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 refers to low dissolved oxygen (DO) conditions when concentrations fall below 2 mg.L^{-1} (or < 30% of saturation. This 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 (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 river discharges and to reduce water flushing time to promote the dilution by well-oxygenated waters and/or the seaward dispersion of oxygen-consuming matter (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 freshwater 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. Over the last decades, a decrease of the Garonne River flow was observed due to changes in precipitation, but also by the water abstraction for hydroelectric dam and irrigation (Schmidt et al, 2017). This is associated with an increase of the number of days the river flow is below 110 m^{3}.s^{-1}: on average 26.9 days/year for the period 2008-2018 compared to 1.4 days/year for the period 1975-1985 (http://www.hydro.eaufrance.fr/indexd.php). Such 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 threshold of 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 system of the metropolis drains an urban area of 578 km² and serves 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 release of treated and untreated wastewater represents 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 flow data are from the WWTP (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 are 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. However, the reference simulation was run with an even more severe and constant low flow of 40 $m^3.s^{-1}$ from July 15 to September 30. This flow is different from the real river flow recorded in 2006 (75 vs 60 continuous days of river flow below 110 $m^3.s^{-1}$, respectively), in order to better visualize the impact of potential management solutions on oxygenation (Fig. 2a). In addition, to produce more realistic simulation of treated and untreated wastewater discharges, we used the WWTP flow of 2014, a year presenting similar volumes compared to 2006, to run the reference simulation. Indeed, the sewage network of the Bordeaux metropolis was improved in 2011, inducing a reduction of the contribution of SO to the total urban discharges from 16% in 2006 to 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 from WWTP as what was done 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 km², 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% 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). Indeed the wastewater transferred to WWTPs results, after treatment, in higher amounts of discharged ammonia than in effluents directly coming out from 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% (KP15) and 20% (KP25) (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 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 flow significantly reduces 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 reduces 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 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 would have prevented 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, i.e. +33%, 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 may be seen as an academic exercise 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
	Outlet relocated to KP15	Qref	Q_{WW} 2014 at Parempuyre
	Outlet relocated 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
	Outlet relocated to KP15	26.9	23.5	1.8	4	24.4	9.7	0.8	33
	Outlet relocated 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%
	Outlet relocated to KP15	-33%	-47%	+2%	-65%	-8%	-17%	-3%	-76%
	Outlet relocated 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
Outlet relocated to KP15	+++	+	WWTP outfall relocation
Outlet relocated to 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. Inset 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, $m^3.s^{-1}$): a & b present the whole simulation period, from January to October; d & e present a zoom from May to October. 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.

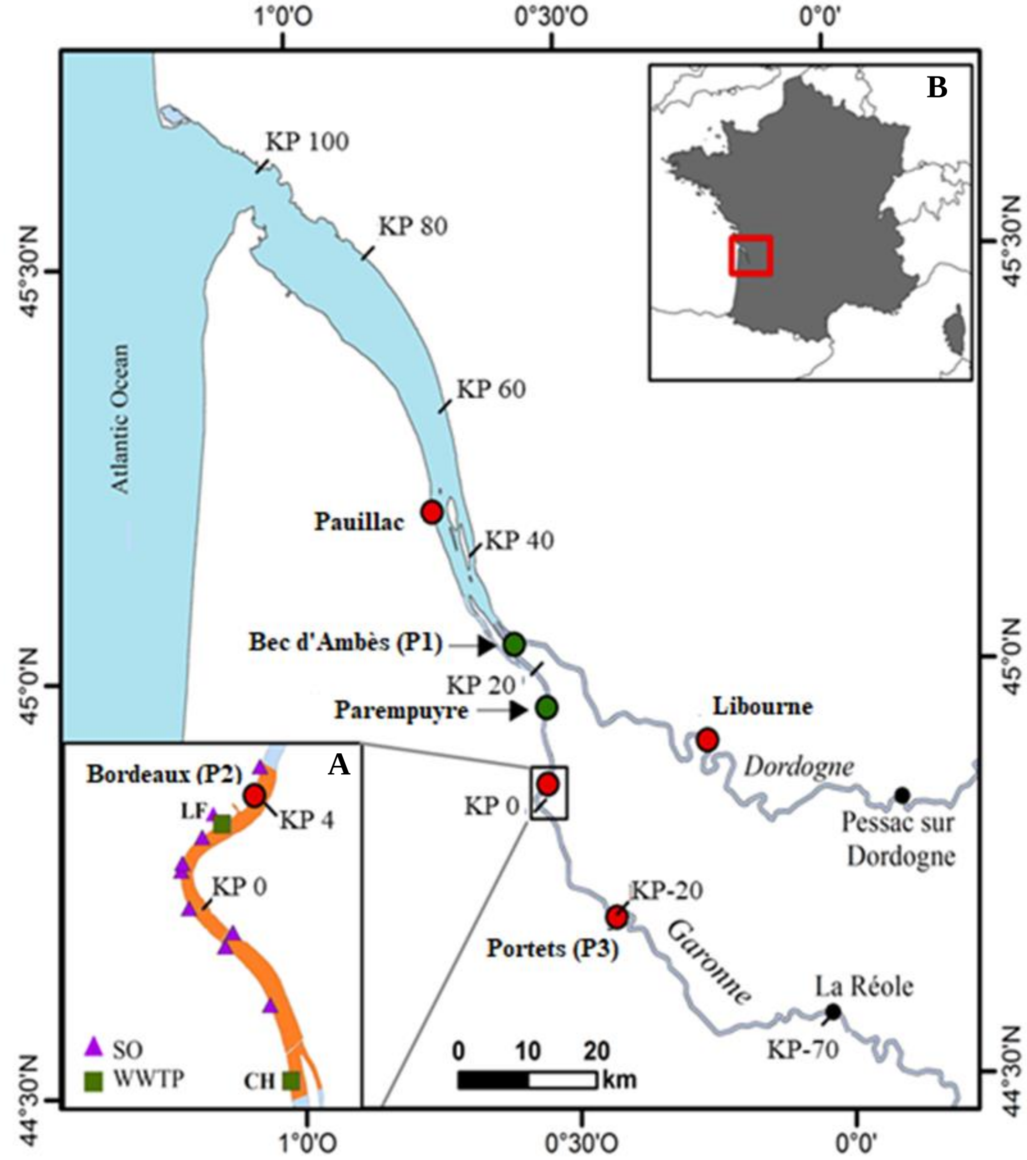
Figure 3: Snapshot of the vertical transect of simulated DO saturation along the Garonne tidal river for the scenarios with urban effluent discharge points in Bordeaux (a), KP15 (b) and KP25 (c). P1, P2 and P3 indicate the locations of Bec d’Ambès, Bordeaux and Portets, respectively. The contribution 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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B
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Atlantic Ocean
Pauillac
Bec d'Ambès (P1)
Parempuyre
Libourne
Dordogne
Pessac sur Dordogne
Portets (P3)
Garonne
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A
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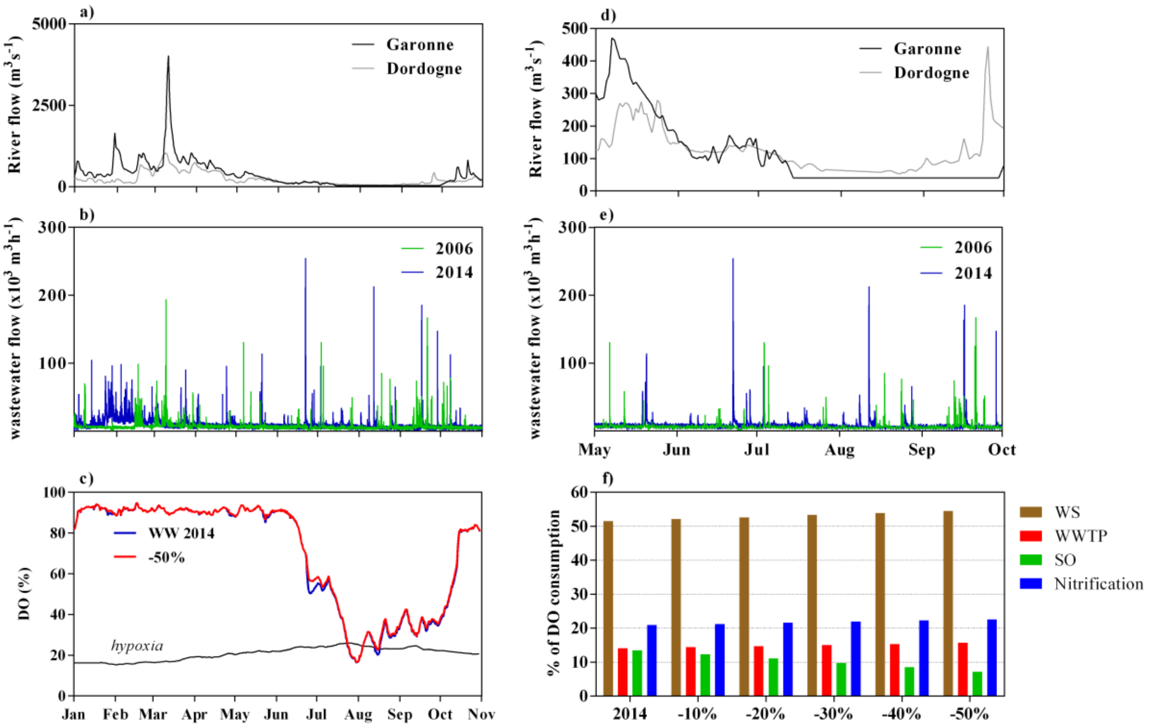
Figure 2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River flow (m^{3}s^{-1})
5000
2500
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Garonne
Dordogne
b)
wastewater flow (x10^3 m^{3}h^{-1})
300
200
100
2006
2014
c)
DO (%)
100
80
60
40
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WW 2014
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hypoxia
Jan
Feb
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d)
River flow (m^{3}s^{-1})
500
400
300
200
100
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Garonne
Dordogne
e)
wastewater flow (x10^3 m^{3}h^{-1})
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200
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% of DO consumption
60
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-10%
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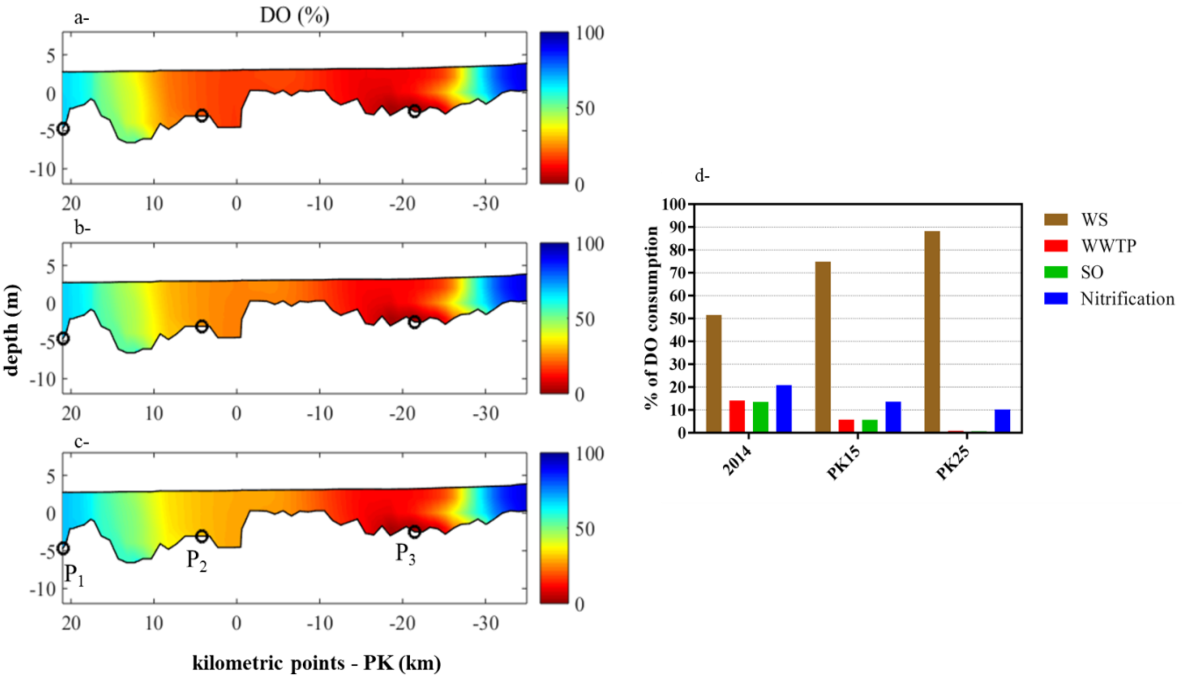
-50%
WS
WWTP
SO
Nitrification

Figure 3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DO (%)
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-30
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P1
P2
P3
kilometric points - PK (km)
d-
% of DO consumption
100
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2014
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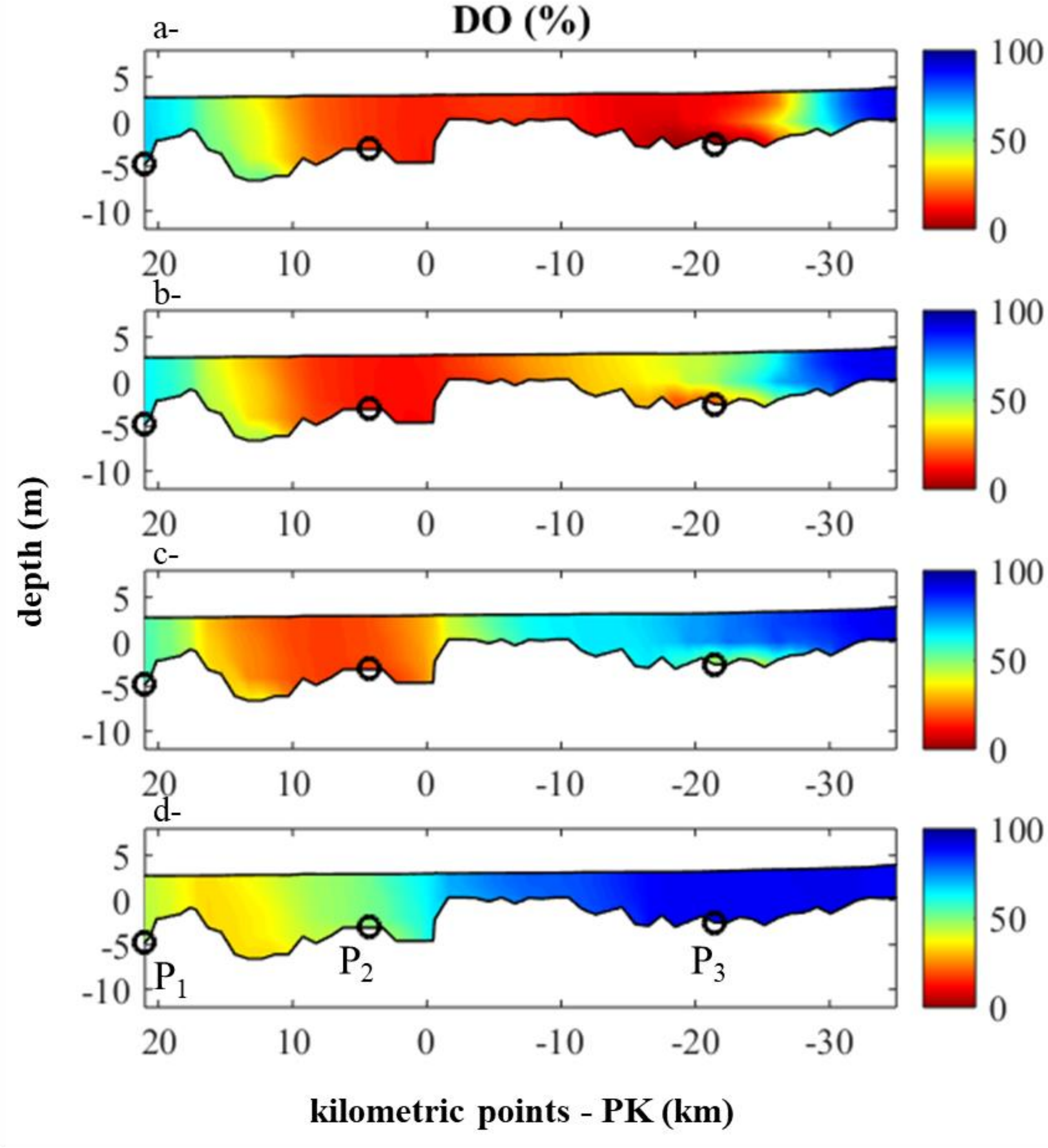
WWTP
SO
Nitrification

Figure 4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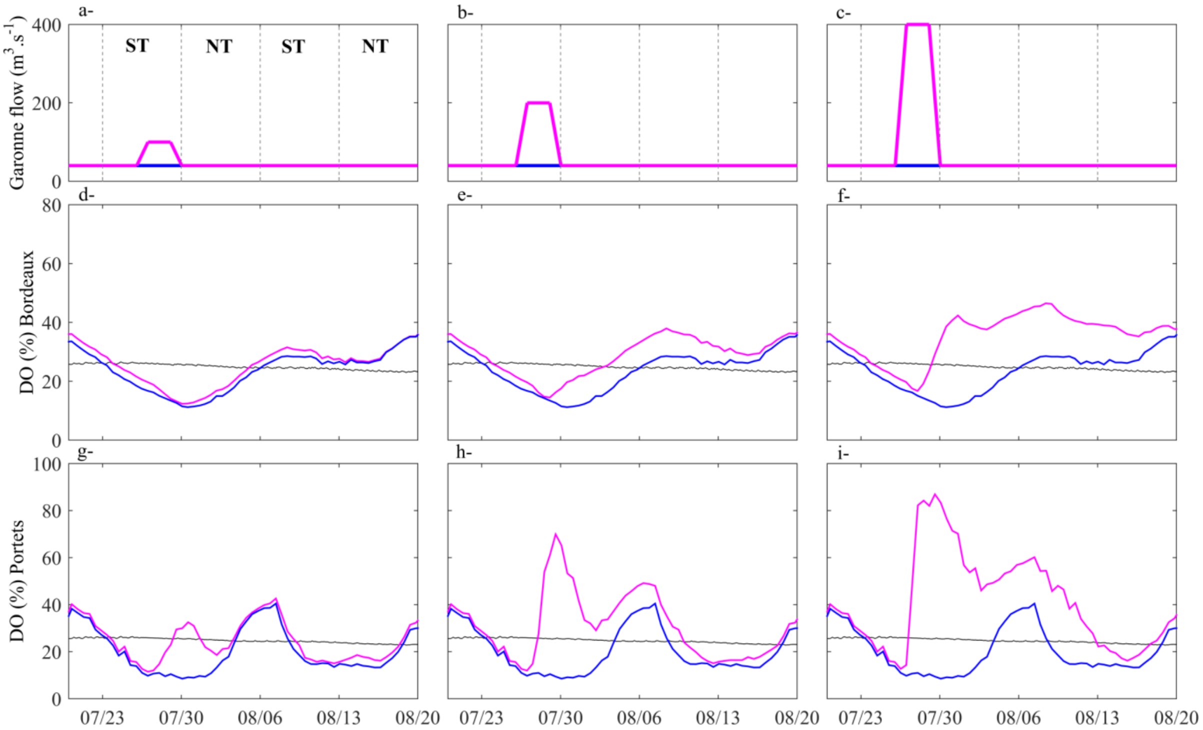
P3
kilometric points - PK (km)

Figure 5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Garonne flow (m^3.s^{-1})
400
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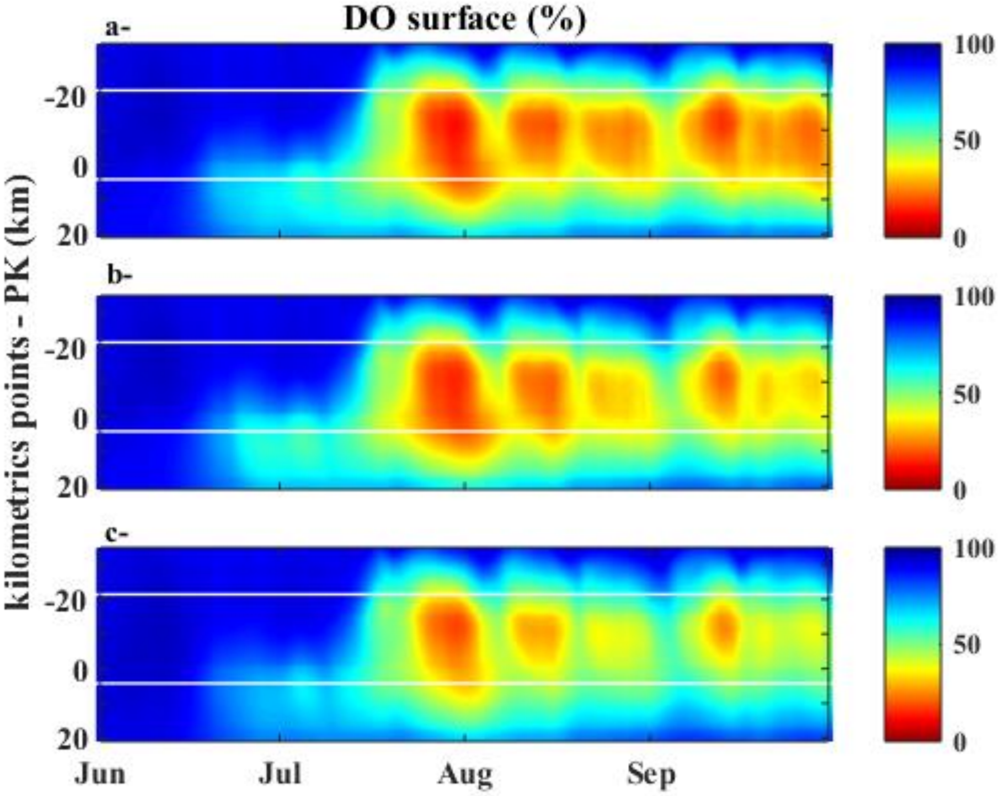
DO (%) Bordeaux
80
60
40
20
0
g-
h-
i-
DO (%) Portets
100
80
60
40
20
0
07/23
07/30
08/06
08/13
08/20

Figure 6


DO surface (%)
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b-
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kilometrics points - PK (km)
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-20
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Aug
Sep
100
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