eaufrance.fr). The biogeochemical model uses measured water temperature from Bordeaux station (MAGEST network; Etcheber et al. (2011), http://magest.oasu.u-bordeaux.fr/) and wind and incident light intensity from Pauillac station (Météo France). The boundary conditions of biogeochemical variables were detailed by Lajaunie-Salla et al. (2017), and the data of organic matter and nutrients were retrieved from the works of Etcheber et al. (2007), Lemaire (2002), Lemaire et al. (2002) and Veyssy (1998). Urban wastewater discharges are included in the model with biodegradable POC and DOC and NH_4 loads representative of water flowing from WWTP and from SO (every 5 minutes; concentration data are from Lanoux (2013), and the flow data are from the SUEZ environment; Fig. 1).

The model was compared with data available for the TGR and tested on the basis of three criteria: (i) the ability to reproduce the observed DO variability at a seasonal scale, (ii) the ability to reproduce the spring-neap tidal cycle, and (iii) a statistical evaluation based on the Willmott skill score (WSS, Willmott (1982)). In brief, the model performed well (WSS > 0.7) in the lower TGR around Bordeaux and is less accurate in the upper section (WSS < 0.5); the model and its validation were presented in detail by Lajaunie-Salla et al. (2017).

In this work, we want to demonstrate the advantage and/or effectiveness of urban water networks and treatment processes for limiting hypoxia events during critical conditions. The reference simulation is based on the real conditions of 2006, which was a critical year from the point of view of river discharge, temperature and hypoxia. A 21-day heat wave occurred, and the summer water temperature reached a maximum of 29.5°C, with an average of 24.6°C. The reference simulation considered a severe and constant low flow of 40 $m^3.s^{-1}$ from July 15 to September 30, which is different from the real river flow recorded (60 continuous days of river flow below 110 $m^3.s^{-1}$) but helps to visualize the impact of potential solutions on oxygenation (Fig. 2a). The sewage network of the Bordeaux metropolis was improved in 2011, after which we used a time series of 2014 to reach our objectives to find management solutions to mitigate hypoxia events. The SO discharges constituted 16% in 2006 and 12% in 2014.

2.3 The scenarios

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

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

- the increase in wastewater storage during storms. For this, fractions of 10, 20, 30, 40 and 50% of untreated wastewater SO was transferred to WWTP discharges (taking into account the organic matter and nutrient loads of WWTP). In comparison with the reference simulation, an improvement of 50% in WW treatment corresponds to a reduction of 26% of POC, 3% of DOC and an increase of 6% of NH_4 loads.

- the implementation of an outfall that releases urban effluents downstream. Two wastewater discharge points were tested: (1) at 21 km (same distance as in the Thames Estuary) corresponding to position KP25 (Fig. 1), where the currents are relatively high and could disperse urban effluents relatively quickly, and (2) at 11 km, corresponding to KP15 as an alternative and less expensive solution (Fig. 1). Although this solution seems difficult to implement due to technical and financial constraints, it is interesting to investigate its potential environmental benefits.

For the support of low river flow during the driest season, two actions were tested according to the maximum stored water volume in the dams (58 hm^3) of the upper Garonne River (Tab. 2):

- low-intensity and long-term support (LTS) from 15th July by 10, 20 and 30 $m^3.s^{-1}$ during 67, 33 and 22 days, respectively.

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

Finally, two scenarios that coupled wastewater management actions and the support of low river flow were simulated (Tab. 2):

- a LTS of 10 $m^3.s^{-1}$ over 67 days was combined with the reduction of 50% of untreated wastewater SO, which is transferred to WWTP discharges;

- a LTS of 10 $m^3.s^{-1}$ over 67 days was combined with the reduction of 50% of untreated wastewater SO, which is transferred to WWTP discharges and to the relocation of wastewater discharges 11 km (KP15) downstream of Bordeaux (Fig. 1).

The 16 scenarios were run over 10 months, from January 1 to October 31. To evaluate the improvement of DO level, three indicators were used: (i) the minimum DO value (DO_{min}); (ii) the number of hypoxia days, i.e., DO < 2 $mg.L^{-1}$; and (iii) the summer-averaged rates of biogeochemical processes consuming DO in the Bordeaux and Portets areas (6.6 and 1.2 km^2, respectively). The grid cells in front of Bordeaux and Portets were chosen because Bordeaux is directly under the impact of urban effluents and because Portets represents the presence of TMZ in the upper TGR.

3 Results

3.1 Action 1: Wastewater management

- **Action 1.1: Reduction in sewage overflows**

The simulations of sewage overflow reduction do not show an increase in DO_{min} at Bordeaux and Portets (Tab. 2). However, some short but significant differences in the modeled DO time series in Bordeaux are noticeable during the largest sewage overflow events (Fig. 2c). In fact, wastewater overflows represent, on average, 12% of the urban effluents but could represent up to 98% during storm events. For the scenario SO-50%, there is a slight increase in DO level by 6 and 2%sat in late June and mid-August, respectively (Fig. 2c). The total DO consumption by biogeochemical processes decreases up to 6% at Bordeaux (Tab. 3). The rate of mineralization of urban organic matter decreases considerably, by 31% and 33%, with a reduction of 50% of SO flow at Bordeaux and Portets, respectively (Tab. 3). In fact, at Bordeaux, the material brought by the SO contributes 7% of the total DO consumption, with a reduction of 50% with versus 13% without reduction (Fig. 2d). In contrast, the nitrification process and degradation of treated urban effluents were slightly increased by the reduction in SO flow (Fig. 2d & Tab. 3) because the wastewater removed from SOs is transferred to WWTPs, which include ammonia at the difference of SOs (Lanoux, 2013).

In these simulations, sudden wastewater release events from SO (late June) did not occur simultaneously with the maximum temperature (i.e., late July). In such a case, a more critical hypoxia event would have occurred. However, the modeling results show that the improvement of SO management contributes to improving the DO level only locally and temporarily in the vicinity of the city of Bordeaux.

- **Action 1.2: Downstream relocation of wastewater discharges**

In the case of a relocation of urban effluent discharge at KP15, only 4 days of hypoxia were simulated with a minimum of 1.8 $mg.L^{-1}$ (Tab. 2), which represents a reduction of 9 days in comparison with the reference simulation. In the case of the relocation of urban effluents discharge farther downstream at KP25, the model simulated no hypoxia and a minimum DO value of 2.1 $mg.L^{-1}$ (Tab. 2). The oxygen level in the vicinity of Bordeaux was improved. According to the model, figure 3 highlights that the displacement of the urban wastewater discharge point downstream significantly improves the oxygen levels in the TGR around Bordeaux and appears to be an efficient action to mitigate hypoxia near Bordeaux (Fig. 3). Moreover, the DO concentration does not change downstream of Bordeaux, maintaining a value of over 50% saturation. Under these relocation scenarios, the amount of urban organic matter and ammonia are relatively low at Bordeaux. Urban effluents are diluted by downstream estuarine waters and exported toward the Gironde. In fact, urban effluents reach the city of Pauillac, approximately 50 km downstream of Bordeaux (Fig. 1) after 1 and 1.5 days when effluents are released at KP25 and KP15, respectively, versus 2.5 days when they are discharged near Bordeaux. With the downstream relocation of urban discharge, DO levels are strongly improved in the TGR, without significantly altering the oxygenation condition downstream of Bordeaux. This phenomenon is due to shorter residence times of effluents and larger dilutions with oxygenated estuarine waters downstream.

A downstream relocation (KP15 or KP25) significantly decreases total DO consumption in the lower TGR by 33% and 47%, respectively: the mineralization of urban matter is reduced by 65% and 95%, and the nitrification is reduced by 47% and 69%, respectively (Tab.3). At Portets, even if the total DO consumption decreases only by 8%, the degradation of urban matter decreases strongly by 76% and 94% and the nitrification is reduced by 17% and 20% when urban effluents are discharged in KP15 and KP25, respectively (Tab. 3). In fact, the mineralization of urban matter occurs downstream of TGR, with less impact on the DO in this area, thanks to the dilution effect with estuarine waters. Finally, at Bordeaux, the contribution of urban effluents to the DO consumption decreases from 27% to 2%, and nitrification decreases from 20% to 10% (Fig. 3d).

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

3.2 Action 2: Support of summer river discharge

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

The simulations of low-intensity and long-term support ~~(LTS)~~ of water flow show an increase in the DO_{min} not only at Portets but also at Bordeaux (Tab. 2). At Bordeaux, the DO_{min} increases by only 0.3 $mg.L^{-1}$, and the number of simulated hypoxia days decreases by only 2 days for a discharge increase of 30 $m^3.s^{-1}$. However, in Portets, oxygen levels are much more improved: the additional flows significantly reduce the number of hypoxic days, reducing them from 52 days (reference simulation) to 29, 39 days or 40 days with supports of 10, 20 or 30 $m^3.s^{-1}$, respectively (Tab. 2).

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

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

- **Action 2.2: Intense and short-term support of low water discharge**

An intense and short-term support ~~(STS)~~ of freshwater allows low-oxygenated water to be pushed downstream and induces a strong dilution of estuarine water with well-oxygenated fluvial waters due to the large amount of water supply (100, 200 and 400 $m^3.s^{-1}$) (Fig. 4 & Fig. 5). Figure 4 highlights this phenomenon and the improvement of oxygen level along the TGR, reaching saturation level around Portets and higher than 50% of saturation around Bordeaux (Fig. 4). The model results show decreases in the number of hypoxia days in Bordeaux and Portets (Tab. 2). The water half-renewal times are less than 1 day at Portets and decrease from 6.6 to 1.6 days at Bordeaux with increasing discharge support from 100 to

400 $m^3.s^{-1}$. During short term support, the DO concentrations increase faster at Portets than at Bordeaux (Fig. 4 & Fig. 5). During a semidiurnal tidal cycle, the DO rises by 9%sat at Bordeaux and by 56%sat at Portets with an input of 400 $m^3.s^{-1}$. The higher the river flow support, the faster the waters of the TGR are reoxygenated.

The total oxygen consumption decreases with STS only at Portets (Tab. 3). At Bordeaux, the decrease in nitrification is counterbalanced by an increase in river organic matter mineralization (Tab. 3). The intense short-term support moves the TMZ downstream to Portets, reducing organic matter mineralization in the area of Portets (Tab. 3 & Fig. 4).

Intense short-term support of freshwater (400 $m^3.s^{-1}$) is not able to maintain a good oxygen level all summer in Portets. After the massive water input, the DO level stayed above the hypoxia threshold for 17 days but then decreased again (Fig. 5i). This type of management is very powerful as an urgent remediation during severe hypoxia to quickly improve the oxygenation levels of TGR waters, particularly in the upper section of the tidal river. For example, during the heat wave of the end July 2006 (Fig. 2c), STS avoided hypoxia. In the case of late hypoxia occurring at the end of the summer, STS may be efficient if the stored water volume is sufficient. Other scenarios of short term supports were made during neap tides (not shown) but were not very relevant because hypoxia events occur during spring tides (Etcheber et al. 2011, Lanoux et al. 2013, Lajaunie-Salla et al. 2017).

3.3 Synthesis of management actions efficiency

These different simulated scenarios allow us to quantitatively estimate the efficiency of different management options to reduce hypoxia in the TGR. The two management solutions have locally different impacts on DO (Tab. 4): optimization of the urban wastewater network reduces hypoxia in the lower TGR, whereas water replenishment during low water periods enhances DO levels in the upper TGR. The improvement of the wastewater network by a reduction in labile organic matter input reduces oxygen consumption in Bordeaux waters. The alternative, consisting of discharging urban effluents downstream of the lower TGR, has the advantage of diluting wastewater with the Gironde water and favoring their dispersion downstream in the wider sections of the estuary. In addition, taking into account the increasing gradient of temperature landward (Schmidt, personal data), wastewater effluents would be discharged in cooler waters (approximately 1-2°C) than those at Bordeaux. The water replenishment during low water periods is also a powerful solution, which favors the dilution of upper TGR waters with well-oxygenated freshwater and limits the upstream TMZ displacement. Combining these two management solutions can improve the oxygen level both in the upper TGR and around Bordeaux. Figure 6 reveals a reduction in hypoxia event frequency from 6 to 2 events in the TGR. Moreover, the extension of hypoxia is significantly reduced between KP0 and KP20. The scenario combining a discharge support of +10 $m^3.s^{-1}$, a reduction of 50% of SO release and discharge of urban effluents at KP15 suggests an improvement of water quality over the entire TGR (Fig. 6): only 2 days below the hypoxia threshold (Tab. 2) and the oxygen consumption by urban organic matter degradation is totally reduced (by 100%, Tab. 3).

Regarding the projected population growth of the city of Bordeaux (one million inhabitants will be reached in 2030, http://www.bordeaux-metropole.fr) and the objectives of the European Water Framework Directive to maintain good water quality, the reduction in the impact of urban wastewater networks in urban areas appears to be a major challenge for the coming years. The construction of an outfall under the river could be an efficient solution to totally mitigate hypoxia at Bordeaux, but this solution is, for instance, an academic scenario considering its cost and technical constraints. Moreover, the environmental impact on the ecosystem of such construction can hinder this solution. The support of summer river flow could certainly be optimized by reducing water use for agricultural purposes in the watershed during summer and by improving the release of stored water as a function of meteorological conditions. In the case of unfavorable conditions (heat wave, drought) in early summer, LTS could be implemented. However, if these conditions occur late in summer, intense STS could be considered. An alternative solution could be intermittent support, with water release of 100 $m^3.s^{-1}$ during spring tide and all summer (July and August, i.e., 4 spring tides). By the continuation of the improvement in the urban wastewater network and by the simultaneously maintenance of good river flow levels, both management options may improve the oxygen level on the TGR.

4 Conclusion

A 3D biogeochemical model for the Tidal Garonne River coupling hydrodynamics and sediment transport was applied to assess the efficiency of different management solutions to improve the DO level in waters. This study tested different scenarios of management solutions that can be implemented by local water authorities. Whereas a reduction in SO flows contributes only to improving DO levels locally and temporarily, the downstream relocation of WWTP outfalls totally mitigates hypoxia in the TGR and seems to be the most efficient management solution, despite being difficult to implement in practice. The support of low river flow limits the propagation of the TMZ upstream of the TGR and dilutes the estuarine waters with fresh oxygenated waters. A low-intensity support over the summer maintains a good oxygen level of waters during the entire drought period and prevents hypoxia in the upper TGR. In contrast, an intense support of low water flow for 3 days improves the oxygen levels along the entire TGR quickly and considerably, but only for a few weeks. The improvement in the urban effluent network and the support of low-river flow periods from dams or irrigation reduction are complementary. They contribute to reoxygenating the river water near the city of Bordeaux and upstream of the Tidal Garonne

River, respectively. The biogeochemical numerical model helps guide the management policy of urban effluents and watersheds to limit and mitigate hypoxia events.

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Table 1: Forcing of the different scenarios simulated with the model. (Qref: river flow of 2006; $Q_{G/D}$: river flow of Garonne and Dordogne Q_{WW}: wastewater flow; SO: sewage overflow)

Scenarios		River flow	Wastewater flow
	Reference	Qref = $Q_{G/D}$ 2006 + Q_G = 40 $m^3.s^{-1}$ from 15/07 to 30/09	Q_{WW} 2006
Management of wastewater discharges	**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
	Release moved to KP15	Qref	Q_{WW} 2014 at Parempuyre
	Release moved to KP25	Qref	Q_{WW} 2014 at Bec d'Ambès
Support of low river flow	**+10 $m^3.s^{-1}$**	Qref ; Q_G < 50 $m^3.s^{-1}$: Q_G +10 $m^3.s^{-1}$ over 67 days	Q_{WW} 2006
	+20 $m^3.s^{-1}$	Qref ; Q_G < 50 $m^3.s^{-1}$: Q_G +20 $m^3.s^{-1}$ over 33 days	Q_{WW} 2006
	+30 $m^3.s^{-1}$	Qref ; Q_G < 50 $m^3.s^{-1}$: Q_G +30 $m^3.s^{-1}$ over 22 days	Q_{WW} 2006
	+100 $m^3.s^{-1}$	Qref ; Q_G +100 $m^3.s^{-1}$ over 3 days	Q_{WW} 2006
	+200 $m^3.s^{-1}$	Qref ; Q_G +200 $m^3.s^{-1}$ over 3 days	Q_{WW} 2006
	+400 $m^3.s^{-1}$	Qref ; Q_G +400 $m^3.s^{-1}$ over 3 days	Q_{WW} 2006
Combined options	**-50% +10 $m^3.s^{-1}$**	Qref ; Q_G < 50 $m^3.s^{-1}$: Q_G +10 $m^3.s^{-1}$ over 67 days	Q_{WW} 2014 – 50% SO
	-50% + KP15 +10 $m^3.s^{-1}$	Qref ; Q_G < 50 $m^3.s^{-1}$: Q_G +10 $m^3.s^{-1}$ over 67 days	Q_{WW} 2014 – 50% SO at Parempuyre

Table 2: Minimum simulated DO (in % of saturation and in mg.L^{-1}), the corresponding temperature and the number of hypoxia days in Bordeaux and Portets for each scenario. (WW: wastewater)

Scenarios		Bordeaux				Portets			
		T (°C)	DO_{min} (%)	DO_{min} (mg.L^{-1})	Days of hypoxia	T (°C)	DO_{min} (%)	DO_{min} (mg.L^{-1})	Days of hypoxia
	Reference	27.4	13.5	1.0	13	24.4	8	0.7	52
Management of wastewater discharges	**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 KP15	26.9	23.5	1.8	4	24.4	9.7	0.8	33
	Release moved to KP25	26.9	26.9	2.1	0	24.4	10	0.8	32
Support of low river flow	**+10 m^{3}s^{-1}**	26.9	13.8	1.1	13	24.4	12.7	1.0	29
	+20 m^3.s^{-1}	26.8	15.3	1.2	11	24.4	8.3	0.7	39
	+30 m^3.s^{-1}	26.8	17	1.3	11	24.4	8.3	0.7	40
	+100 m^3.s^{-1}	26.9	12.3	1.0	12	24.4	8.4	0.7	48
	+200 m^3.s^{-1}	27.4	14.5	1.1	10	24.4	8.3	0.7	44
	+400 m^3.s^{-1}	27.7	16.7	1.3	5	24.4	9.1	0.7	37
Combined options	**-50% +10 m^3.s^{-1}**	26.9	14.5	2	14	24.4	12.5	1	26
	-50% + KP15 +10 m^3.s^{-1}	26.9	24.9	2	2	26.9	14.1	1.1	22

Table 3: Differences (in %) of biogeochemical process rates impacting DO between the scenarios and reference simulations during summer in Bordeaux and Portets (WW: wastewater; WS: watershed)

Scenarios		Bordeaux				Portets			
		total	nitrification	mineralization TOC_{WS}	mineralization TOC_{WW}	total	nitrification	mineralization TOC_{WS}	mineralization TOC_{WW}
Management of wastewater discharges	WW of 2014	-1%	+11%	0	-13%	-1%	+4%	0	-16%
	-10%	-2%	+12%	0	-16%	-1%	+4%	0	-16%
	-20%	-3%	+13%	0	-20%	-1%	+6%	0	-23%
	-30%	-4%	+13%	+1%	-24%	-1%	+6%	+1%	-26%
	-40%	-5%	+14%	+1%	-28%	-1%	+6%	+1%	-29%
	-50%	-6%	+14%	+1%	-31%	-1%	+6%	+1%	-33%
	Release moved to KP15	-33%	-47%	+2%	-65%	-8%	-17%	-3%	-76%
	Release moved to KP25	-47%	-66%	+3%	-95%	-8%	-20%	-2%	-94%
Support of low river flow	+10 $m^3.s^{-1}$	1%	-6%	+6%	0	-2%	-20%	-1%	-4%
	+20 $m^3.s^{-1}$	0%	-6%	+5%	0	+1%	-14%	+2%	-2%
	+30 $m^3.s^{-1}$	0%	-6%	+4%	0	-2%	-13%	-2%	-3%
	+100 $m^3.s^{-1}$	0%	-2%	+2%	0	-5%	-4%	-5%	-3%
	+200 $m^3.s^{-1}$	0%	-5%	+4%	-1%	-9%	-10%	-9%	-6%
	+400 $m^3.s^{-1}$	0%	-11%	+9%	-1%	-13%	-14%	-13%	-8%
Combined options	-50% +10 $m^3.s^{-1}$	-2%	+10%	+11%	-30%	+2%	-9%	+5%	-36%
	-50% + KP15 +10 $m^3.s^{-1}$	-46%	-70%	+14%	-100%	-2%	-31%	+6%	-100%

Table 4: Summary of management solution efficiency and recommendations (WW: wastewater; WS: watershed)

Management solutions	Efficiency to mitigate hypoxia		Recommendation
	Lower TGR	Upper TGR	
SO reduction: -50%	++	+	Implementation of SOs
WW discharges at KP15	+++	+	WWTP outfall relocation
WW discharges at KP25	+++	+	WWTP outfall relocation
LTS	+	++	Preventive measures against hypoxia: reduction in freshwater subtraction during summer
STS	++	+++	Curative measures at spring tide during severe drought
LTS - SO reduction -50%	+	++	Reduction in freshwater subtraction during summer and implementation of SOs
LTS - SO reduction: -50% - WW discharges at KP15	+++	++	Reduction in freshwater subtraction during summer, implementation of SOs and WWTP outfall relocation

Figure 1: The Gironde-Garonne-Dordogne estuary, including the Tidal Garonne River in southwestern France (Inset B). "KP" denotes the distances in km from the city center of Bordeaux; the control grid cell at Bordeaux is at KP4 and Portets is at KP20. Insert A precises position of the sewage overflows (purple triangles) and of the two wastewater treatment plants (green squares). The area in orange represents the area of Bordeaux for which the biogeochemical fluxes were calculated.

Figure 1: Time series of Garonne River (black) and Dordogne River (gray) flow of the reference simulation (a & d, $m^3.s^{-1}$), wastewater discharges (WWTP±SO) for 2006 (green) and 2014 (blue) (b & e, $m^3.s^{-1}$). Comparison of simulated DOmin evolution (over tidal cycle in %sat) in Bordeaux with urban effluents of 2014 (blue) and with a 50% reduction in SOs (red) (c). The contribution on DO consumption (%) of degradation of watershed organic matter (brown), WWTP (red), SO (green) and nitrification (blue) in Bordeaux (f). For nitrification processes, ammonium comes from watershed and wastewater.

Figure 3: Snapshot of the vertical transect of simulated DO saturation along the Garonne tidal river for the scenarios with urban effluent discharge points in Bordeaux (a), KP15 (b) and KP25 (c). P1, P2 and P3 indicate the locations of Bec d'Ambès, Bordeaux and Portets, respectively. The contribution on DO consumption (%) of degradation of watershed (brown), WWTP (red), SO (green) and nitrification (blue) processes at Bordeaux (d). For nitrification processes, ammonium comes from watershed and wastewater.

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

Figure 5: Time series of river flow (top, $m^3.s^{-1}$), DOmin (over tidal cycle) at Bordeaux (middle, %sat) and DO at Portets (bottom, %sat) for the scenarios of short river flow increases by 100 $m^3.s^{-1}$ (a, d and g), 200 $m^3.s^{-1}$ (b, e and h) and 400 $m^3.s^{-1}$ (c, f and i). The blue line represents the simulation of reference.

Figure 6: Spatiotemporal evolution of daily average surface DO (saturation in %) along the Tidal Garonne River section for the scenarios of reference (a) combining +10 $m.s^{-1}$ of river flow and reduction of 50% of S0 releases (b), and +10 $m^3.s^{-1}$ of river flow, a reduction of 50% of SO releases and urban effluent discharges at KP15 (c). The y-axis represents the kilometric points, and the white lines represent Bordeaux and Portets.

Figure 1

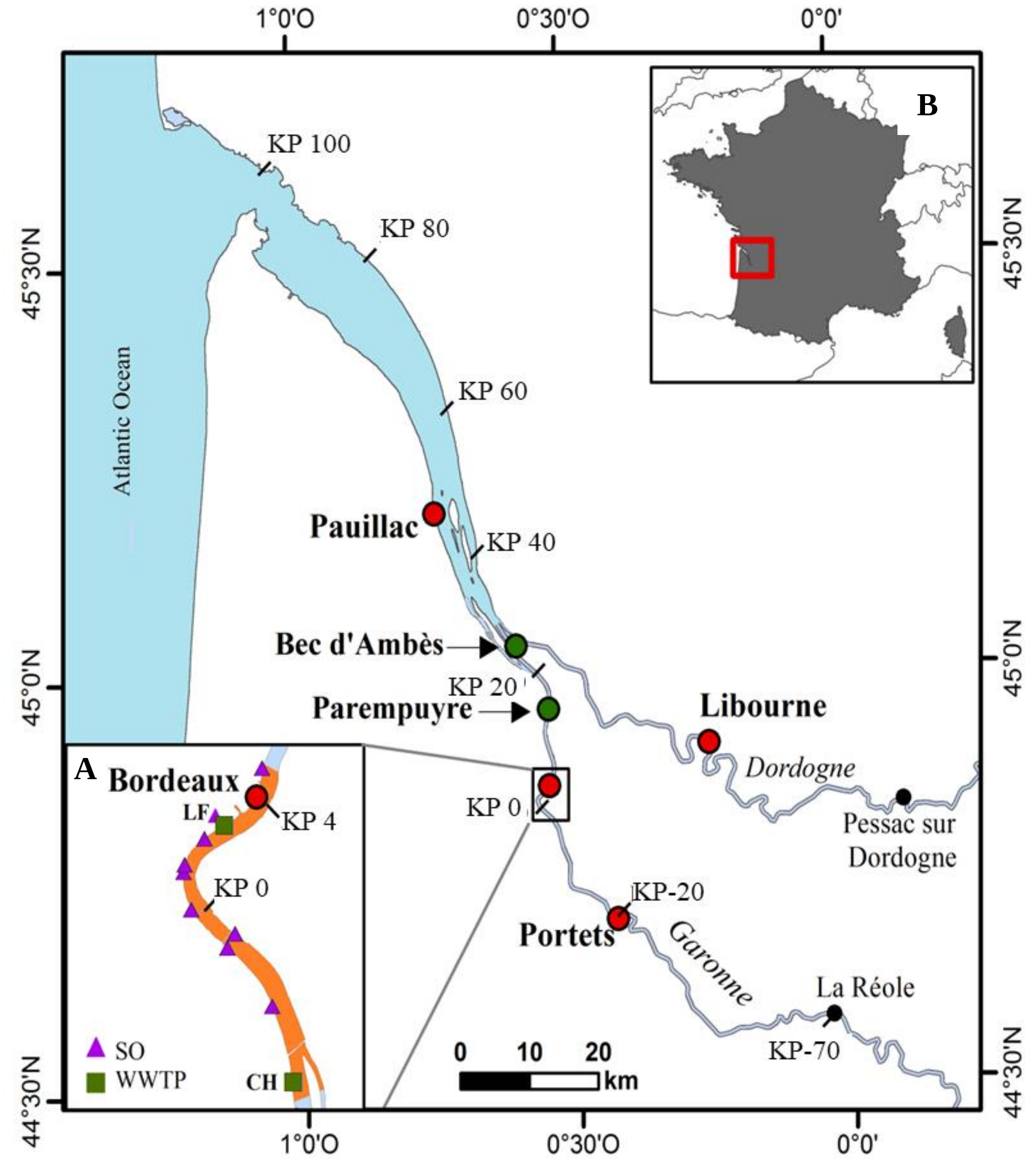

1°0'O
0°30'O
0°0'
45°30'N
45°0'N
44°30'N
B
Atlantic Ocean
KP 100
KP 80
KP 60
Pauillac
KP 40
Bec d'Ambès
KP 20
Parempuyre
Libourne
Dordogne
Pessac sur Dordogne
KP 0
KP-20
Portets
Garonne
La Réole
KP-70
0 10 20 km
A
Bordeaux
LF
KP 4
KP 0
SO
WWTP
CH

Figure 2

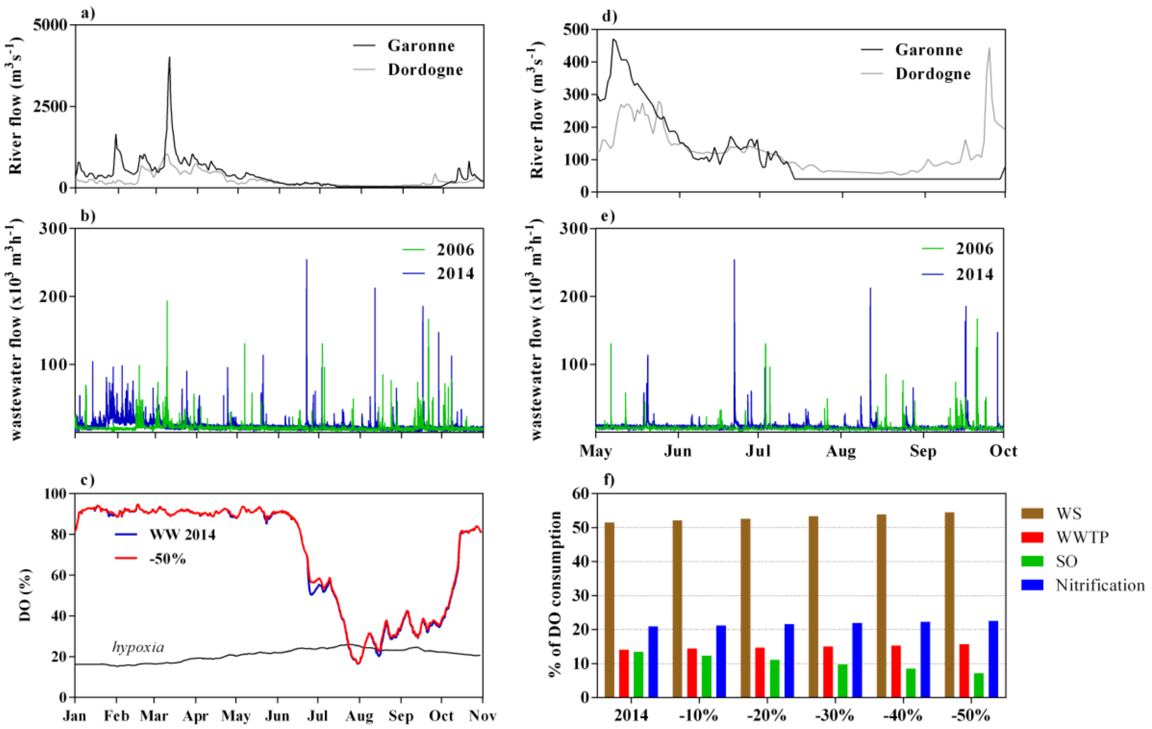
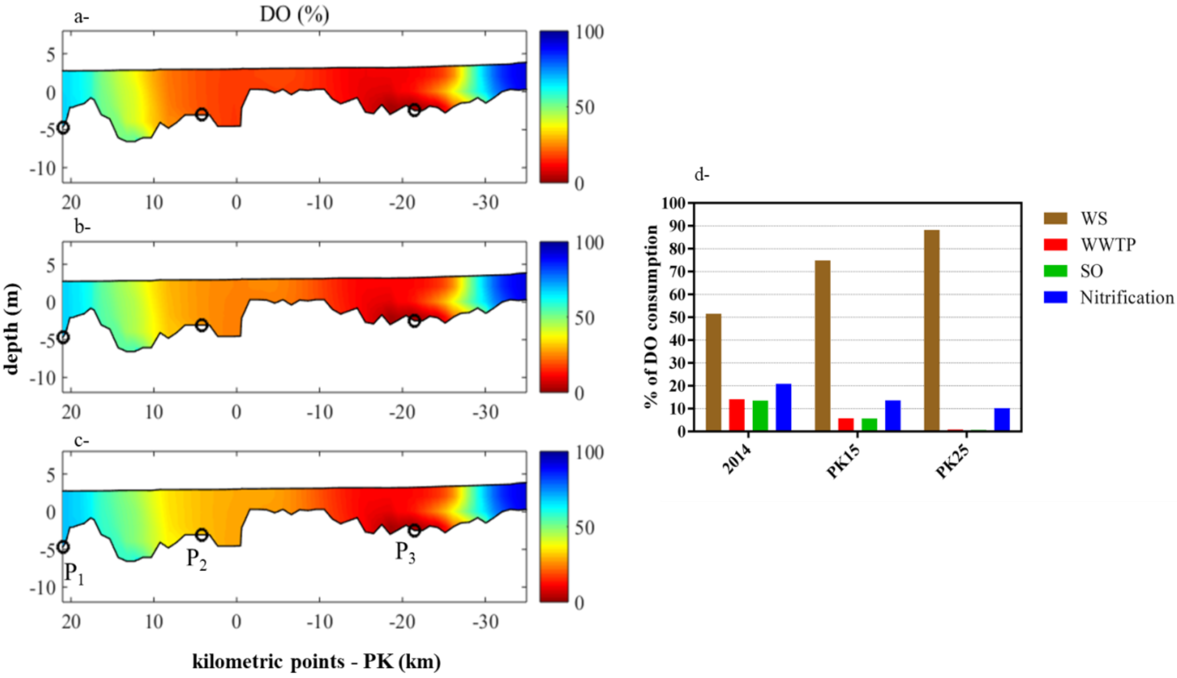
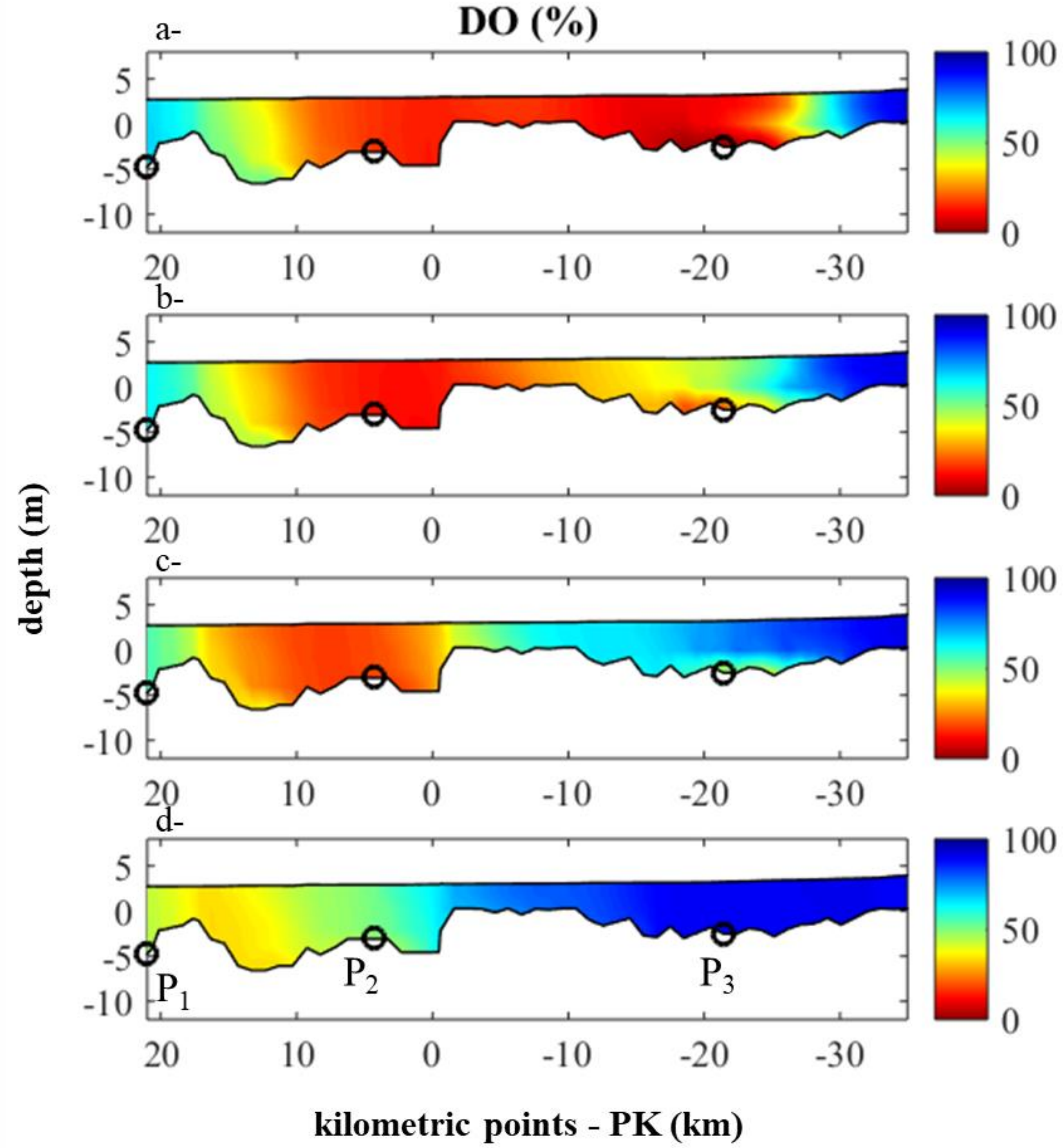

a)
River flow (m^3s^{-1})
5000
2500
0
Garonne
Dordogne
b)
wastewater flow ($x10^3$ m^3h^{-1})
300
200
100
2006
2014
c)
DO (%)
100
80
60
40
20
0
WW 2014
-50%
hypoxia
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
d)
River flow (m^3s^{-1})
500
400
300
200
100
0
Garonne
Dordogne
e)
wastewater flow ($x10^3$ m^3h^{-1})
300
200
100
2006
2014
May
Jun
Jul
Aug
Sep
Oct
f)
% of DO consumption
60
50
40
30
20
10
0
2014
-10%
-20%
-30%
-40%
-50%
WS
WWTP
SO
Nitrification

Figure 3



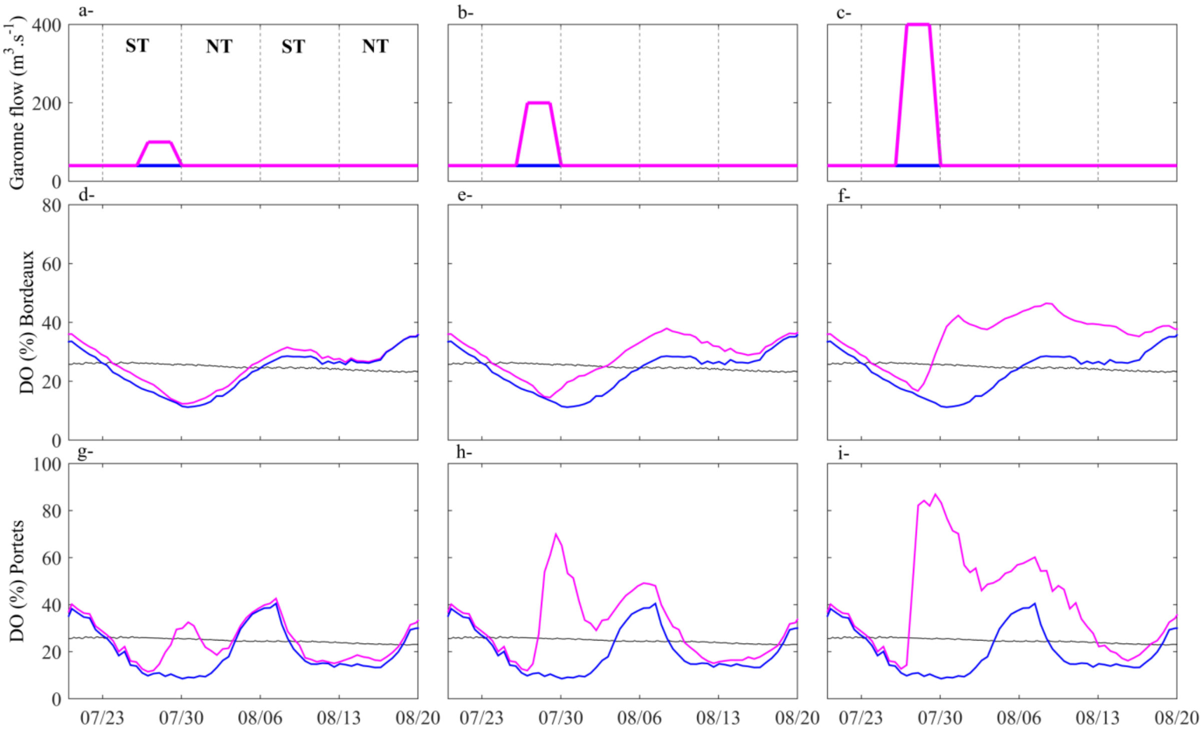
a-
DO (%)
b-
c-
depth (m)
kilometric points - PK (km)
P1
P2
P3
d-
% of DO consumption
2014
PK15
PK25
WS
WWTP
SO
Nitrification

Figure 4



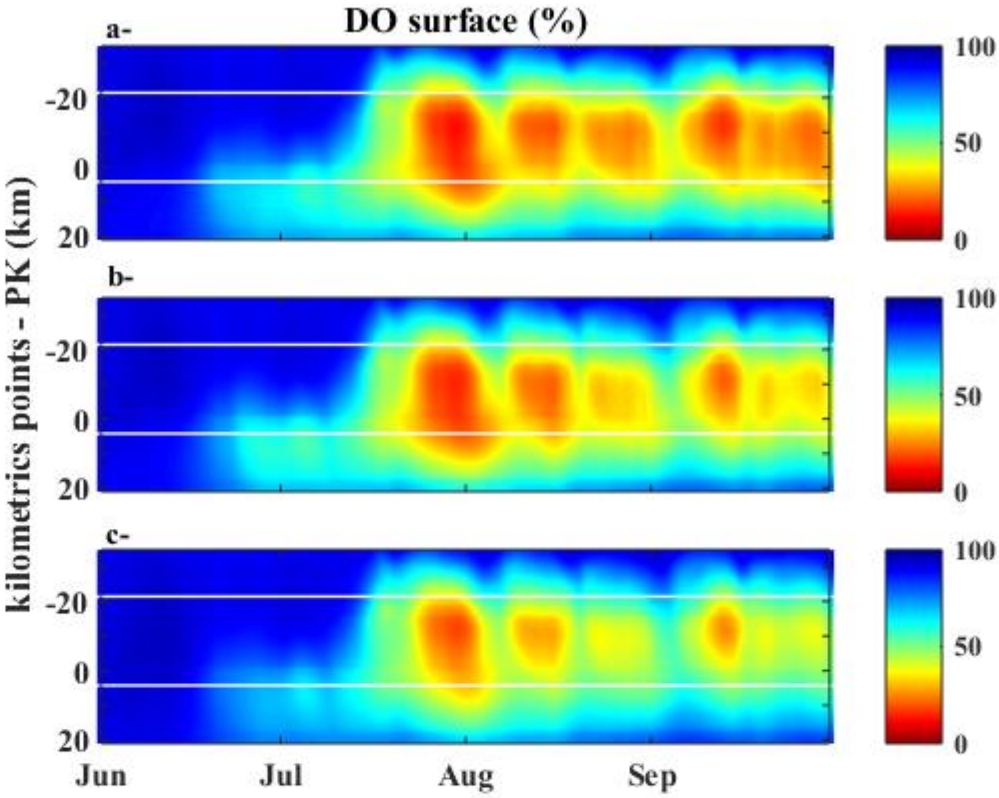
DO (%)
a-
b-
c-
d-
depth (m)
5
0
-5
-10
20
10
0
-10
-20
-30
100
50
0
P1
P2
P3
kilometric points - PK (km)

Figure 5



a-
b-
c-
ST
NT
ST
NT
Garonne flow (m^3.s^{-1})
400
200
0
d-
e-
f-
DO (%) Bordeaux
80
60
40
20
0
g-
h-
i-
DO (%) Portets
100
80
60
40
20
0
07/23
07/30
08/06
08/13
08/20

Figure 6


DO surface (%)
a-
b-
c-
kilometrics points - PK (km)
-20
0
20
100
50
0
Jun
Jul
Aug
Sep