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Estuaries and Coastal Zones in Times of Global Change

Proceedings of ICEC-2018

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Estuaries and Coastal Zones in Times of Global Change

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Preface

This book compiles 48 chapters organised in seven parts with a brief introduction to each chapter. These chapters were selected among a total of 110 manuscripts from 15 countries presented and discussed at the 6th International Conference on Estuaries and Coasts (ICEC-2018) which was held from 20 to 23 August 2018 in Caen, France. Using this opportunity, we would like to acknowledge the numerous reviewers (see Reviewers) for their thorough evaluation which was fundamental for this selection and for the overall quality of this book (two reviewers/paper). Though only 46% of the papers are selected, the scope of this book is kept deliberately as broad and interdisciplinary as for the ICEC-2018 conference, encompassing the latest advances and the most innovative developments related to the respective conference topics which might be viewed in the context of global change.

Previous ICEC conferences were held in 2003 in Hangzhou/China (1st), 2006 in Guangzhou/China (2nd), 2009 in Sendai/Japan (3rd), 2012 in Hanoi/Vietnam (4th) and 2015 in Muscat/Oman (5th). This conferences series aims to bring together leading academic scientists, researchers and practitioners to share their results, the solutions adopted and the challenges encountered in diverse topics related to estuarine, deltaic and coastal environments.

The 6th ICEC-2018 has been jointly organised by GIS HED^2 (Groupement d'Intérêt Scientific "Hydraulique pour l'Environnement et le Développement Durable", France), University of Caen-Normandy and IRTCES (International Research and Training Centre on Erosion and Sedimentation). GIS HEDD includes 34 (i.e. almost all) French national research institutions in hydraulic engineering and university laboratories. GIS HED^2 has been recognised and supported by French Ministries (Ministry of Research and Ministry of Ecology and Sustainable Development).

As such, the ICEC conference series represents an ideal interdisciplinary platform for the presentation and discussion of the state-of-the art and the most recent innovations, trends and future challenges in estuaries and coasts.

As reflected by the table of contents and by the number of chapters of different parts, a wide range of topics is covered with a clear focus on sediment transport and morphological changes in estuaries and coasts. Each part is briefly introduced by an overall comment on the contextual relevance or/and content of the chapter followed by a very short outline of the constitutive chapters.

In the first part with seven chapters, both modelling and monitoring of different aspects of saline intrusion in estuaries and other water bodies are addressed with a particular focus on case studies from China, France, France, Italy and Egypt.

Overall, this part illustrates the high complexity of the processes associated with saline intrusion and its impacts on ecosystems and human activities, implying inter alia that combined modelling and monitoring may represent the only viable approach to cope with such complexity and the ensuing challenges.

Second part with seven chapters is focused on CFD modelling of marine renewable energy (MRE) systems and their interactions with currents, sediments on the bed of the water body and the associated ecosystems. This includes seawater pumped storage power stations (SPPS), oscillating water columns (OWC), tidal energy converters (TEC) and offshore wind turbines (OWT).

As an overall conclusion which might be tentatively drawn from these contributions, it is worth mentioning that the interactions between MRE systems/farms, currents, sediments and ecosystems are generally in two way, implying that integrated modelling approaches and more efficient coupling of different models (e.g. hydrodynamic, geo-morphodynamic and ecological large-scale models) are necessary to cope with such complex interactions.

In the third part with ten chapters, the prime focus is the modelling of sediment transport and geo-morphological changes in estuaries and deltas, particularly including the effects of human activities on these changes. The chapters encompass a broad spectrum of diverse modelling approaches and processes, also including management tools for estuarine environments such as mapping and geo-ecological indicators. Besides the applications of common hydro-morphodynamic codes such as Delft3D and MIKE21 for the study of the effect of river flooding on morphological changes, and the study of tidal currents and sediment transport processes in estuaries and bays, these also include other modelling approaches. Among the latter, it is worth to mention a 3D multi-class modelling of sediment flux to implement dredging and dumping processes, a 3D non-hydrostatic model for coherent flow structures and the associated scour until equilibrium, a two-phase Eulerian approach for CFD modelling of sediment plumes, a 3D advanced CFD model coupled with a multi-layered mixed sediment (sand + mud) model for the study of sediment exchanges between estuary and sea as well as the associated uncertainties.

Among the lessons learned from this part, it should be underlined that generally there is no model readily available to resolve at local and regional scales the diverse processes/interactions associated with sediment transport and geo-morphological changes in estuaries and deltas; i.e. from local to regional scales and short to long term. Therefore, the first step is a proper selection of (i) the CFD models and/or the geo-morphodynamic models (including grid resolutions) and (ii) the coupling approaches which are most appropriate to the problem under study. After a proper calibration/validation of the proper model system, it is fundamental, before the ultimate application of the validated model system, to use it for systematic sensitivity analysis of the most relevant parameters within their uncertainty ranges. Though an exact quantification of the uncertainties of the simulation results is generally hardly possible, an approximate uncertainty assessment is required for the latter to be practically useful.

In the fourth part with twelve chapters, various coastal processes associated with waves, current and sediment transport using numerical tools, laboratory experiments, field surveys and remote sensing imagery are addressed with a focus on engineering applications. The thirteen chapters may be subdivided in three groups depending on their focus: (i) Application of aerial/satellite imagery and/or field surveys for the study of shoreline changes (First four chapters), (ii) Numerical modelling of the interactions between waves, currents and sediment transport with a focus on engineering problems (Next four chapters) and (iii) Mitigating measures (Five last chapters). The applications in the first group of papers encompass diverse types of coasts (mud, sand, mixed sand-gravel) and diverse effects on shoreline evolution (coastal structures, ports, river sediment supply, mangroves and aquaculture development). The second group also covers modelling studies of diverse impacts and processes, such as the effects of changes in wave regimes and river discharges on sediment fluxes to estuaries and in adjacent beaches, the effects of current–wave interactions at inlets on boating operations, the effect of storms on cohesive and non-cohesive sediment transport/deposition and morphodynamic changes in waterways and the impact of engineering works on suspended sediment transport near critical infrastructures. In the third group, the focus is rather on nature-based solutions (e.g. eco-geosystems) and soft solutions (e.g. groyne like net systems) to reduce coastal erosion as well as on wave transformation and conditions triggering co-oscillating tides for the improvement of predictions and warning systems.

Overall, the contributions show that most of the lessons learned in the third part for the modelling in estuaries and deltas (see above) also generally apply for coastal environments. In addition, they show implicitly that the efficient management of future coastal risks requires a full understanding of the evolution of the coastal environment and the underlying processes/interactions, which can very often only be achieved through a synergetic combination of numerical modelling, laboratory experiments, field surveys and remote sensing techniques such as airborne/satellite imagery. They also show that the trend to mitigate coastal risks in the context of global change is clearly towards nature-based solutions.

Fifth part with four chapters deals with experimental studies related to various effects related to sediment transport and flow, such as (i) the effect of sediment availability/supply on the characteristics of bed forms (dunes and ripples), horizontal coherent flow structures in compound vegetated channels as well as their effect on transverse exchange processes and the importance of the latter for engineering applications related to mitigation measures, such as forests and river bank protection, (ii) the effects of sediment size/concentration and concentration of other minerals and organic matter on sediment flocculation and settlement, (iii) the effects of abrupt changes in river flow discharge and sediment supply on the short-term response of alluvial fans and (iv) the effects of rough and smooth ice covers on bed scour around pile groups.

Altogether, these five chapters represent an opportune confirmation of the necessity and value of physical modelling for the improvement of process understanding. The latter, besides the validation of numerical models, is crucial, particularly in the study of highly complex processes, such as fan formation and evolution in deltas and other geosystems where computational modelling supported by airborne/satellite imagery still dominates and where physical modelling has been experiencing a revival in recent years.

In the sixth part with four chapters focusing on the impacts of human activities on sediment transport and the morphological evolution of estuaries and coastlines. Various activities such ports, waterways, river damming (e.g. hydropower dams), sand mining, river narrowing, navigation infrastructures and dredging are considered by using different approaches, such as monitoring data analysis, diverse numerical models or their combination.

Overall, these studies support the results of previous studies, showing among others that human activities are responsible for the reductions in sediment flux in rivers and in sediment fluxes from rivers to the ocean, and confirm the range of the reported relative contributions of the different types of human activities to these reductions.

Seventh part with four chapters is dedicated to monitoring with a focus on remote sensing and satellite image analysis, generally supported by field surveys. The applications cover different processes and purposes in highly complex estuarine and deltaic environments, such as (i) the analysis of sediment dynamics (e.g. erosion/progradation, morphological changes) to provide synoptic maps of biophysical characteristics of sediments, (ii) the study of seasonal and spatial variations to provide maps with high spatial resolution for potential sediment transport trends and (iii) the analyses of historical hourly water level data in rivers and deltaic coasts to provide long-term hydrological data for the planning and management purposes.

Overall, the results well illustrate the recent advances in the applications of diverse remote sensing techniques and the potential of their combination as well as that of their deployment together with in situ measurement techniques.

Finally, we would also like to thank the authors for their contributions and nice collaboration in the revision process, the members of the Local Organisation Committee for their devotement and contribution to the very successful

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Monitoring Field Surveys and Remote Sensing

Saline Intrusion and Impacts: Modelling and Monitoring Case Studies

Saline intrusion within coastal rivers and hydro-environments is a complex process that may generate significant impacts on natural ecosystems and human activities. In order to assess in a detailed way potential consequences, monitoring strategies are developed in sensitive coastal areas and are frequently combined with modelling approaches. The current part is dedicated to various operational approaches covering both aspects for monitoring and modelling and implemented in different coastal contexts and especially in major estuaries.

The first chapter by Sabine Schmidt addresses the situation of one of the largest European estuary: the Gironde. Over 14 years, since 2004, a multi-sites and high-frequency monitoring system (MAGEST) have been set up, and four physico-chemical parameters, including salinity, are recorded with the objective 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. Sabine Schmidt 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 on fluvial discharge. The ongoing regional changes suggest an increase in salinity in the Tidal Garonne River in the next decades.

In the second chapter, Veerapaga et al. have developed a numerical analysis with a 3D hydrodynamic model on a conceptual estuary in order to discuss the variation of salinity intrusion and mixing types in terms of estuary length, width, depth and bathymetry. The obtained results will allow readers and researchers to understand how those variables may affect the saline intrusion and what could be the different expected mixing conditions.

The third and fourth chapters by Ding Lei et al. are dedicated to the response of saline intrusion within the Yangtze Estuary in China. The impact of saline intrusion may strongly affects the water supply conditions of the city of Shanghai that relies up to 70% on the Yangtse for water services. A modelling approach based on a 3D model is used to assess the interest to block the saline intrusion and to maximize freshwater within the North Branch of the estuary. The results demonstrate the efficiency of the concept that requests further developments to reach the operational state. The model is also used to investigate the potential risk of salt intrusion on the Dongfengxisha reservoir that was created in 2014 and dedicated to provide freshwater resources to estuary residents. The authors demonstrate the interest to implement a tidal gate on the North branch within the Yangste estuary.

In the fifth chapter, Shi et al. present the case of the Qiantang Estuary in China. Strong tidal bore, high sediment concentration, severe erosion/deposition and human activities characterize this estuary. The authors propose the law of interaction among runoff, channel volume and salinity by means of the analysis of the long-term hydrological and measured salinity data. A 2D salinity movable bed mathematical model considering water flow, sediment salinity transport and riverbed deformation and other multiple factor couplings has been established. The actually measured water flow, sediment, salinity and other data are used to verify the salinity transport process, and the model established can reflect the actual transport law of water flow, sediment and salinity in the Qiantang Estuary. The study shows that riverbed scouring and silting have a large effect on the salinity transport for the medium and long term at the Qiantang Estuary. The best results are obtained with a movable bed model for salinity forecast. This movable riverbed model has been successfully applied to predict the saltwater intrusion in the protection process against salt tide to guarantee the safety of water supply in Hangzhou City.

The last two chapters by Mastrocicco et al. and by Shalby et al. address the situation of wetlands and coastal lagoons in Italy and in Egypt. Direct evaporation from surface water bodies like lakes, wetlands and lagoons will increase due to temperature increase leading to salt accumulation. To understand the hydrological exchanges between the transitional coastal wetlands of the Variconi oasis, the unconfined aquifer of the Volturno River Delta and the Tyrrhenian Sea, the contributions of various processes were monitored and assessed. Physical–chemical parameters like salinity, pH, Eh and temperature were monitored. The results show that the permanent wetlands fed by both the Volturno River and the Tyrrhenian Sea show a smoothed salinity peak during the summer season; while the ephemeral wetlands hydraulically disconnected from the aquifer show high salinity peaks during the summer season due to evapo-concentration processes. The projected increase in salinity of these wetlands due to coastal erosion, augmented evapotranspiration rates and sea-level rise could be of serious concern for the biodiversity. Lake Burullus, the second largest coastal lagoon in Egypt, has a great economic situation which is vulnerable to climate change threats. The authors have used MIKE 21 to develop an eco-hydrodynamic model for the lake. Based on a regional climate model (RCM) and meteorological data extracted for one Representative Concentration Pathways (RCPs) scenario, the results show that the water depths in the lake will increase; waters will be warmer and more saline. These processes will significantly affect the water quality status of the lake and its economic situation. In both cases, the authors underline the interest to implement urgently monitoring and management strategies in order to preserve those fragile environments.

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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

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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

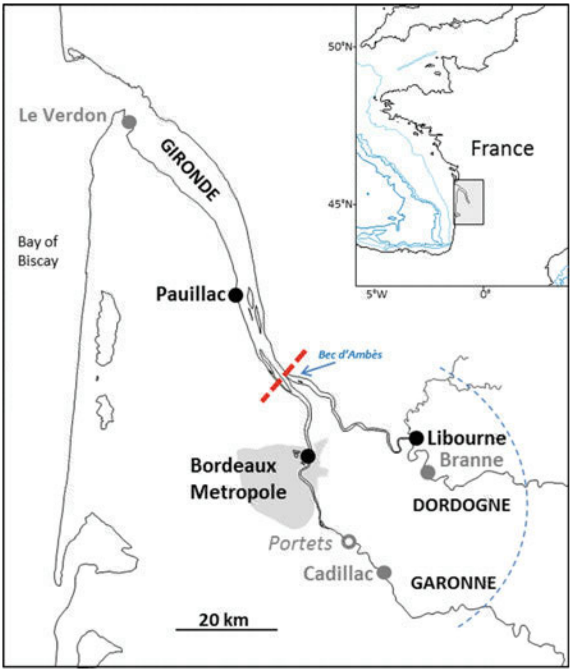

Fig. 1 The Gironde fluvio-estuarine system. The dotted arc shows the upstream limit of the tidal influence. The red dashed line highlights the historical limit of saline intrusion. The sites of the MAGEST network are also indicated: the four first instrumented stations (in dark) and the three new stations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

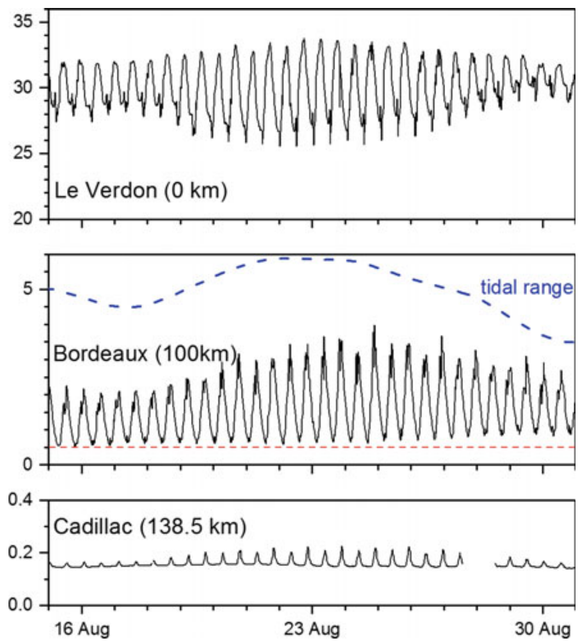

Fig. 2 High-frequency salinity record (every 20 min) at Le Verdon, Bordeaux and at Cadillac during a neap–spring—neap cycle, from August, 14–31, 2017. The dashed curve in the middle panel shows the daily tidal range (in meter). The red line underlines the threshold of salinity intrusion. Numbers in brackets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

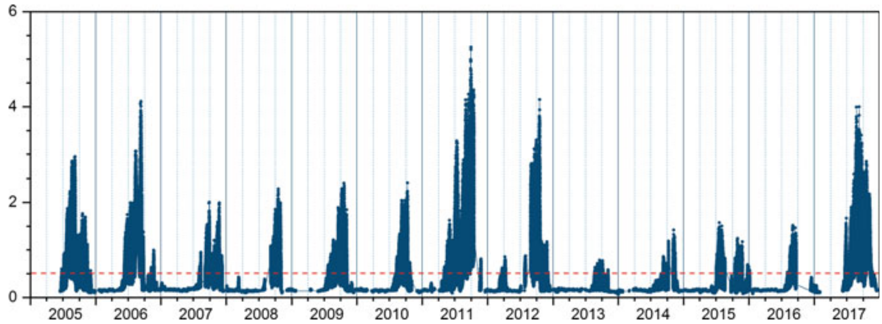

Fig. 3 Multi-annual chronic of salinity, measured every 10 min, at Bordeaux from 2005 to 2017. The red line underlines the threshold of salinity intrusion

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 (Fig. 3). 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 only disrupt during a brief wet event late July. Despite missing data, it is obvious salt

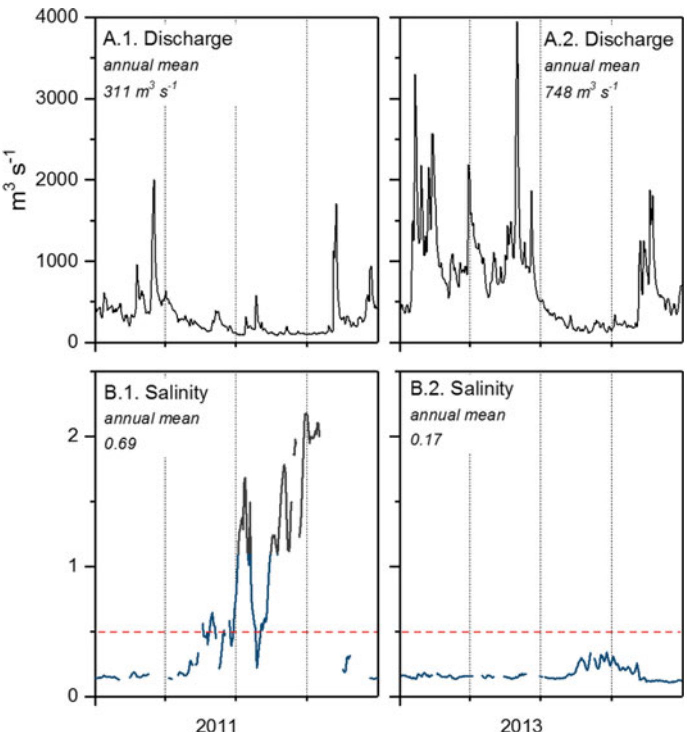

Fig. 4 Comparison of daily mean Garonne discharge (1) and salinity* (2) during 2011 (A) and 2013 (B). Daily mean salinities were calculated based on the MAGEST high-frequency measurements in surface waters. The red line underlines the threshold of salinity intrusion. Numbers in italic correspond to the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

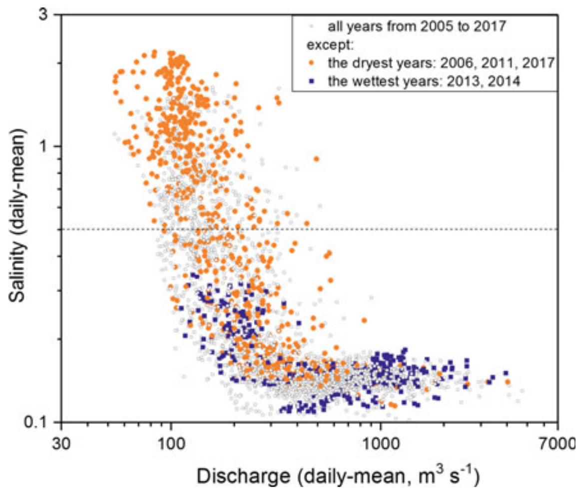

Fig. 5 Salinity* against daily mean Garonne discharge at Bordeaux. Daily mean salinities (salinity*) were calculated based on the MAGEST high-frequency measurements in surface waters. All years are plotted from 2005 to 2017. The wettest years (2013, 2014) are represented by orange circles; the driest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

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*

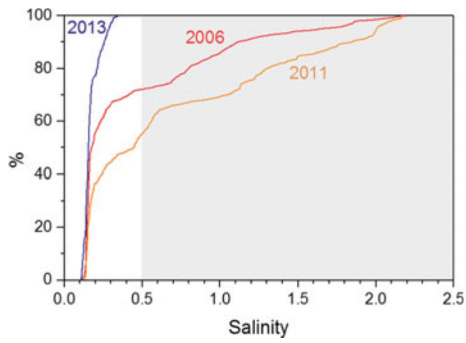

Fig. 6 Cumulative distribution function plot of summer salinity* in 2006, 2011 and 2013. Summer salinity* correspond to data acquired during July, August and September of each considered year

higher than 0.5 represent 29% and 44.5%, respectively, of data acquired from July to September (Fig. 6).

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 (Fig. 7).

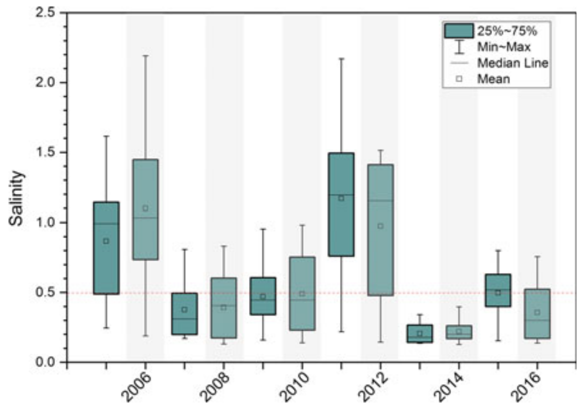

Fig. 7 Box plot of summer salinity*. Summer salinity* correspond to data acquired during July, August and September of each considered year

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.

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