A 14-Year Multi-sites and High-Frequency Monitoring of Salinity in the Tidal Garonne River (S-W France) Reveals Marked Inter-annual Variability in Marine Intrusion

Sabine Schmidt

A 14-Year Multi-sites and High-Frequency Monitoring of Salinity in the Tidal Garonne River (S-W France) Reveals Marked Inter-annual Variability in Marine Intrusion

Sabine Schmidt

Abstract With its 625 km^2, the Gironde estuary (S-W France) is one of the largest European estuaries. The tidal Garonne and Dordogne Rivers, whose confluence is located at about 75 km from the mouth, form its fluvial section. The Tidal Garonne River (TGR) represents about 2/3 of the freshwater inputs to the Gironde. For a long time it has been accepted the limit of saline intrusion, identified by a salinity higher than 0.5, was nearly at the confluence. In the last decades, there has been a significant decrease of the annual mean TGR discharge, likely to influence marine intrusion. It is often difficult to establish changes in marine intrusion in estuaries due to the limited available data set. This work presents the interest of a multi-sites and high frequency monitoring system, called MAGEST, that records since 2004 four physico-chemical parameters, including salinity, to establish a reference database of water-quality of this large fluvio-estuarine system, in order to address current and future water-quality issues, including saline intrusion. This work presents in details the 14-year time series of salinity along the Garonne-Gironde continuum. Not surprisingly, there are large differences among the instrumented stations depending on their localization. High-frequency salinity chronic at Bordeaux is used to assess the occurrence of saline intrusion in the Tidal Garonne River, revealing marked inter-annual variability in marine intrusion depending of fluvial discharge. The ongoing regional changes suggest an increase of salinity in TGR in the next decades.

Keywords Gironde estuary · Salinity · Monitoring · High-frequency · Fluvial discharge · Variability

This is a pre-print of a contribution published in K., Guillou S., Gourbesville P., Thiébot J. (eds)

Estuaries and Coastal Zones in Times of GlobalChange. Springer Water. Springer, Singapore

The final authenticated version is available online at: https://doi.org/10.1007/978-981-15-2081-5_1.

S. Schmidt (✉)
UMR5805 EPOC, CNRS, OASU, Université de Bordeaux, 33615 Pessac, France
e-mail: icec-2018@sciencesconf.org; sabine.schmidt@u-bordeaux.fr

K. D. Nguyen et al. (eds.), *Estuaries and Coastal Zones in Times of Global Change*, Springer Water,
https://doi.org/10.1007/978-981-15-2081-5_1

1 Introduction

Estuaries form a natural interface in which rivers and oceans meet, mixing both fresh and salt waters. Thus, salinity presents large spatial and seasonal variations, depending of the degree of water mixing (Savenije 1993; Uncles and Stephens 2011). The balance between the landward transport of salt by tidal processes and its seaward return by freshwater discharges determines the limit of salinity intrusion along an estuary. The main factor that affects the upstream limit of saline intrusion is freshwater inflow. In a context of global change, salinity intrusion in estuaries is expected to increase due to the cumulative effect of decrease in freshwater flows (changes in rain rate, increase of water abstraction in the watershed) and to sea level rise. At present, it is still difficult to establish changes in marine intrusion in estuaries due to the limited available data set.

The Gironde estuary (S-W France) and its tributaries, the tidal Garonne and Dordogne Rivers, constitute one of the largest European estuaries (Fig. 1). It has long been recognized that the limit of saline intrusion (salinity > 0.5) was to about 75 km from the mouth, at the Garonne-Dordogne confluence during low fluvial discharge

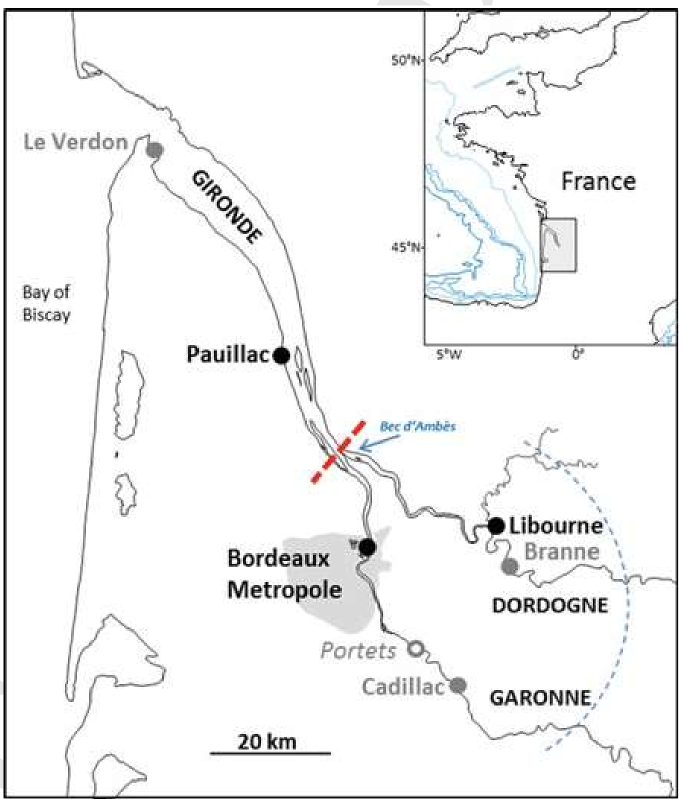

Fig. 1 The Gironde fluvio-estuarine system. The dotted arc shows the upstream limit of the tidal influence. The red dashed line highlights the historical limit of saline intrusion. The sites of the MAGEST network are also indicated: the four first instrumented stations (in dark) and the three new stations (in grey) started in 2017

periods, with incursions upstream Bordeaux (about 100 km of the mouth) at high tide (Allen 1972). By contrast, the upstream limit of tidal influence extends about 100 km more landward What about 40 years later, considering the local hydro-morphological evolution. The Garonne mean annual discharge has decreased by 31% since the last six decades (Jalón-Rojas et al. 2015) and the duration of low-water periods increased (Schmidt et al. 2017). Both climate change and increase in water abstraction in the watershed (hydropower dams and agriculture) explain these changes. It is now established the cumulative impact of changes in hydrology and morphology (upstream shift of accretion zone, gravel extractions) have also enhanced tidal range in the Tidal Garonne River (TGR) (Jalón-Rojas et al. 2018). Therefore, one could speculate these discharge and tide changes may have led to a landward extension of the saltwater intrusion beyond its historical limit.

This work presents a 14-years continuous time series of salinity in surface waters at Bordeaux in the Tidal Garonne River. This multi-year salinity chronic enables to illustrate the variability of salinity at different timescales, and to assess the occurrences of saline intrusion. These results demonstrate the interest of long-term monitoring to better understand inter-annual salinity dynamic and to produce reliable records essential for the identification of saline intrusions in estuaries.

2 Study Site and the MAGEST Network

The macrotidal and highly-turbid Gironde fluvio-estuarine system is located in the South-West France and drains daily about 684 $m^3\ s^{-1}$ (104–6048; 2005–2014) to the Bay of Biscay (Jalón-Rojas et al. 2018). Tides at the mouth are semidiurnal, with a tidal range varying from about 2.5–5 m on mean neap/spring tides. The Tidal Garonne River represents about 2/3 of the freshwater inputs to the Gironde. The mean annual Garonne discharge is 597 m for the period 1913–2018 (data from http://www.hydro.eaufrance.fr/stations/O9000010 station Tonneins). However, since 2004, the year a high-frequency monitoring network was established, mean annual discharges were usually below this level. Years 2005, 2011 and 2017 were particularly dry (347, 311, 340 $m^3\ s^{-1}$, respectively); only the years 2013 (748 $m^3\ s^{-1}$) and 2014 (634 $m^3\ s^{-1}$) were above the reference mean.

Since 2004, a real-time, multi-sites and high frequency monitoring network, called MAGEST, records four selected parameters, including salinity, to establish a reference database of water-quality of this large fluvio-estuarine system and to address current and future water-quality issues (Etcheber et al. 2011). A consortium of local water authorities (research laboratories, water and river basin agencies, port and energy operators) have joined in the effort to develop this network, which is operated by the laboratory EPOC (University Bordeaux, CNRS). This project started in 2004–2005 with four stations: in the central estuary (Pauillac) and in the Tidal Garonne (Bordeaux, Portets) and Dordogne (Libourne) Rivers (Fig. 1). Today, this network encompasses the whole estuary from the mouth (Le Verdon) to the upper tidal rivers

(Cadillac, Branne). The first sites were equipped of automated systems that measured temperature, salinity, turbidity and dissolved oxygen every 10 min (Etcheber et al. 2011). These systems, installed on floating pontoons, pumped water 1 m below the surface; estuarine waters circulated next thought a measurement chamber. The automated stations needed power supply, and the maintenance was expensive and complicate. Thanks for the technological development, there are now performant multi-sensor probes that simplify fieldwork. Since 2017, all sites of the MAGEST network are equipped by SAMBAT probes (NKE Instrument), which measure the same parameters. To optimize battery life, the measurement frequency is now 20 min. The two systems send data via GSM transmission.

3 Salinity Variability at Different Timescales

Large amplitude tidal waves propagate in the Gironde-Garonne system, with an amplification from the mouth to the upper tidal Garonne River. The tides reach their maximum amplitude (up to 6.3 in spring tides) and current velocities at about Cadillac (Fig. 1) (Bonneton et al. 2015). The strong tidal currents create an intense mixing and salinity profiles are rather homogeneous through the water column in TGR (personal data). Then, only the site localization and the daily tidal range determine salinity.

The neap-spring-neap (NSN) cycle in the second half of August 2017 gives a good illustration of the salinity range along the Gironde-Garonne continuum (Fig. 2)

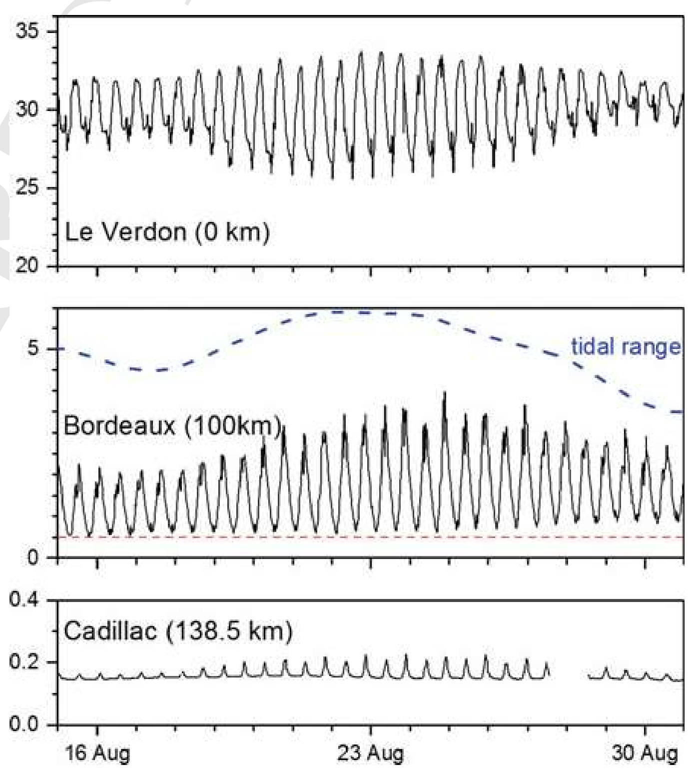

Fig. 2 High-frequency salinity record (every 20 min) at Le Verdon, Bordeaux and at Cadillac during a neap–spring—neap cycle, from August, 14–31, 2017. The dashed curve in the middle panel shows the daily tidal range (in meter). The red line underlines the threshold of salinity intrusion. Numbers in brackets correspond to the distance from the mouth

483190_1_En_1_Chapter ☑ TYPESET ☐ DISK ☐ LE ☑ CP Disp.:13/12/2019 Pages: 10 Layout: T1-Standard

during a dry period. At the mouth (Le Verdon), not surprisingly salinity is the highest: raw values are comprised between 25.5 and 33.8. Daily-average salinity varies a little, between 29.5 and 30.8. But the amplitude during a semi-diurnal tide cycle increases from 3.0 m at neap tide to 8.2 at spring tide. At Bordeaux, located 100 km from the mouth, the NSN cycle is always obvious on salinity variability (Fig. 2). But, salinities recorded at Bordeaux are much lower compared to Le Verdon, which is not surprising considering the distance from the mouth. Salinities range between 0.53 and 3.99, depending of tidal range. As a result, daily-mean values (1.19–1.91) are systematically higher to 0.5. At Cadillac, 38.5 km upstream Bordeaux (138.5 km from the mouth), minimum salinity is about 0.14, which corresponds to the baseline of the Garonne River. There is a weak imprint of tidal cycle, with values reaching 0.22 at high tide. These results indicate that the limit of salinity intrusion is probably located between 110 and 130 km from the mouth for this period, which recorded the highest salinities in 2017 whereas the Garonne discharge was below 100 $m^3 s^{-1}$ over 15 consecutive days.

The MAGEST salinity chronic gives the opportunity to investigate the occurrence of salinity intrusion in the Tidal Garonne River. There is a clear seasonal pattern in salinity, the lowest values (around 0.14) are always observed during winter. Then, there is usually a progressive increase of salinity from spring to summer, when the highest values are reached annually. The annual salinity maximum may vary from year to year: from 0.78 in 2013 to 5.25 in 2011. Depending of the year, the period during which salinity exceeds 0.5 may last from 2 to 5–6 months.

An atypical feature is the occurrence of salinity peaks beyond the Garonne baseline (0.14) during dry winters (2008, 2011, 2012). Jalón-Rojas et al. (2015) have also reported a concomitant presence of turbidity maximum zone in the Tidal Garonne River during the same periods. Winter events are less frequents and more limited in intensity and duration compared to the summer salt intrusion. However, the winter 2012 is remarkable with salinity exceeding the threshold of 0.5 from March to mid-April.

4 Salinity and Fluvial Discharge

A zoom on the two extreme years, the driest 2013 and the wettest 2011 of the period 2005–2017, is now detailed. As the changes in salinity during a semi-diurnal tide cycle are large (Fig. 2), salinity higher to 0.5 could be only the result of a brief salt incursion at high tides. To assess effective salinity intrusion, the choice in the following figures is to use daily-mean salinity (next salinity*; Fig. 4) to better evidence the link between fluvial discharge and salinity at Bordeaux. In 2011, following two weak floods, fluvial discharge reached early in the season the levels usually observed in summer. As a result, the onset of salinity* above the Garonne baseline occurred also very soon, compared to the other years (Fig. 3). The first saline incursions were measured late May. Then there is a gradual increase of salinity* up to 2.1 following the decrease in discharge and the rhythm of neap-spring tide cycles. This trend is

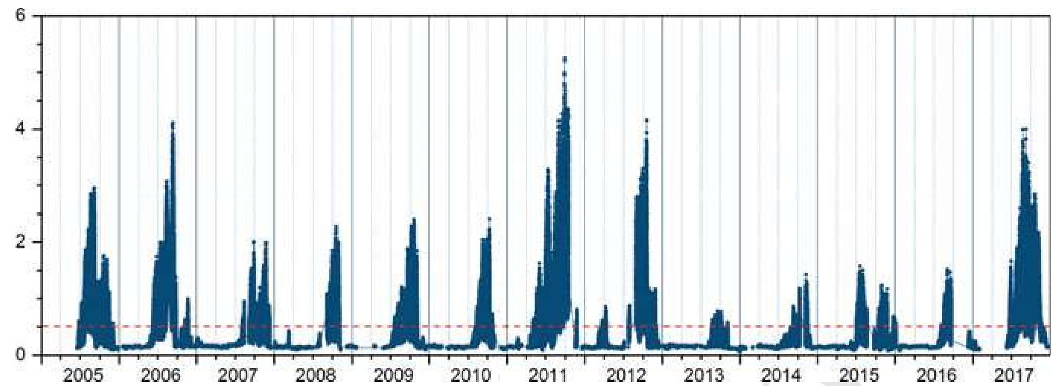

Fig. 3 Multi-annual chronic of salinity, measured every 10 min, at Bordeaux from 2005 to 2017. The red line underlines the threshold of salinity intrusion

only disrupt during a brief wet event late July. Despite missing data, it is obvious salt was flushed away from the Tidal Garonne River in October 2011 when the Garonne discharge increased durably.

The salinity* record in 2013 is readily different. The first 2013 semester is particularly wet, forbidding the intrusion of saline waters. With the summer decrease of fluvial discharge, there is a slight increase in salinity*. However the combination of this late arrival and of rather high summer flow limits the rise in salinity* at a maximum value of 0.34 at spring tides. The first autumnal flood evacuated almost immediately extra salt.

The comparison of years 2011 and 2013 illustrates the link between discharge and salinity. To precise this relationship, salinity* was plotted against daily mean discharge (Fig. 5). For fluvial discharge higher to 1000 $m^3\ s^{-1}$, salinity* is systematically below 0.16, which corresponds to the baseline level of the Tidal Garonne River. Between 300 and 1000 $m^3\ s^{-1}$, salinity* presents some variability, but most values remain below 0.5. For example, during the wettest years, summer fluvial discharges always stayed above 110–120 $m^3\ s^{-1}$, and salinity* was rather low, never exceeding 0.4. Then, when fluvial discharge decrease from 300 $m^3\ s^{-1}$ to very dry conditions, salinity* rapidly increase above the threshold of 0.5, up to 2.2. This indicates a limit of saline intrusion clearly upstream Bordeaux these years.

5 Occurrence of Saline Intrusion

During the period 2005–2017, wet summers did not favour salt intrusion in the Tidal Garonne River. Salinity* remains always below the limit of 0.5 (Figs. 5 and 6). This may correspond roughly to the past observations. On the opposite, dry summers are associated with a marked presence of salt. In summers 2006 and 2011, salinities* higher than 0.5 represent 29% and 44.5%, respectively, of data acquired from July to September (Fig. 7).

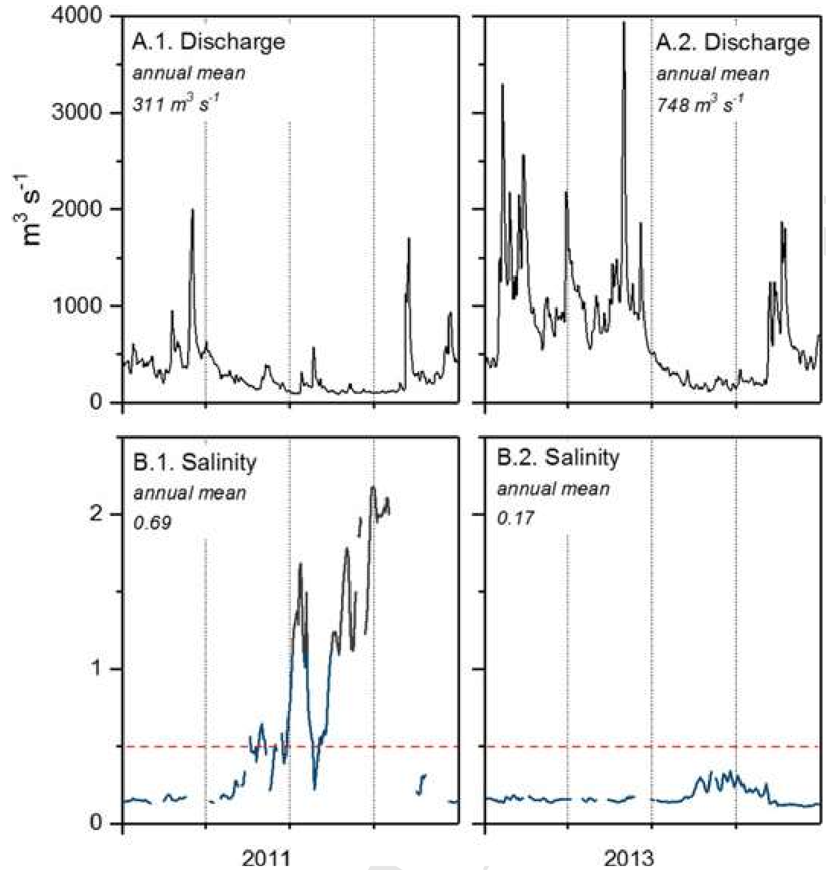

Fig. 4 Comparison of daily mean Garonne discharge (1) and salinity* (2) during 2011 (A) and 2013 (B). Daily mean salinities were calculated based on the MAGEST high-frequency measurements in surface waters. The red line underlines the threshold of salinity intrusion. Numbers in italic correspond to the annual means of discharge and of salinity for 2011 and 2013

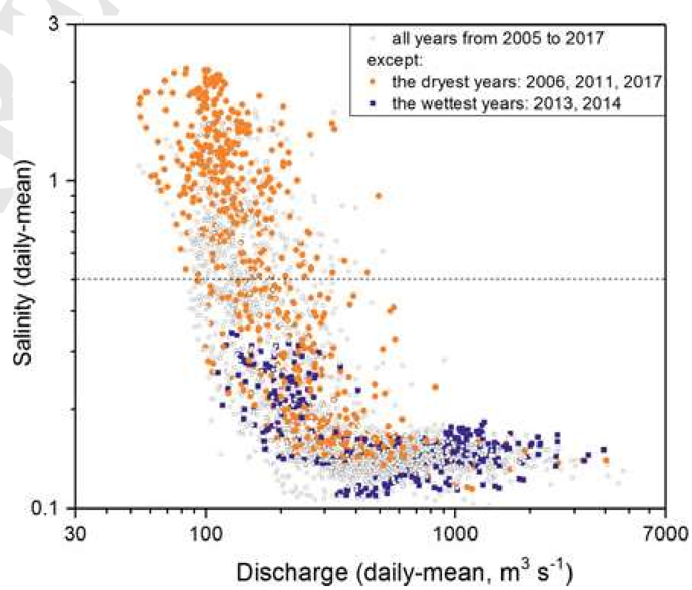

Fig. 5 Salinity* against daily mean Garonne discharge at Bordeaux. Daily mean salinities (salinity*) were calculated based on the MAGEST high-frequency measurements in surface waters. All years are plotted from 2005 to 2017. The wettest years (2013, 2014) are represented by orange circles; the driest (2006, 2011, 2017) by blue squares

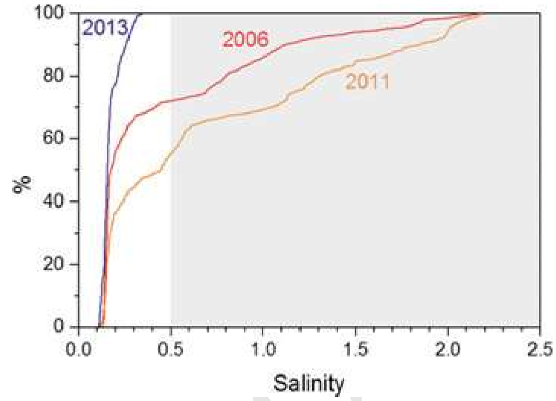

Fig. 6 Cumulative distribution function plot of summer salinity* in 2006, 2011 and 2013. Summer salinity* correspond to data acquired during July, August and September of each considered year

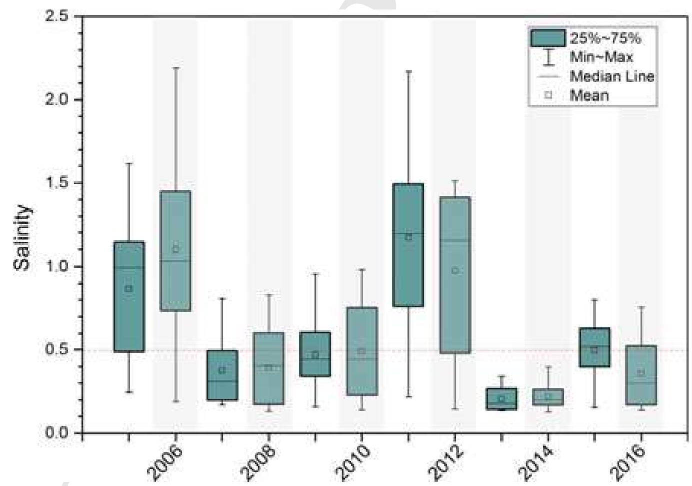

Fig. 7 Box plot of summer salinity*. Summer salinity* correspond to data acquired during July, August and September of each considered year

Statistics on summer salinity record shows that, except the two wettest years 2013 and 2014, each year since 2005 has registered salinity intrusion. One could speculate the historical limits of saline intrusion is no more relevant. However, such a conclusion could be hazardous. Indeed the multi-year salinity record at Bordeaux testifies of a large salinity variability during semi-diurnal and neap-spring tide cycles. In addition a brief wet event as observed in 2011 could also temporary reduce salinity to levels below 0.5. Therefore, concluding on a change of the limit of the saline intrusion since early 70s is not possible due to the limited dataset available at that time.

6 Conclusions

The 14-year multi-sites and high frequency monitoring of salinity along the Gironde-Garonne continuum shows large difference among the instrumented stations depending on their localization. In addition, the time-series highlights strong inter-annual variability in marine intrusion in the Tidal Garonne River. Whereas in winter and spring, daily mean salinity is usually low, summer fluvial discharges usually promote salinity intrusion, amplified by spring tides. In the coming decades, the projected regional decrease in fluvial discharges and sea level rise suggests an increased presence of salt waters in the Tidal Garonne River, at least in summer.

Acknowledgements This network is funded by the following organisms: AEAG (Agence de l'Eau Adour-Garonne), SMIDDEST (Syndicat MIxte pour le Développement Durable de l'ESTuaire de la Gironde), SMEAG (Syndicat Mixte d'Etudes et d'Aménagement de la Garonne), EPIDOR (Etablissement Public Interdépartemental de la Dordogne), EDF, GPMB (Grand Port Maritime de Bordeaux), BORDEAUX METROPOLE, Conseil Régional Aquitaine, Conseil Général de Gironde, IRSTEA, CNRS, and Université de Bordeaux.

References

Allen, G. P. (1972). Etude des processus sédimentaires dans l'estuaire de la Gironde, Thèse Doctorat es Sciences, Université de Bordeaux I, No. 353, 314pp.

Bonneton, P., Bonneton, N., Parisot, J.-P., & Castelle, B. (2015). Tidal bore dynamicus in funnel-shaped estuaries. *Journal of Geophysical Research – Oceans*.

Etcheber, H., Schmidt, S., Sottolichio, A., Maneux, E., Chabaud, G., Escalier, J.-M., et al. (2011). Monitoring water quality in estuarine environments: lessons from the MAGEST monitoring program in the Gironde fluvial-estuarine system. *Hydrological and Earth System Sciences, 15*, 831–840.

Jalón-Rojas, I., Schmidt, S., & Sottolichio, A. (2015). Turbidity in the fluvial Gironde Estuary (S.-W. France) based on 10-year continuous monitoring: sensitivity to hydrological conditions. *Hydrological and Earth System Sciences, 19*, 2805–2819.

Jalón-Rojas, I., Sottolichio, A., Hanquiez, V., Fort, A., & Schmidtm S. (2018). To what extent multidecadal changes in morphology and fluvial discharge impact tide in a convergent (turbid) tidal river. *Journal of Geophysical Research – Oceans*, #2017JC013466RR.

Savenije, H. H. (1993). Composition and driving mechanisms of longitudinal tidal average salinity dispersion in estuaries. *Journal of Hydrology, 144*, 127–141.

Schmidt, S., Bernard, C., Escalier, J.-M., Etcheber, H., & Lamouroux, M. (2017). Assessing and managing the risks of hypoxia in transitional waters: a case study in the tidal Garonne River (South-West France). *Environmental Science and Pollution Research, 24*, 3251–3259.

Uncles, R. J., & Stephens, J. A. (2011). The effects of wind, runoff and tides on salinity in a strongly tidal sub-estuary. *Estuaries and Coast, 24*, 758–774.

Author Queries

Chapter 1

Query Refs.	Details Required	Author's response
AQ1	Kindly note that 'Jalon-Rojas et al. (2017)' has been changed to 'Jalón-Rojas et al. (2018)' so that this citation matches the list.	
AQ2	Please check and provie the significance of the asterisk throught the chapter.	
AQ3	Please check and confirm if the inserted citation of Fig. 7 is correct. If not, please suggest an alternate citation.	

MARKED PROOF

Please correct and return this set

Please use the proof correction marks shown below for all alterations and corrections. If you wish to return your proof by fax you should ensure that all amendments are written clearly in dark ink and are made well within the page margins.

Instruction to printer	*Textual mark*	*Marginal mark*
Leave unchanged	• • • under matter to remain	Ⓥ
Insert in text the matter indicated in the margin	⋏	New matter followed by ⋏ or ⋏ⓧ2
Delete	/ through single character, rule or underline or ⊢⊣ through all characters to be deleted	or
Substitute character or substitute part of one or more word(s)	/ through letter or ⊢⊣ through characters	new character / or new characters /
Change to italics	— under matter to be changed	
Change to capitals	≡ under matter to be changed	≡
Change to small capitals	= under matter to be changed	=
Change to bold type	~ under matter to be changed	~
Change to bold italic	under matter to be changed	
Change to lower case	Encircle matter to be changed	≢
Change italic to upright type	(As above)	
Change bold to non-bold type	(As above)	
Insert 'superior' character	/ through character or ⋏ where required	or under character e.g. or
Insert 'inferior' character	(As above)	⋏ over character e.g.
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	or and/or or
Insert double quotation marks	(As above)	or and/or or
Insert hyphen	(As above)	⊢⊣
Start new paragraph		
No new paragraph		
Transpose		
Close up	linking characters	
Insert or substitute space between characters or words	/ through character or ⋏ where required	Y
Reduce space between characters or words	| between characters or words affected	T