Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2018-381
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 28 January 2019

Natural Hazards and Earth System Sciences
Open Access
Discussions

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

Katixa Lajaunie-Salla[1,2,*], Aldo Sottolichio[1], Sabine Schmidt[1], Xavier Litrico[2], Guillaume Binet[2], Gwenaël Abril[1,3,4].

[1] Laboratoire EPOC, Environnements et Paléoenvironnements Océaniques et Continentaux UMR 5805, CNRS – Université de Bordeaux – Pessac, France

[2] LyRE, SUEZ research center, Bordeaux, France

[3] Programa de Geoquímica, Universidade Federal Fluminense, Niterói, RJ, Brazil.

[4] Biologie des Organismes et Ecosystèmes Aquatiques (BOREA), UMR 7208, Muséum National d'Histoire Naturelle, CNRS, Sorbonne Université, Université de Caen Normandie, Université des Antilles, IRD, Paris, France.

* Now at Aix Marseille Université, CNRS/INSU, Université de Toulon, IRD, Mediterranean Institute of Oceanography (MIO) UMR 7294

Corresponding Author: katixa.lajaunie-salla@mio.osupytheas.fr

Acknowledgments

This study was funded by the Aquitaine Region (DIAGIR project) and LyRE (SUEZ research center) who co-sponsored a PhD grant to K. Lajaunie-Salla. This work was also supported by the Cluster of Excellence COTE at the Université de Bordeaux (ANR-10-LABX-45). The authors are grateful to the MAGEST network for the availability of data and to the SGAC and Bordeaux Metropole for providing urban effluent data and fruitful discussions. This work was supported by the Avakas cluster resources of the Mésocentre de Calcul Intensif Aquitain (MCIA) of the University of Bordeaux

Highlights

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

Abbreviations

DO: dissolved oxygen
DOC: dissolved organic carbon
LTS: long-term support
NT: Neap tide
POC: particulate organic carbon
SO: sewage overflow
ST: Spring tide
STS: short-term support
TGR: Tidal Garonne River
TMZ: turbidity maximum zone
WS: watershed
WW: wastewater
WWTP: wastewater treatment plant

Abstract

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

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

1 Introduction

In view of the ongoing global change, it is essential to find management strategies for hypoxia mitigation (dissolved oxygen (DO) concentration < 2 $mg.L^{-1}$ or < 30% of saturation, Rabalais et al. (2010)). Coastal hypoxia is a widespread phenomena since the middle of the 20th century due to the combined effect of the increase in temperature and anthropogenic activities (Breitburg et al., 2018). Hypoxia is a major environmental issue, which stresses marine organisms and perturbs the functioning of coastal ecosystem (Vaquer-Sunyer and Duarte, 2008). Due to their strategic position for fish migration, a good oxygenation of estuarine waters is crucial (Rabalais et al., 2010). Usually, coastal and transitional zones receive increasing organic matter and nutrients inputs from watershed and urban effluents, that lead to an extension of eutrophic and hypoxic areas (Diaz, 2001). In macrotidal estuaries, the DO consumption by heterotroph processes is exacerbated by the presence of a turbidity maximum zone (TMZ) which limits primary production (Goosen et al., 1999). Estuarine deoxygenation is the result of the complex interaction of several environmental factors such as temperature, river flow, the quantity of urban effluents discharged in the aquatic system, high turbidity and sediment dynamics (Talke et al., 2009). For that reason , recovering or maintaining 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, a first obvious action to mitigate hypoxia is to improve urban wastewater network and treatment and to reduce the input of organic matter and nutrients to the estuary. In several European estuaries undergoing urban inputs, water quality improvement were achieved: in the Thames Estuary since the installation and renovation of a wastewater treatment plant (WWTP) in 1980s (Andrews and Rickard, 1980; Tinsley, 1998), in the Seine River since the construction of a WWTP in 1990s (Billen et al., 2001). In the

Scheldt Estuary, the sewage network was also improved and two WWTPs were 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 the urban sewage and stormwater collection. During heavy rain and storm events, the capacity of 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 network in real time to regulate flow and avoid overflow of untreated wastewater (EPA, 2006; Gonwa, 1993). This control was developed in several cities, such as Québec (Pleau et al., 2005) or Tokyo (Maeda et al., 2002). An additional management solution was tested in the Thames Estuary: the construction of a 24-km long outfall under the riverbed, which 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 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 therefore could be to modify the local residual circulation and to reduce water flushing time, to promote the renewal of well-oxygenated waters, and/or the seaward dispersion of oxygen-consuming material (Lajaunie-salla et al., 2018). This implies to provide 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).

In order to optimize preventive management strategy, the efficiency of the potential solutions needs to be evaluated. For that, numerical modelling is an efficient tool to assess quantitatively hypoxia mitigation by management scenarios. Moreover, models allow to provide guidelines for setting objectives to maintain a good water quality of coastal environment (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 few hypoxia events have been reported, for example during summer 2006 (Lanoux et al., 2013). Previous work highlighted that these low DO level are due to the combination of the presence of TMZ high water temperature, drought periods and urban effluents inputs (Lajaunie-Salla et al., 2017; Lanoux et al., 2013; Schmidt et al., 2017). Such a perspective of a permanent summer hypoxia in the lower TGR implies 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 urban wastewater network and fresh water replenishment during low water periods.

2 Materials and Methods

2.1 Study Area

The Garonne River, located in Southwest of 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 macro-tidal fluvio-estuarine system is characterized by the presence of a TMZ, where suspended sediment concentration in surface waters are > 1 $g.L^{-1}$ (Allen, 1972). The position of the TMZ varies seasonaly : during low river flow it is present in the Tidal Garonne River, from PK25 to PK-70 (Fig.1). The rest of the year, the TMZ is located around Pauillac (Fig.1) at downstream of the Gironde Estuary (Jalón-Rojas et al., 2015)

The annual mean Garonne River flow is 680 m^3s^{-1} for the period 1913-2018, with the highest values in winter (mean of 720 $m^3.s^{-1}$) and the lowest in summer and early automn (mean of 190 $m^3.s^{-1}$) (http://www.hydro.eaufrance.fr/indexd.php). Since mid 80s, there has been an increase in the number of days with a river flow below 110 m^3s^{-1} (Etcheber et al., 2013). Such a decrease in the Garonne flow limits the reoxygenation of TGR waters with well-oxygenated freshwaters and favours the upstream advection and the concentration of TMZ (Lajaunie-salla et al., 2018). Six water reservoirs are located in the upper Garonne River, which can store a maximum water volume of 58 hm^3: this volume corresponds to an equivalent river flow of 95 m^3s^{-1} during one week. This water storage is used to maintain the Garonne discharge above the critical thresholds for the ecosystem during 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 drains an urban area of 578 km² and serves a population estimated at 749 595 inhabitants in 2015. The part of the sewage system is composed of a combined sewer network: two wastewater treatment plants (WWTP), Clos de Hilde and Louis Fargue, and nine sewage overflows (SO). The continuous releases of treated and untreated wastewaters represent up to 1.5 % of the fluvial Garonne discharge (Lanoux et al., 2013).

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 a real time control of urban drainage network was developed in order to reduce urban effluents during rainy weather (Andréa et al., 2013). This system had allowed to decrease the volume of untreated wastewater released by 30% in 2013 and 40% in 2014 and 2015 (Robitaille et al., 2016), improving the overall net epuration 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 and its avalidation is presented in detail in Lajaunie-Salla et al. (2017). Briefly, the transport model solves the advection/dispersion equations for dissolved and particulate variables, i.e. suspended sediment, salinity and biogeochemical variables. The biogeochemical model includes all the processes that produce and consume oxygen in the water column, taking into account different types of dissolved and particulate organic matters: 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 use measured water temperature (MAGEST network; Etcheber et al. (2011), https://twitter.com/Gironde_Magest), wind and incident light intensity (Météo France). Urban wastewater discharges are included in the model (Fig.1).

The reference simulation is based on the real conditions of year 2006, which was a critical year from the point of view of river discharge, temperature and hypoxia. A 21-days heat wave occured 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^3s^{-1} from July 15 to September 30, which is different from the real river flow recoreded, but helps to visualize the impact of potential solutions on oxygenation (Fig.2a). However, we used urban effluents time series of 2014, as the WWTP rehabilitation in 2011 permitted to reduce the percentage of SO discharge (12% in 2014; 16% in 2006).

2.3 The scenarios

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

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

- the increase of wastewater storage during heavy rains. For this, a fraction of 10, 20, 30, 40 and 50%, of untreated wastewater SO was transferred to WWTP discharges;
- the implementation of an outfall, that releases urban effluents downstream. Two wastewater discharge points were tested: at 11 km (PK15) and 21 km (PK25) downstream Bordeaux (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 available volume of stored water (Tab.2):

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

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

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

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

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

3 Results

3.1 Action 1: Wastewater management

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

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

For the scenario SO-50%, there is a slight increase of 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 to 7% of total DO consumption with the reduction of 50% against 13% without reduction (Fig.2d). In addition, the contribution of WWTP matter degradation represents 16% when untreated water discharge is reduced by 50%, against 14% without reduction (Fig.2d). In contrast, the nitrification process is slighty increased by the reduction of SO flow (Tab.3) because the wastewater removed from SOs is transferred to WWTPs, which are enriched in ammonia compared to SOs (Lanoux, 2013).

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

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

In the case of a relocation of urban effluents discharge at PK15, only 4 days of hypoxia are 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 case of a relocation of urban effluents discharge more downstream at PK25, the model simulates no hypoxia and a minimum DO value of 2.1 mg.L^{-1} (Tab.2). According to the model, the displacement of the urban wastewater discharge point downstream shows a significant improvement of oxygen levels in the TGR around Bordeaux (Tab.2 & Fig.3) and appears to be an efficient action to mitigate hypoxia near Bordeaux (Fig.3). Under these relocation scenarios, the amount of urban organic matter and ammonia are lower at Bordeaux. Urban effluents are diluted by downstream estuarine waters and exported toward the Gironde. In fact, urban matters reach the city of Pauillac, about 50 km downstream Bordeaux (Fig. 1) after 1 and 1.5 days when effluents are released at PK25 and PK15, respectively, against 2.5 days when they are discharged near Bordeaux. With the relocation of urban discharge downstream, DO levels are strongly improved in the TGR, without significantly altering the oxygenation condition downstream. This is due to shorter residence times and larger dilution with oxygenated estuarine waters downstream.

A downstream relocation (PK15 or PK25) 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 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 PK 15 and PK25, respectively (Tab.3). In fact the mineralization of urban matter occurs downstream of TGR with little impact on DO due to dilution effect with estuarine waters. Finally, at Bordeaux the contribution of urban effluents on DO consumption decreases from 27% to 2% and nitrification from 20% to 10% (Fig. 3d).

The discharge of wastewater downstream city center improves considerably 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 very high turbidities 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 of DO_{min} not only at Portets, but also at Bordeaux (Tab.2). At Bordeaux, the DO_{min} increases only by 0.3 mg.L^{-1} and the number of simulated hypoxia days decreases only by 2 days for a discharge increase of 30 m^{3}s^{-1}. However in Portets, oxygen levels are much more improved: the additional flows reduce significantly the number of hypoxic days: it drops from 52 days (reference simulation) to 29, 39 days or 40 days for a support of 10, 20 or 30 m^{3}s^{-1} respectively (Tab2).

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

These simulations show that a low-intensity and long-term support of river flow reduces considerably hypoxia events in the upper TGR, but not sufficiently to influence significantly Bordeaux waters. The average time to renew half of the water volume in Bordeaux is 22 and 67 days in 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 good oxygen level during all summer in the upper TGR. An addional river flow > 10 m^{3}s^{-1} during two months will be a feasibly solution to avoid hypoxia events upstream Bordeaux, and freshwater storage should be optimized to reach these objectives.

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

An intense and short-term support (STS) of freshwater 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). Model results show a decrease of the number of hypoxia days in Bordeaux and Portets (Tab.2). Water half-renewal times are less than 1 day at Portets, and decrease from 6.6 to 1.6 at Bordeaux with increasing discharge support from 100 to 400 m^{3}s$^-$

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

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

Intense STS (400m^3s^{-1}) is not able to maintain good level of oxygen all summer long. After the massive water input, DO level stays above the hypoxia threshold during one or two weeks only and then decreases again (Fig.5). This type of management is very powerful as an urgent remediation during a severe hypoxia to improve quickly the oxygenation levels of TGR waters, more particularly in the upper section of the tidal river. For example, during the heat wave of end-July 2006 (Fig.2c), STS would have avoided hypoxia. In the case of a late hypoxia occuring at the end of the summer, STS may be efficient if the stored water volume is sufficient.

3.3 Synthesis of management actions efficiency

These different simulated scenarii allow us to estimate quantitatively the efficiency of different options of management to reduce hypoxia in the TGR. The two management solutions have locally different impacts on DO (Tab.4): optimization of urban wastewater network reduces hypoxia in the lower TGR, whereas the water replenishment during low water periods enhances DO levels in the upper TGR. The improvement of wastewater network by a reduction of labile organic matter input reduces oxygen consumption in Bordeaux waters. The alternative, consisting in discharging urban effluents downstream the lower TGR, has the advantage to dilute wastewater with the Gironde water and to favor 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, about 1-2°C, than at Bordeaux. The water replesnishment 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. The scenario combining an increase of 10 m^3s^{-1} of the Garonne River flow, a reduction of 50% of SO releases and discharge of urban effluents at PK15 suggests an improvement of water quality over the entire TGR (Fig.6): only 2 days below the hypoxia thereshold (Tab.2) and the oxygen consumption by urban matter degradationis totally reduced (Tab.3).

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

4 Conclusion

The 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 of waters. This study tested different scenarios of management solutions that can be implemented by local water autorithies to maintain the best water quality as possible. Whereas a reduction of SO flows contributes only to improve localy and temporary DO levels, the downstream relocation of WWTP outfalls totally mitigates hypoxia in 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 TMZ upstream of the TGR and dilutes estuarine waters with fresh oxygenated waters. A low-intensity support over the summer maintains a good oxygen level of waters during all the drought period and prevents hypoxia in the upper TGR. In contrast, an intense support of low water flow during 3 days improves quickly and considerably oxygen levels along the entire TGR, but only during few weeks. The improvement of urban effluents network and the support of low river flow periods from dams, or irrigation reduction, are complementary. They contribute to reoxygenate waters near the city of Bordeaux and upstream of Tidal Garonne River, respectively. The biogeochemical numerical model turns out helpful to guide management policy of urban effluents and watershed, in order to limit and mitigate hypoxia events.

References

Allen, G. P.: Étude des processus sédimentaires dans l’estuaire de la Gironde, Université de

Bordeaux., 1972.

Andréa, G., Ahyerre, M., Pérarnaud, M., Komorowski, F. and Schoorens, J.: Gestion Dynamique des RUTP du bassin versant Louis Fargue à Bordeaux: mise en oeuvre et premiers résultats opérationnels, NOVATECH 2013., 2013.

Andrews, M. J. and Rickard, D. G.: Rehabilitation of the inner Thames estuary, Mar. Pollut. Bull., 11(11), 327–332, doi:10.1016/0025-326X(80)90051-X, 1980.

Best, M. A., Wither, A. W. and Coates, S.: Dissolved oxygen as a physico-chemical supporting element in the Water Framework Directive, Mar. Policy, 55, 53–64, doi:10.1016/j.marpolbul.2006.08.037, 2007.

Billen, G., Garnier, J., Ficht, A. and Cun, C.: Modeling the Response of Water Quality in the Seine River Estuary to Human Activity in its Watershed Over the Last 50 Years, Estuaries, 24(6B), 977–993, doi:10.2307/1353011, 2001.

Billen, G., Garnier, J. and Rousseau, V.: Nutrient fluxes and water quality in the drainage network of the Scheldt basin over the last 50 years, Hydrobiologia, 540(1), 47–67, doi:10.1007/s10750-004-7103-1, 2005.

Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G. S., Limburg, K. E., Montes, I., Naqvi, S. W. A., Pitcher, G. C., Rabalais, N. N., Roman, M. R., Rose, K. A., Seibel, B. A., Telszewski, M., Yasuhara, M. and Zhang, J.: Declining oxygen in the global ocean and coastal waters, Science (80-.)., 359(February), doi:10.1126/science.aam7240, 2018.

Diaz, R. J.: Overview of hypoxia around the world., J. Environ. Qual., 30(2), 275–281, doi:10.2134/jeq2001.302275x, 2001.

EPA: Real time control of urbain drainage networks, Washington, Office of Research and Development., 2006.

Etcheber, H., Schmidt, S., Sottolichio, A., Maneux, E., Chabaux, G., Escalier, J.-M., Wennekes, H., Derriennic, H., Schmeltz, M., Quéméner, L., Repecaud, M., Woerther, P. and Castaing, P.: Monitoring water quality in estuarine environments: lessons from the MAGEST monitoring program in the Gironde fluvial-estuarine system, Hydrol. Earth Syst. Sci., 15(3), 831–840, doi:10.5194/hess-15-831-2011, 2011.

Etcheber, H., Coupry, B., Coynel, A., Sauquet, E., Baron, J., Bernard, C., Cuende, F. X. and Leurent, T.: Disponibility of surficial continental waters, in Impact of climate change in the

Aquitaine region. Scientific Report., edited by H. Le Treut, p. 365, Pessac., 2013.

Even, S., Mouchel, J. M., Servais, P., Flipo, N., Poulin, M., Blanc, S., Chabanel, M. and Paffoni, C.: Modelling the impacts of Combined Sewer Overflows on the river Seine water quality, Sci. Total Environ., 375(1–3), 140–151, doi:10.1016/j.scitotenv.2006.12.007, 2007.

Gonwa, W.: Efficient Real Time Control and Operation of Interconnected Wastewater Collection Systems, Marquette University., 1993.

Goosen, N. K., Kromkamp, J., Peene, J., Rijswijk, P. van and Breugel, P. van: Bacterial and phytoplankton production in the maximum turbidity zone of three European estuaries: the Elbe, Westerschelde and Gironde, J. Mar. Syst., 22, 151–171, 1999.

Jalón-Rojas, I., Schmidt, S. and Sottolichio, A.: Turbidity in the fluvial Gironde Estuary (southwest France) based on 10-year continuous monitoring: sensitivity to hydrological conditions, Hydrol. Earth Syst. Sci., 19(2001), 2805–2819, doi:10.5194/hess-19-2805-2015, 2015.

Kemp, W. M., Testa, J. M., Conley, D. J., Gilbert, D. and Hagy, J. D.: Coastal hypoxia responses to remediation, Biogeosciences Discuss., 6, 6889–6948, doi:10.5194/bgd-6-6889-2009, 2009.

Lajaunie-salla, K., Sottolichio, A., Schmidt, S., Litrico, X., Binet, G. and Abril, G.: Future intensification of summer hypoxia in the tidal Garonne River (SW France) simulated by a coupled hydro sedimentary-biogeochemical model, Environ. Sci. Pollut. Res., doi:10.1007/s11356-018-3035-6, 2018.

Lajaunie-Salla, K., Wild-Allen, K., Sottolichio, A., Thouvenin, B., Litrico, X. and Abril, G.: Impact of urban effluents on summer hypoxia in the highly turbid Gironde Estuary , applying a 3D model coupling hydrodynamics , sediment transport and biogeochemical processes, J. Mar. Syst., 174, 89–105, doi:10.1016/j.jmarsys.2017.05.009, 2017.

Lanoux, A.: Caratérisation et rôle respectif des apports organiques amont et locaux sur l’oxygènation des eaux de la Garonne estuarienne, Université de Bordeaux., 2013.

Lanoux, A., Etcheber, H., Schmidt, S., Sottolichio, A., Chabaud, G., Richard, M. and Abril, G.: Factors contributing to hypoxia in a highly turbid, macrotidal estuary (the Gironde, France), Environ. Sci. Process. Impacts, 15(3), 585–595, doi:10.1039/c2em30874f, 2013.

Maeda, M., Mizushima, H. and Ito, K.: Development of the Real-Time Control (RTC) System for Tokyo Sewage System, Glob. Solut. Urban Drain., 1–16, doi:doi:

10.1061/40644(2002)317, 2002.

Pleau, M., Colas, H., Lavallée, P., Pelletier, G. and Bonin, R.: Global optimal real-time control of the Quebec urban drainage system, Environ. Model. Softw., 20(4), 401–413, doi:http://dx.doi.org/10.1016/j.envsoft.2004.02.009, 2005.

Rabalais, N. N., Levin, L. A., Turner, R. E., Gilbert, D. and Zhang, J.: Dynamics and distribution of natural and human-caused coastal hypoxia, Biogeosciences, 7, 585–619, doi:10.5194/bgd-6-9359-2009, 2010.

Robitaille, L., Komorowski, F., Fortier, V., Chadoutaud, E. and Rousseau, J.-P.: Gestion Dynamique des RUTP du bassin versant Louis Fargue à Bordeaux: en route vers une seconde phase de déploiement, NOVATECH 2016., 2016.

Schmidt, S., Bernard, C., Escalier, J.-M., Etcheber, H. and Lamouroux, M.: Assessing and managing the risks of hypoxia in transitional waters: a case study in the tidal Garonne River (South-West France), Environ. Sci. Pollut. Res., doi:10.1007/s11356-016-7654-5, 2017.

Skerratt, J., Wild-Allen, K., Rizwi, F., Whitehead, J. and Coughanowr, C.: Use of a high resolution 3D fully coupled hydrodynamic, sediment and biogeochemical model to understand estuarine nutrient dynamics under various water quality scenarios, Ocean Coast. Manag., 83, 52–66, doi:10.1016/j.ocecoaman.2013.05.005, 2013.

Soetaert, K., Middelburg, J. J., Heip, C., Meire, P., Van, S., Maris, T. and Damme, S. Van: Long-term change in dissolved inorganic nutrients in the heterotrophic Scheldt estuary (Belgium, The Netherlands), Limnol. Oceanogr., 51(1), 409–423, 2006.

Talke, S. A., Swart, H. E. and de Jonge, V. N.: An Idealized Model and Systematic Process Study of Oxygen Depletion in Highly Turbid Estuaries, Estuaries and Coasts, 32(4), 602–620, doi:10.1007/s12237-009-9171-y, 2009.

Taverny, C., Elie, P. and Boét, P.: La vie piscicole dans les masses d’eau de transition : Proposition d’une grille de qualité pour la température, l’oxygène dissous, la salinité et la transparence., 2009.

Tinsley, D.: The Thames estuary: a history of the impact of humans on the environment and a description of the current approach to environmental management, in A Rehabilitated Estuarine Ecosystem SE - 2, edited by M. Attrill, pp. 5–26, Springer US., 1998.

Vanderborght, J.-P., Folmer, I. M., Aguilera, D. R., Uhrenholdt, T. and Regnier, P.: Reactive-transport modelling of C, N, and O2 in a river–estuarine–coastal zone system: Application to the Scheldt estuary, Mar. Chem., 106(1–2), 92–110, doi:10.1016/j.marchem.2006.06.006, 2007.

Vaquer-Sunyer, R. and Duarte, C. M.: Thresholds of hypoxia for marine biodiversity., Proc. Natl. Acad. Sci. U. S. A., 105(40), 15452–15457, doi:10.1073/pnas.0803833105, 2008.

Zhang, P., Pang, Y., Pan, H., Shi, C., Huang, Y. and Wang, J.: Factors Contributing to Hypoxia in the Minjiang River Estuary, Southeast China, Int. J. Environ. Res. Public Health, 12(8), 9357–9374, doi:10.3390/ijerph120809357, 2015.

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

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 PK15	Qref	Q_{WW} 2014 at Parempuyre
	Realease moved to PK25	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% + PK15 +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.

Scenarios		Bordeaux				Portets			
		T (°C)	DO_{min} (%)	DO_{min} (mgL^{-1})	Days of hypoxia	T (°C)	DO_{min} (%)	DO_{min} (mgL^{-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 PK15	26.9	23.5	1.8	4	24.4	9.7	0.8	33
	Realease moved to PK25	26.9	26.9	2.1	0	24.4	10	0.8	32
Support of low river flow	**+10 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% + PK15 +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

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 PK15	-33%	-47%	+2%	-65%	-8%	-17%	-3%	-76%
	Realease moved to PK25	-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% + PK15 +10 $m^3 s^{-1}$	-46%	-70%	+14%	-100%	-2%	-31%	+6%	-100%

Table 4: Summary of management solutions efficiency and recommandations

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

Figure 1: The Gironde-Garonne-Dordogne estuary including the Tidal Garonne River in the southwestern France (Inset B). "PK" denotes the distances in km from the city center of Bordeaux; the control grid cell at Bordeaux is at PK-4 and Portets is at PK-20. The insert A precises the position of 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 2: Time series of Garonne River (black) and Dordogne River (grey) flow of the reference simulation (a, m^3s^{-1}), wastewater discharges (WWTP+SO) for year 2006 (green) and 2014 (blue) (b, m^3s^{-1}). Comparison of simulated DO_{min} evolution (over tidal cycle in %sat) in Bordeaux with urban effluents of 2014 (blue) or 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 (d). For nitrification processes, ammonium is coming from watershed and wastewater.

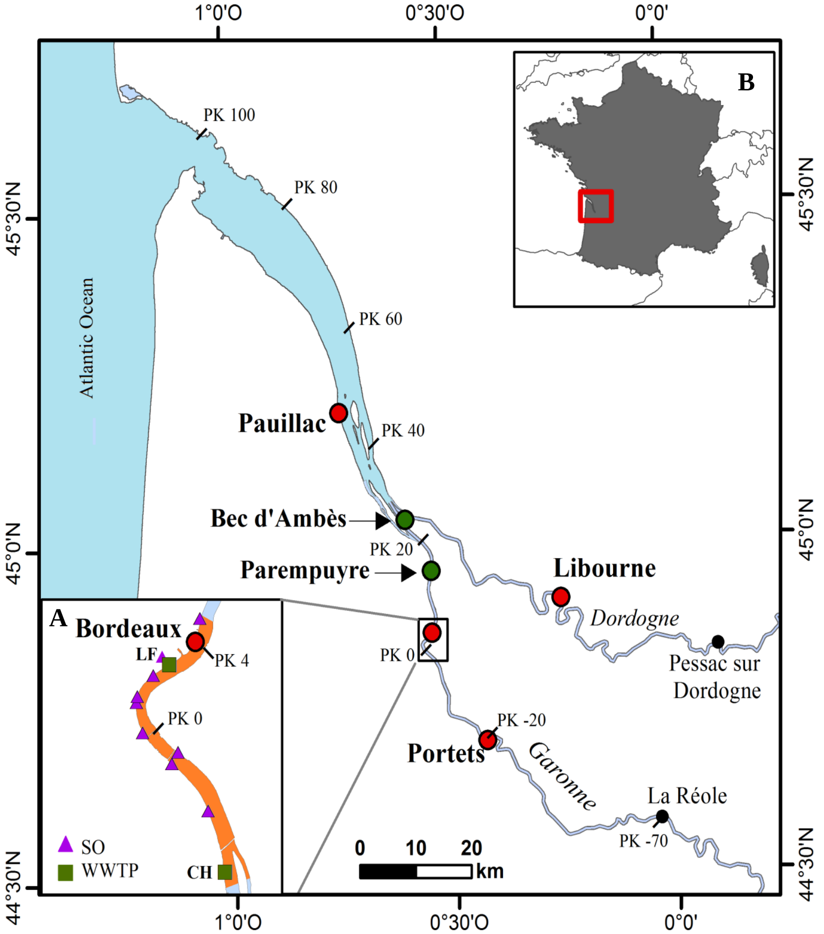
Figure 3: Snapshot of the vertical transect of simulated DO saturation along the Garonne tidal river for the scenarios with an urban effluents discharges points in Bordeaux (a), at PK15 (b) and at PK25 (c). P1, P2 and P3 indicate the locations of Bec d'Ambès, Bordeaux and Portets, respectively. The contribution on DO consumption (%) of degradation of watershed (brown), WWTP (red), SO (green) and nitrification (blue) processes at Bordeaux (d). For nitrification processes, ammonium is coming 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^3s^{-1} (b), 200 m^3s^{-1} (c) and 400 m^3s^{-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^3s^{-1}), DO 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: Spatiotemporal evolution of daily average surface DO (saturation in %) along the Tidal Garonne River section for the scenarios of reference (a) combining +10 m^3s^{-1} of river flow and reduction of 50% of S0 releases (b), and +10 m^3s^{-1} of river flow, a reduction of 50% of SO releases and urban effluents discharges at PK15 (c). The y-axis represents the kilometric points, and the white lines represent Bordeaux and Portets.

515 **Figure 1**



516

Figure 2

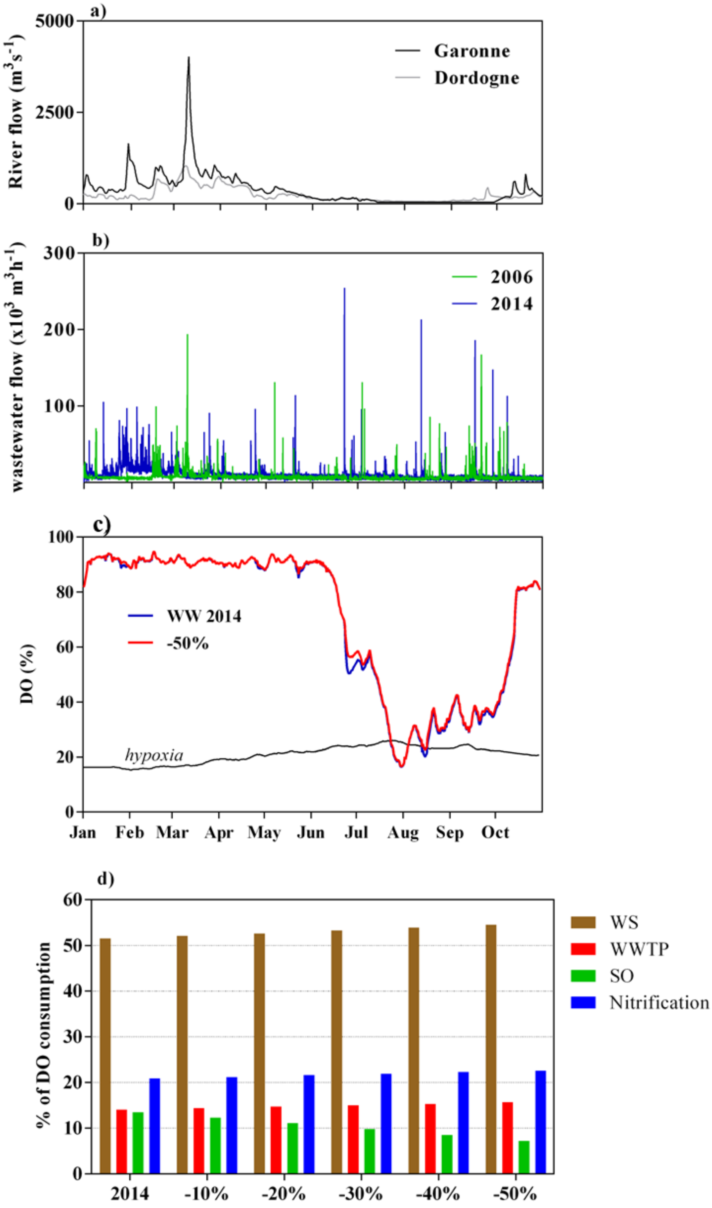
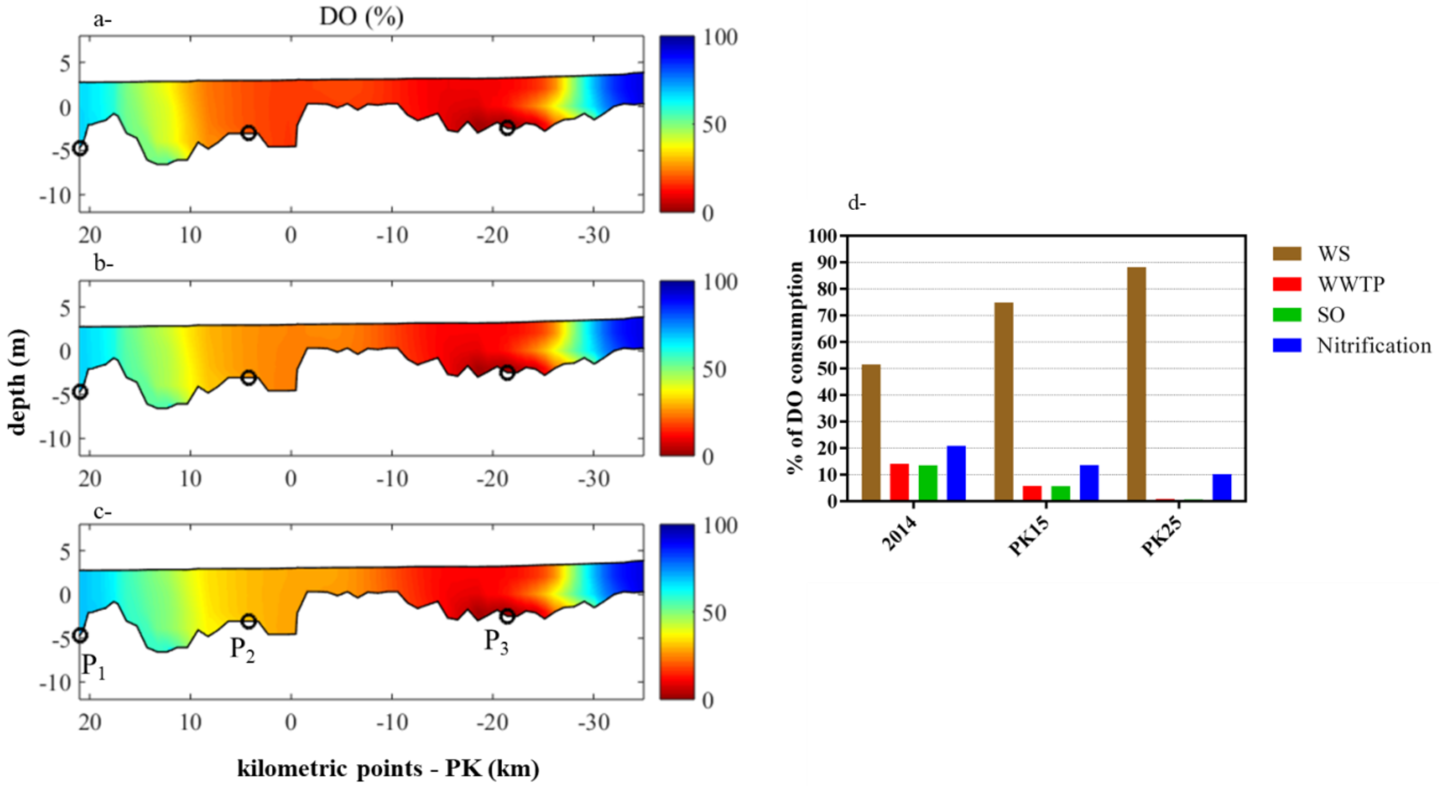
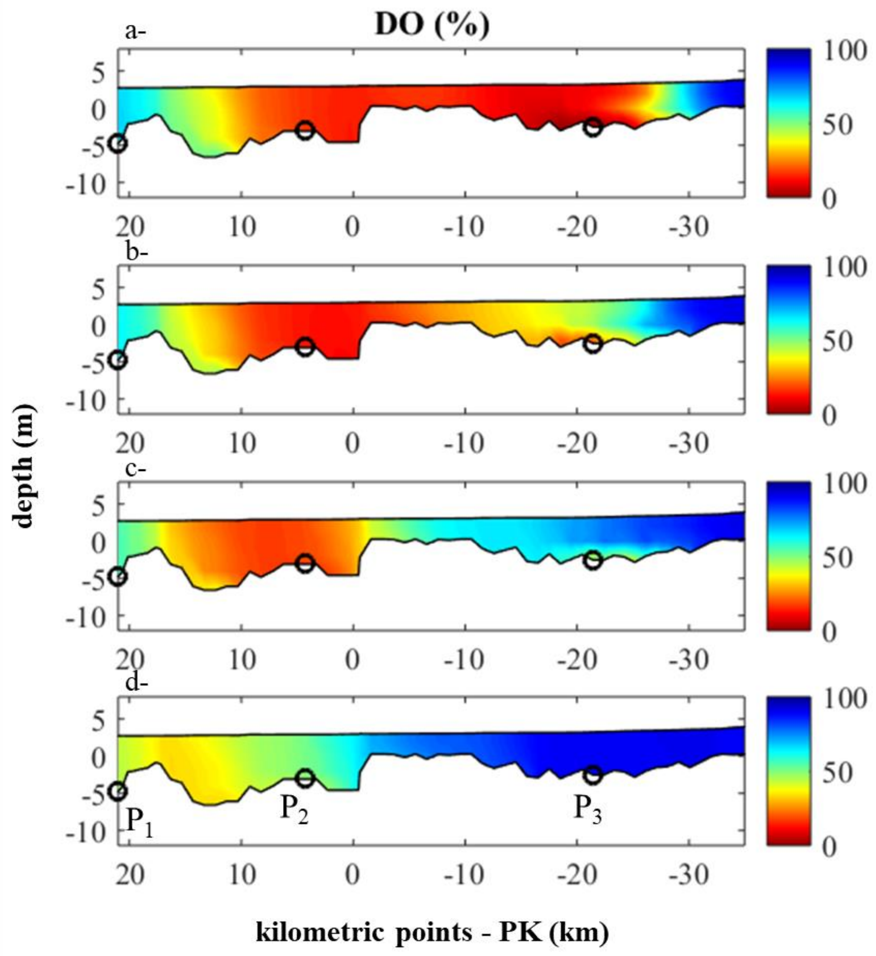

a)
River flow (m^3 s^{-1})
5000
2500
0
Garonne
Dordogne
b)
wastewater flow (x10^3 m^3 h^{-1})
300
200
100
2006
2014
c)
DO (%)
100
80
60
40
20
0
WW 2014
-50%
hypoxia
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
d)
% of DO consumption
60
50
40
30
20
10
0
2014
-10%
-20%
-30%
-40%
-50%
WS
WWTP
SO
Nitrification

Figure 3


a-
DO (%)
b-
c-
depth (m)
5
0
-5
-10
20
10
0
-10
-20
-30
100
50
0
P_1
P_2
P_3
kilometric points - PK (km)
d-
% of DO consumption
100
90
80
70
60
50
40
30
20
10
0
2014
PK15
PK25
WS
WWTP
SO
Nitrification

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2018-381
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 28 January 2019

521 **Figure 4**



522

Figure 5

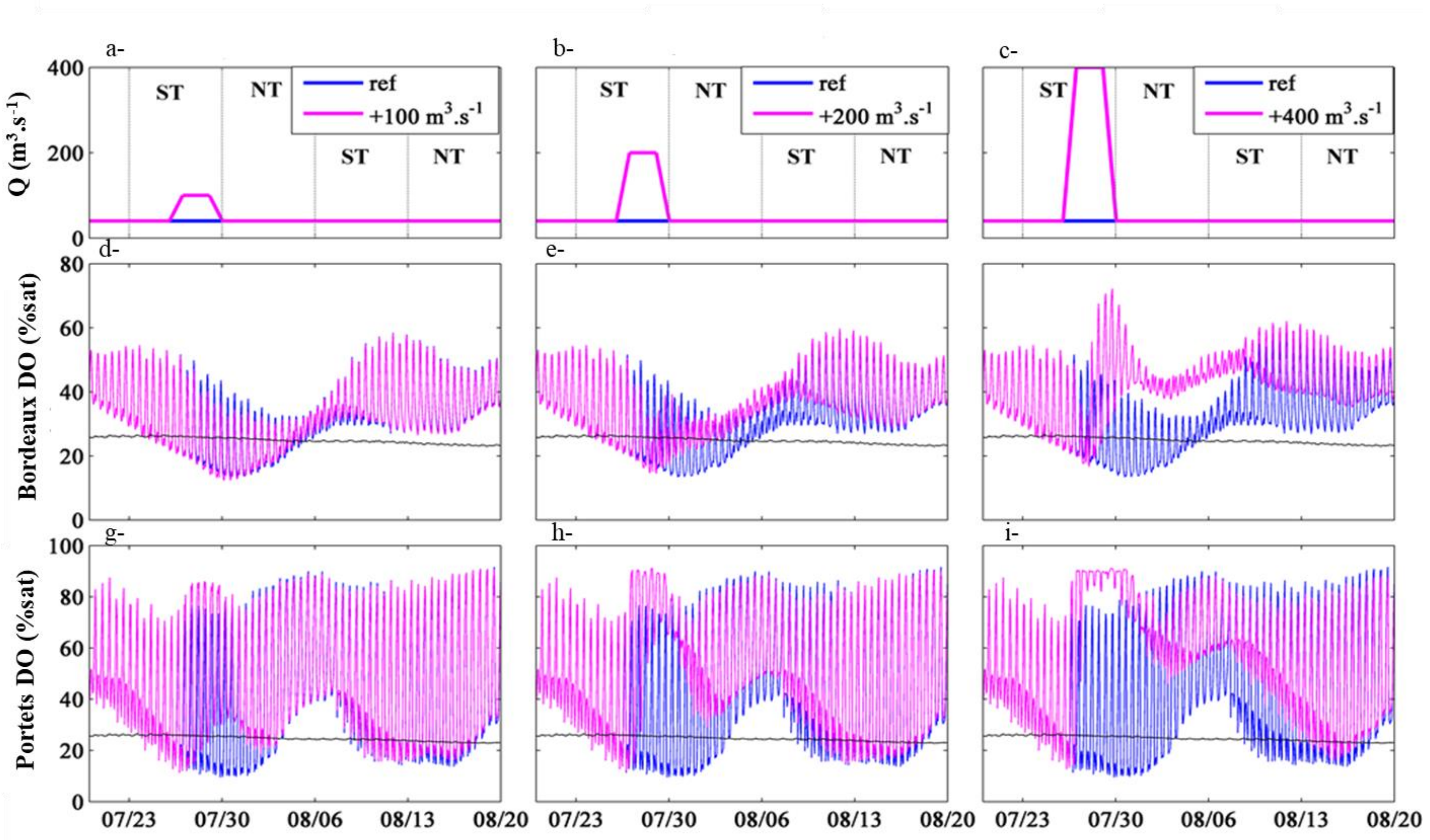
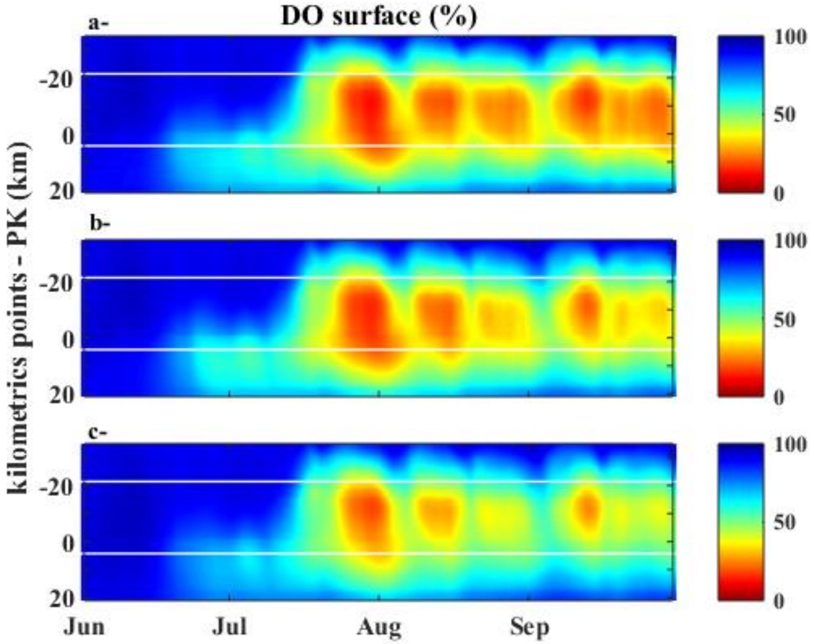

a-
b-
c-
d-
e-
f-
g-
h-
i-
Q ($m^3.s^{-1}$)
Bordeaux DO (%sat)
Portets DO (%sat)
ST
NT
ST
NT
ref
+100 $m^3.s^{-1}$
+200 $m^3.s^{-1}$
+400 $m^3.s^{-1}$
0
200
400
0
20
40
60
80
0
20
40
60
80
100
07/23
07/30
08/06
08/13
08/20

Figure 6


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