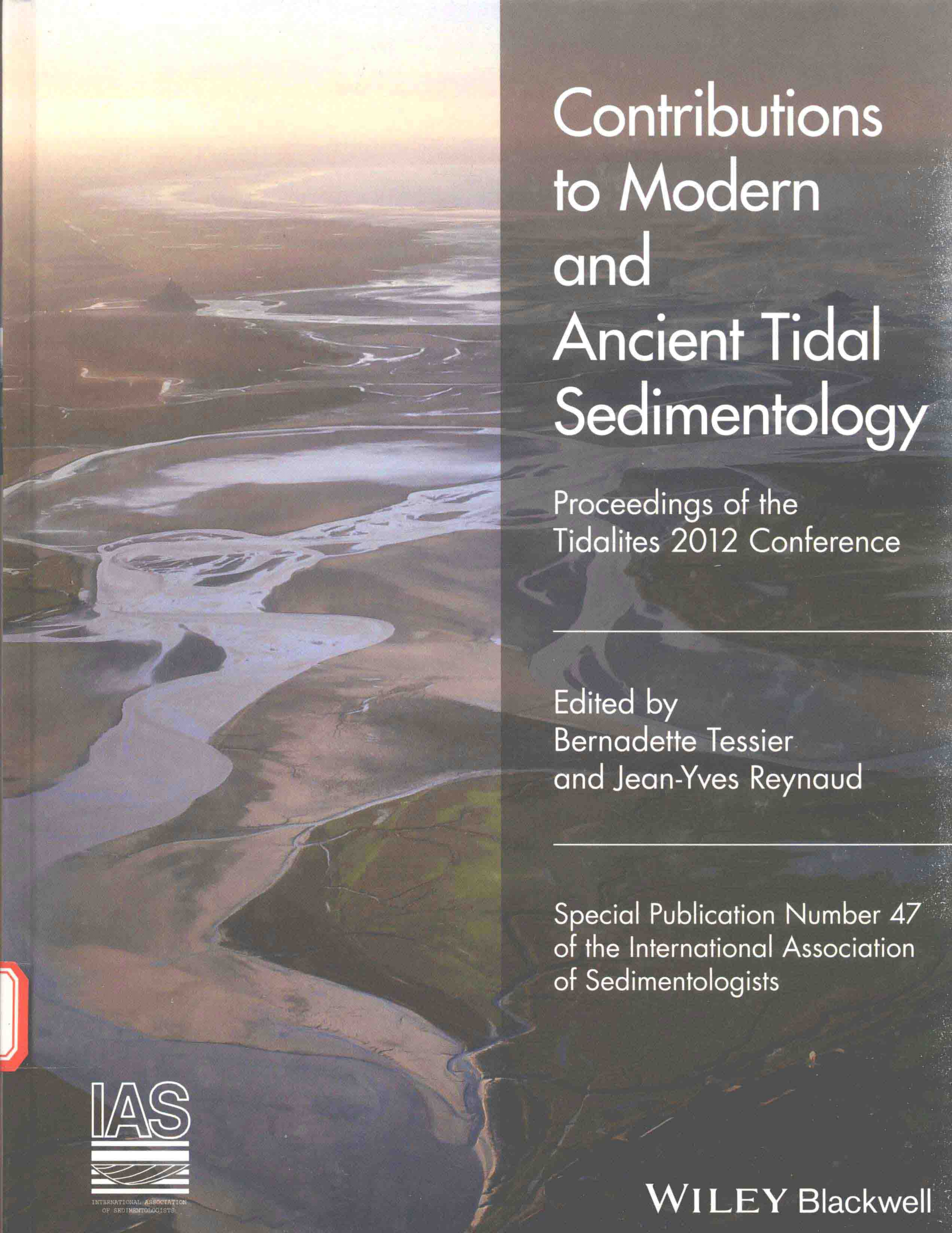

Contributions to Modern and Ancient Tidal Sedimentology

Proceedings of the Tidalites 2012 Conference

Edited by
Bernadette Tessier
and Jean-Yves Reynaud

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Cover image: An aerial photograph of the Bay of Mont-Saint-Michel (NW France). In the foreground, the tide-dominated estuarine system occupying the whole eastern part of the Bay (Photograph by P. Gigot, December 25th, 2009).

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Contributions to Modern and Ancient Tidal Sedimentology: an introduction to the volume

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HISTORY OF THE 'TIDALITES' CONFERENCE PROCEEDINGS

Besides pioneer works of the 60s, the tidal sedimentologist community really emerged in the 70s (see Klein, 1998). The first international conference on tidal sedimentology took place in 1973 in Florida (USA). It was devoted to carbonate facies, less to siliciclastic deposits and mostly to intertidal areas. The conference resulted in a book gathering case studies (Ginsburg, 1975). The fining-upward tidal flat sequence represented at this time the tidal facies model; and this was mainly applied to carbonates. The growing knowledge in siliciclastic tide-dominated environments was synthesized a few years later by Klein (1977). Following the paper of Visser (1980) demonstrating the record of tidal cycles in estuarine dunes, clastic tidal sedimentology evolved quickly towards more comprehensive and quantitative studies, both ancient and modern. A community was born.

In 1985, this community met in Utrecht (Netherlands) at the '1st Clastic Tidal Deposits symposium'. The proceeding book contains 31 papers, covering a large spectrum of topics, including facies and stratigraphic studies, from the offshore to the nearshore (de Boer *et al.*, 1988). Few articles are devoted to processes and modelling but many focus on modern shelf tidal bodies description and surveying. As noted by Davis *et al.* (1998), the concept of tidal bundles is expressed for the first time in this book.

The 2nd conference, held in 1989 in Calgary (Canada), gave rise to another book of 26 papers (Smith *et al.*, 1991). Beyond the increasing range of topics covered (e.g. the study of primary processes, such as flocculation), this book contains the pioneer paper by G. Allen establishing the estuarine tripartite facies and stratigraphic model of the Gironde estuary (SW France). The growing knowledge on modern tidal settings has been applied at the scale of petroleum reservoirs (e.g. Cretaceous Western Interior seaway).

The 3rd conference, named 'Tidal Clastics', took place in 1992 in Wilhelmshaven (Germany). The proceeding book (Flemming & Bartholomä, 1995) contains 23 papers, highlighting the increasing interest for studies dedicated to modern processes and facies in nearshore settings such as tidal inlets and tidal deltas. Wave and tide interactions are also considered. Ground penetrating radar appears as a new technique to explore ancient tidal subsurface outcrops.

In 1996, the 4th conference was held in Savannah (USA) and founded the 'Tidalites' name of the series. The proceeding book (Alexander *et al.*, 1998) contains 17 papers and three thematic sessions; one on the Wadden Sea, a second one on tidal rhythmites and a third one on stratigraphy, with study cases of reconstructions of incised valley fills (in the Holocene and the rock record).

This conference was marked by a decrease in participation and correlatively a decrease in the number of papers published in the proceedings. This probably reflects the increase in the range of topics covered by the tidal sedimentologist community and, hence, the need to publish more continuously in international journals.

This change was confirmed as the next conference, Tidalites 2000, in Seoul (South Korea), brought only 12 papers, published in a special volume of the Korean Society of Oceanography (Park & Davis, 2001) and was mostly devoted to modern tidal settings in China, Korea and Japan.

The Tidalites 2004 conference was held in Copenhagen (Denmark) and 19 papers were published in a special issue of Marine Geology (Barholdy & Kvale, 2006). Most articles are dedicated to modern processes and especially on fine-grained sediment dynamics and budgets (turbidity maximum, flocculation, tidal marsh sedimentation).

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Only four papers deal with stratigraphy, one in the Holocene and three in the rock record.

The Tidalites 2008 conference took place in Qingdao (China) and no proceedings were published. During the conference, contributions were mostly focused on open coast tidal flats and tide-dominated deltas characteristic of Asian tidal seas, mud flats and salt marshes, as well as fluid muds in tidal channels. The conference was also marked by an increase of numerical and flume modelling of hydro-sedimentary dynamics and a rise of studies dedicated to climate and anthropogenic changes and coastal engineering.

To summarize, since the beginning, the Tidalites conference logically reflects the research made by the organiser teams rather than a general, worldwide evolution in tidal sedimentology. For instance, the North American conferences, in Calgary and Savannah, have highlighted facies and stratigraphic aspects, in relationship with a petroleum-oriented perspective, while the European meetings, in Wilhemshaven and Copenhagen, focused more on modern settings and processes. The Asian conferences, in Seoul and Qintao, put forward challenging environmental issues. At the same time, the Tidalites community has become more diverse and the pressure on young colleagues for publishing their research works in international journals has increased.

To get a more accurate idea of the tidal sedimentology production in the last years, we made a rapid overview of the articles published between 2009 and 2015 in international journals of the geosciences featuring the keywords *tide* or *tidal* in the title and *sediment* or *deposit* in the abstract. The query sent back about 400 papers mostly covering the following subjects:

- Facies and architecture in siliciclastics: IHS and fluvial-tidal transition. Tidal deltas and inlets. Wave-dominated, open-coast tidal flats. Tidal signature in open coastlines, muddy coastlines, shelves and slope systems. Carbonate peritidal flats and channels, offshore bioclastic carbonate bodies. Tidal straits.
- Biota: Benthic diatoms/foraminifera to assess tidal changes and long-term tidal flat dynamics. Ichnology of tidal environments. Tides and life: bacterial mats, Cambrian explosion.
- Processes and Modelling: Tidal bores, tidal channels and fluid muds. Tidal bars, ridges and inlets. Offshore dunes and shelf sand transport. Internal tides and deep sands, gas hydrates; tide influenced hyperpycnal flows and turbidites. Effect of sea-level rise on tidal range, estuarine circulation. Palaeotidal reconstructions.
- Climate: Effect of storms on tidal systems. Tide-storm interplay in the evolution of offshore dunes. Rapid, climate or sea-level changes and morphodynamic evolution of coastal marshes and freshwater wetlands. Astronomical cycles and tidal rhythmites.
- Environmental studies: Carbon sequestration and geochemical tracing of tidal transport. Pollution records in tidal flats. Anthropogenic effects in tidal environments.

As a consequence of the diversification of tidal sedimentology and increase of contributors, there has been a need for more synthetic productions. Martinius & Van den Berg (2011) opened the way with their atlas of estuarine facies, partly based on the extensive lacquer peel collection of the Utrecht University. Also, the 27th IAS Meeting of Sedimentology in Alghero (Italy) in 2009 had a special session on Tidal Sedimentology, which resulted in a special issue of Sedimentary Geology providing more syntheses and fewer case studies than in the previous edited volumes (Longhitano *et al.*, 2012). During the same period, a special issue of the *Bull. Soc. Géol. France* was published on the incised-valleys around France (Chaumillon *et al.*, 2010). 6 of the 10 contributions in this volume focus on the tide-dominated to tide-influenced estuaries located along the Atlantic and Channel coasts. Finally, the textbook *Principles of Tidal Sedimentology* (Davis & Dalrymple, 2012) is the first general book dedicated to tidal sedimentology since that of Klein (1977) on clastic tidal facies and Stride (1982) on offshore tidal sands. Most authors from the steering committee of the past Tidalites conferences (except carbonate specialists) authored the chapters of this book, which provides the state of the art on typical tidal environments, including a renewed perspective on carbonates and for the first time a specific insight on the deep sea and well-known ancient tidal basins.

OUTLINE OF THE PRESENT VOLUME

The Tidalites 2012 conference was held in Caen (France) and gathered together about 100 colleagues. In addition to the 70 talks and posters covering the main fields of tidal sedimentology, the meeting offered the opportunity to visit the following sites: (i) the Arcachon basin and Gironde estuary on the Atlantic coast (Chaumillon & Féniès, 2012); (ii) the wave-dominated Somme estuary, in the Eastern Channel area (Trentesaux *et al.*, 2012); (iii) the Anjou Miocene tidal crags (André *et al.*, 2012); (iv) the Bay of Mont-Saint-Michel in the Western Channel (Tessier *et al.*, 2012). The four field trip guide-books are grouped together in a single volume (ASF, 2012).

The Caen Tidalite 2012 conference brought about 17 papers, gathered in the present volume. The book content has been organised following a progressive succession ranging from methodological papers to articles on processes and facies in modern and ancient environments and then to papers dealing with stratigraphy of tidal successions. The introductory papers highlight a diversity of tools and methodologies used in modern tidal sedimentology, such as the numerical modelling of tidal circulation in a very shallow water microtidal lagoon (Zhang *et al.*), the satellite monitoring of deltaic mouthbars using SAR data (Tanaka *et al.*) or the GIS database setup for microtidal flat ichnofacies (Baucon & Felletti). The next three papers reflect the relatively recent interest for tidal bore research. Two of them are process-oriented: Furgerot *et al.* document resuspension processes due to the tidal bore in the Mont-Saint-Michel estuary, whilst Fan *et al.* considered the morphodynamic impact of the tidal bore in the Qiantang river. The third paper links tidal bores to sediment supply in a Cretaceous fluvio-estuarine system (Chamizo *et al.*). The recognition of tidal facies is still a matter of discoveries and debate. Fluvial to lacustrine floodplains can be misinterpreted as tidal flats (Flemming), as they share many similar features (Quijada *et al.*). The imprint of tides on the growth of stromatolites is also questioned (Suarez-Gonzalez *et al.*). The geometric analysis of crossbeds is used to locate bedforms within a larger-scale tidal landscape (Chiarella *et al.*). Tidal rhythmite deposition and preservation are discussed with respect to rapid increase in accommodation, either due to tidal channel migration at a local scale (Pelletier *et al.*) or melt-water pulses at a basin scale (Archer *et al.*). The final group of papers illustrates the continued interest in replacing the tidal facies in a high-resolution sequence stratigraphic framework. The multiplicity of tidal ravinement surfaces within a tide-dominated Pleistocene estuarine fill is exemplified (Kitazawa & Murakoshi), while the estuarine to shoreface transition is documented within the infilling of a Holocene coastal plain (Margotta *et al.*). The tide-to-wave, estuarine-to-marine transition is also addressed in an example from the Devonian of Iran (Sharafi *et al.*). Finally, the transgressive reworking of lowstand deltas into headland-attached, tide-dominated sandbodies is documented from the classic example of the Roda sandstones in Northern Spain (Michaud & Dalrymple).

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Hydrodynamic modelling of salinity variations in a semi-engineered mangrove wetland: The microtidal Frog Creek System, Florida

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ABSTRACT

As components of a large-scale ecosystem restoration project, three intertidal lagoons are proposed offline of the Frog Creek and Terra Ceia River (Frog Creek System, Florida), which are mangrove-covered and micro-tidal estuaries. A three-dimensional hydrodynamic model has been developed based on EFDC (Environmental Fluid Dynamics Code) and the effects of proposed lagoons on short-time-scale salinity variations have been evaluated. High resolution airborne LiDAR data is employed to depict the bathymetry of mangrove areas. The model has been calibrated and verified by using water level and salinity observations. Due to the proposed engineered lagoons, the tidal prism will be changed and the following conclusions have been obtained from the numerical experiments. (1) The effect of three engineered lagoons is insignificant under low, moderate and super high inflow conditions and the high inflow condition has the most significant effect on salinity regime. (2) In upstream areas, the salinity is increased because the lagoons will import more saline water. In downstream areas, the salinities with and without lagoons are almost the same during flood tide. However, the surface salinity with lagoons is larger than that without lagoons during ebb tide. (3) In downstream areas, the absolute differences between surface salinities with and without lagoons are larger than those of bottom salinities. On the contrary, the absolute differences of bottom salinities are larger than those of surface salinities in upstream areas. It is of great importance to evaluate reasonably the influence of human activities or natural changes on surrounding environments; and this model can serve as a powerful tool in wetland analysis.

Keywords: Frog Creek System, EFDC, Salinity, Microtidal wetlands, Ecosystem Restoration, Numerical prediction.

INTRODUCTION

Wetland systems are becoming increasingly important for ecological, hydrological and recreational purposes. A better understanding of the functional dynamics of these systems requires a good understanding of the hydrodynamics. The hydrodynamics in estuarine wetlands are highly complex, characterized by tidal influence currents, rough bathymetry, energetic turbulence and steep density gradients caused by the interaction between ocean water and fresh water discharges (MacCready & Geyer, 2010). For coastal environments, complexities can also arise because the intertidal zones may become dry and blocked during low tides (Yang & Khangaonkar, 2009). As a result, in the past decades numerical models have acted as a powerful tool in the study and prediction of estuarine hydrodynamics.

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One of the most difficult aspects is that the numerical models for wetlands have to cope with shallow water depths and complex bottom topography. For estuarine wetland systems, the wetting and drying processes due to the changes of surface water elevation are essential (Ji *et al.*, 2001). Consequently, in order to simulate the estuarine hydrodynamics accurately, high-resolution bathymetric data are necessary, not only for deep river channels but also for intertidal zones. Elevations and geometry details of intertidal zones with subtidal channels have been shown to play an important role in transport and exchange processes in estuaries (Ralston & Stacey, 2005). Airborne LiDAR (Light Detection And Ranging) is a method of detecting distant objects and determining their position and other characteristics by analysis of pulsed laser light reflected from their surfaces. Airborne LiDAR is now being applied in coastal environments to produce accurate, high resolution, cost-efficient bathymetric and topographic datasets (Schmid *et al.*, 2011). Traditional techniques and satellite remote sensing are generally unable to penetrate forest canopies and are not at a sufficiently high level of resolution to depict the micro-topography of mangrove communities. Therefore, LiDAR data can be especially useful for mangrove covered areas even under dense canopies (Knight *et al.*, 2009). With the help of LiDAR data, the accuracy of model bathymetry in the tidal flats can be improved significantly and features of multiple tidal channels can be better represented (Yang & Khangaonkar, 2009).

Located in Tampa Bay area, the Terra Ceia Aquatic Preserve (TCAP) is characterized by inlets and embayments of a drowned shoreline. With increasing development, recreation and economic pressures, the aquatic resources have the potential to be significantly impacted. The TCAP area is composed of open water, inlet bays and tidally influenced creeks. The Terra Ceia River and Frog Creek provide fresh water to the wetland system. A better understanding of the hydrodynamics, such as water level, salinity, stratification, destratification, flushing time and residence time, is urgently needed to provide suggestions for resource management and protection. A large-scale ecosystem restoration project has been undertaken in the wetlands associated with Terra Ceia Bay. As components of a wetland restoration project, three intertidal lagoons have been proposed offline of the Frog Creek System. It is unknown whether the proposed intertidal lagoons will have a significant effect on the existing salinity regime of Frog Creek System. Temperature, salinity and tidal fluctuation are all important physical factors influencing the estuarine environments. For instance, mangroves require an annual average water temperature of about 19°C to survive and mangroves have adapted to the saltwater environment by excluding salt from plant tissues. Although they can survive in fresh water, salt water is a key element in reducing competition from other plants, thus allowing mangroves to flourish. Consequently, understanding the structure and variability of the salinity regime in estuaries is critical to ecological and engineering management decisions. The objective of this work, therefore, is to develop a three-dimensional hydrodynamic model to evaluate the effect of the proposed lagoons on the salinity regime and provide suggestions to ecosystem management. Airborne LiDAR data will be employed to depict the micro-structure of the topography in mangrove covered areas.

DATASETS AND STUDY AREA

Study area

Adjacent to the Gulf of Mexico, TCAP is located along mid-peninsula Florida and is characterized by a humid subtropical climate. The average low air temperature for the area is 16°C; and this generally occurs in January. The average high temperature for the area is 28°C; occurring between July and August. The climate of this area is significantly influenced by the Gulf of Mexico. The annual average rainfall is approximately 1100 mm and occurs primarily during a distinct wet season (June to September) with frequent convective summer thunderstorms. According to Meyers *et al.* (2007), the typical values of evaporation rates for the Tampa bay area range from near zero to about 0.60 cm/day and the long-term average evaporation is 0.28 cm/day.

With the mouth located at the northern end of Terra Ceia Bay, Terra Ceia River and Frog Creek extends in a north and north-east direction for approximately 3.5 km, then continues east for about 8 km (Fig. 1; Zhang *et al.*, 2012). Both Terra Ceia River and Frog Creek are shallow with reduced tidal action and are covered by mangroves. As there is no clear difference between Terra Ceia River and Frog Creek, they are usually considered a single entity and are collectively referred to as the Frog Creek System in this paper. The tidal creek connecting the Frog Creek System

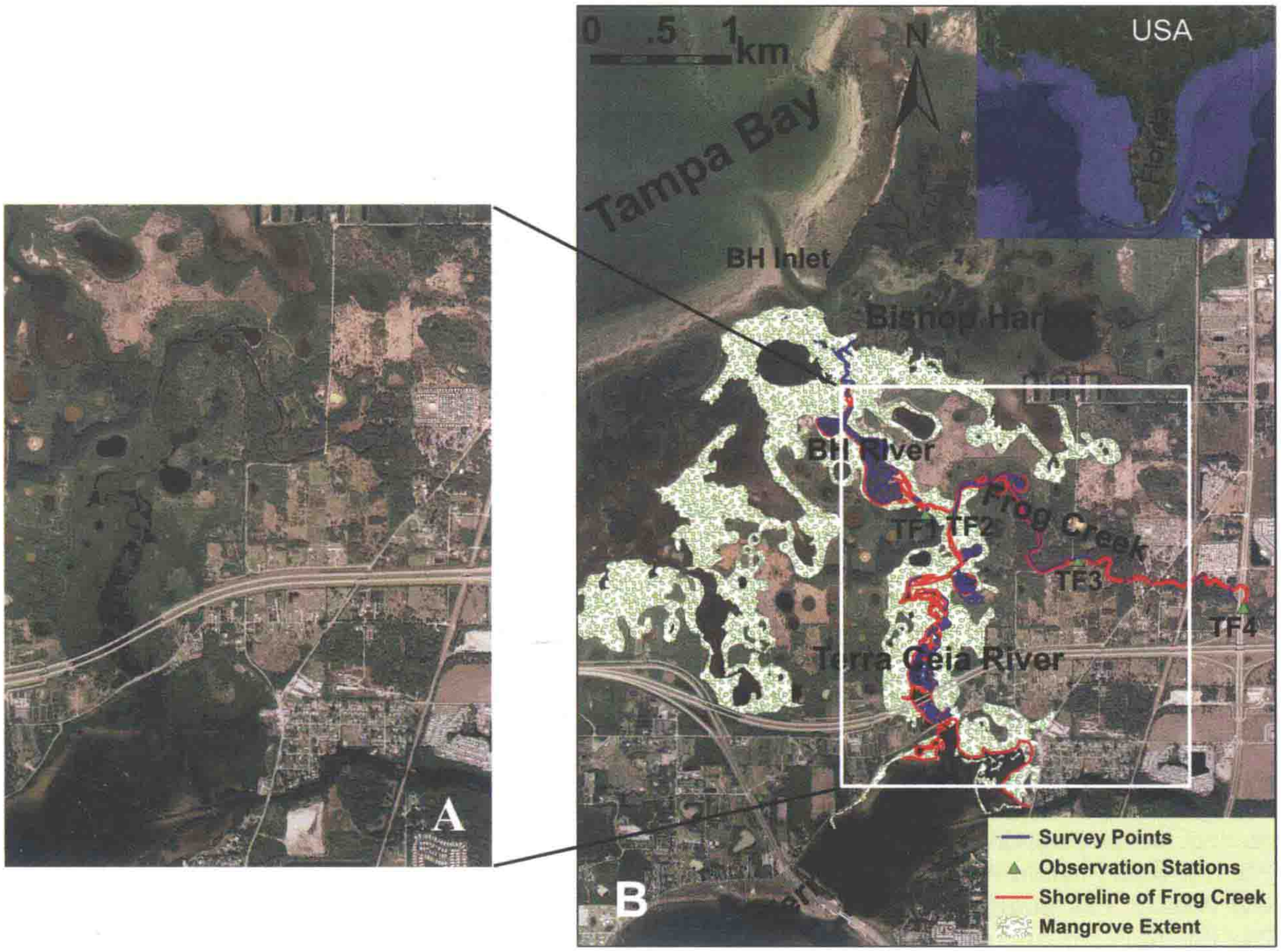

Fig. 1. Study area, showing: (A) The satellite image of the Frog Creek System; (B) Detailed information of the Frog Creek System, where red lines denote the river contours, blue lines indicate the bathymetry survey points, green triangles are the locations of observation stations in the channel and the mangrove covered areas are indicated by the green stippled regions.

to Bishop Harbor is a distinct and unnamed creek, called Bishop Harbor (BH) River in this work. An analysis of sea-level at St. Petersburg shows that about 24% of the variance is associated with the semi-diurnal tidal component, 42% with the diurnal tidal component; and 31% with longer time scales, mostly of non-tidal origin by weather and steric effects (Weisberg & Zheng, 2006). The tidal range is small, with an average value around 0.3 m. No measurements are available but flow velocities associated with tidal dynamics are also weak.

As shown in Fig. 1, the tidally influenced portions of the Frog Creek System are covered by mangrove communities (mangrove forests, mangrove swamps and mangrove islands). There are also some natural lagoons with karstic features which are connected to the Frog Creek System. Water depths range from 0.3 to 1.0 m for most of the study area. The average depth is less than 1.0 m and the deepest depth occurs in the eastern portion of the Frog Creek System, about 1.5 m to 2.3 m. Based on observations over more than four years, the monthly average values of the river discharge of the Frog Creek System are $0.26\,m^3\,s^{-1}$ for June, $0.80\,m^3\,s^{-1}$ for July, $0.95\,m^3\,s^{-1}$ for August, $1.32\,m^3\,s^{-1}$ for September and around $0.10 \pm 0.03\,m^3\,s^{-1}$ for other months. Storm-induced maximum inflows can be as large as $20.00\,m^3\,s^{-1}$ and usually occur in August and September. In the eastern part of the Frog Creek system, these storm-induced inflows can lead to high current velocities with a value larger than $1.0\,m\,s^{-1}$.

Data sources

The USGS LiDAR data for Frog Creek System, with a horizontal resolution of 1.5 m by 1.5 m are available. It is especially useful to depict the micro-topography of mangrove covered areas. With the help of LiDAR, the grid steps for the numerical model in this work can achieve a minimum resolution of around 4 m. In order to obtain the accurate depth of the channels and natural karstic lagoons, several surveys were carried out during the favourable high tide using RTK; and the survey lines are shown in Fig. 1B (blue lines).

The locations of observations used in this work are shown in Fig. 1B. Hourly water level and wind data for Port Manatee Station and hourly atmosphere pressure data for St. Petersburg Station were obtained from the National Oceanic and Atmospheric Administration-National Ocean Service (NOAA-NOS). The hourly water level data for Manatee River Station, located in Terra Ceia Bay, were provided by the U.S. Geological Survey (USGS). Supported by the TCAP water quality monitoring project, the 15 minutes water level data of TF1, TF2 and TF3, located in the channel of the Frog Creek System, were measured by the USGS. For the same time period, the 15 minutes surface and bottom salinity data of Manatee River Station, TF1, TF2 and TF3, were also obtained from the USGS. Hourly precipitation data for the Frog Creek System were provided by South-west Florida Water Management District (SWFWMD). The hourly inflow data for station TF4, the most upstream station, were obtained from a USGS stream gage located at the eastern end of Frog Creek. All data were quality controlled and gap-filled.

Proposed engineered ponds

As indicated by Fig. 1B, the mangrove communities have been degenerated in the northern and north-eastern parts of the Frog Creek System. As part of the Surface Water Improvement and Management (SWIM) Program, three intertidal ponds, A, B and C, shown in Fig. 2, have been proposed in order to recover the wetland environments for marine species. Station TF3 is located in the upstream areas of Frog Creek, upstream of the three ponds. At this station, the high bottom salinities indicate that the saline water can persistently intrude here as a result of favourable bathymetry for upstream transport of saline water, especially under moderate and low inflow conditions. According to the bathymetry survey results, the values of bottom elevation are around −0.7 m near TF1, −1.0 m near TF2 and −2.0 m near TF3; all values refer to the North American Vertical Datum of 1988 (NAVD88). This persistent salt intrusion near TF3 will benefit the purposes of proposed lagoons. The lagoons will be connected to the main waterway of the Frog Creek System through canals which will be deeper than the lagoons to allow for sediment deposition.

MODEL DEVELOPMENT

Model description

A three-dimensional hydrodynamic model, EFDC (Environmental Fluid Dynamics Code) has been modified and used in the present study. EFDC has been applied successfully in many water bodies such as estuaries, lakes, rivers and coastal bays (Ji *et al.*, 2001; Shen & Lin, 2006; Xu *et al.*, 2008; Gong *et al.*, 2009; Shi *et al.*, 2009). EFDC solves the Navier-Stokes equations with free surface, which can simulate density, and topographically-induced circulation, tidal and wind-driven flows, spatial and temporal distributions of salinity, temperature and conservative/non-conservative tracers. It employs stretched (namely sigma) vertical coordinates and curvilinear, orthogonal horizontal coordinates. Another important reason for selecting the EFDC model is that it includes sediment and water quality modules, which will be suitable for future studies of the Frog Creek System.

The Mellor-Yamada's 2.5-level turbulence closure sub-model is implemented in the EFDC model (Mellor & Yamada, 1982). The turbulence sub-model calculates vertical eddy viscosity and diffusivity through simulation of turbulence energy and length scale. Vertical boundary conditions for the solution of the momentum equations are based on the specification of kinematic shear stresses. The bottom friction is described by the quadratic law with the drag coefficient determined by the logarithmic bottom layer as a function of bottom roughness height. Wind stress is specified at the water surface.

Model setup

The bathymetric measurements from *in-situ* RTK surveys and USGS LiDAR datasets are interpolated to the centre of model grids by using an inverse distance weighting method. Specifically, the values for the grids in the river channel are calculated from *in-situ* measurements and the values for the grids in mangrove areas are deduced