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# A case study of sediment transport in the Paranagua Estuary Complex in Brazil

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ABSTRACT

This paper presents transport of a mixture of cohesive sediments and sand in the Paranagua Estuarine Complex in the south of Brazil. The estuary houses a navigation channel from the Atlantic Ocean to a busy harbour. The channel requires frequent dredging owing to sediment deposition to maintain navigable depth for vessels. A three-dimensional process-based model for sediment transport coupled with wave-current models based on the Delft3D modelling system is constructed for the estuary. Extensive field data concerning current velocity, water level, salinity and suspended sediment concentration were collected. The flow model that is necessary to run the sediment transport model was calibrated and validated using field measurements. In this paper only the results concerning the sediment motion are presented. Calibration and validation of the numerical model show that the results of sediment transport represent the field conditions well. Additional support for the validity of the computed results is provided by field data pertaining to bathymetry acquired in 2005 and 2006. The present study gives insight into the motion of cohesive sediments and the morphological behaviour of the estuary, and should help operators maintain the channel for navigation.


## 1. Introduction

Sediment transport and morphological changes in estuaries have recently attracted great deal of attention due to environmental concerns and problems associated with siltation in harbours and navigation channels (Cronin et al., 2009; Giurdino et al., 2009; Villaret et al., 2012). Numerical modelling based on process-based approach has been widely applied to estimate sediment transport by fluid flow which is driven by forces arising from tides, waves, wind and salinity. Chu et al. (2010) apply the two-dimensional version of the process-based model of Delft3D to study sediment transport in the Yangtze estuary. Often there are uncertainties arising from scarcity of field measurements with respect to sediment motion to calibrate and validate the numerical models (Giurdino et al., 2009). Errors are very likely to occur in the measurement of sediment concentrations in the field (Van Rijn et al., 2003; Marone et al., 2012). The various properties defining the cohesiveness of the sediments are difficult to measure in situ (Partheniades, 2009). Over the years modellers of flow have been using 2D depth-averaged models for the computation of flow field and sediment motion. Now three-dimensional models are being applied to take account of the depthwise variations of velocity, sediment concentration etc (Lesser et al., 2004). This paper addresses the details of transport of a mixture of cohesive sediments and sand in the Paranagua Estuarine Complex (PEC) in Brazil. Three-dimensional process-based Delft3D model supported by field observations is set up for the PEC. It is hoped that the results presented herein will give further insight into the motion of cohesive sediments leading to the prediction of the morphological behaviour in the PEC and help engineers maintain the channel for navigation.

## 2. Area of study

The PEC (25° 16′ 34“ S; 48° 17′ 42“ W) is situated in the State of Paraná in the south of Brazil (Fig. 1). The location of the harbour is shown in the inset in Fig. 1. The estuarine complex comprises of two major water bodies, each of which consists of two bays. The water body along the north–south direction is about 30 km long and about 13 km wide and it includes the Laranjeiras and

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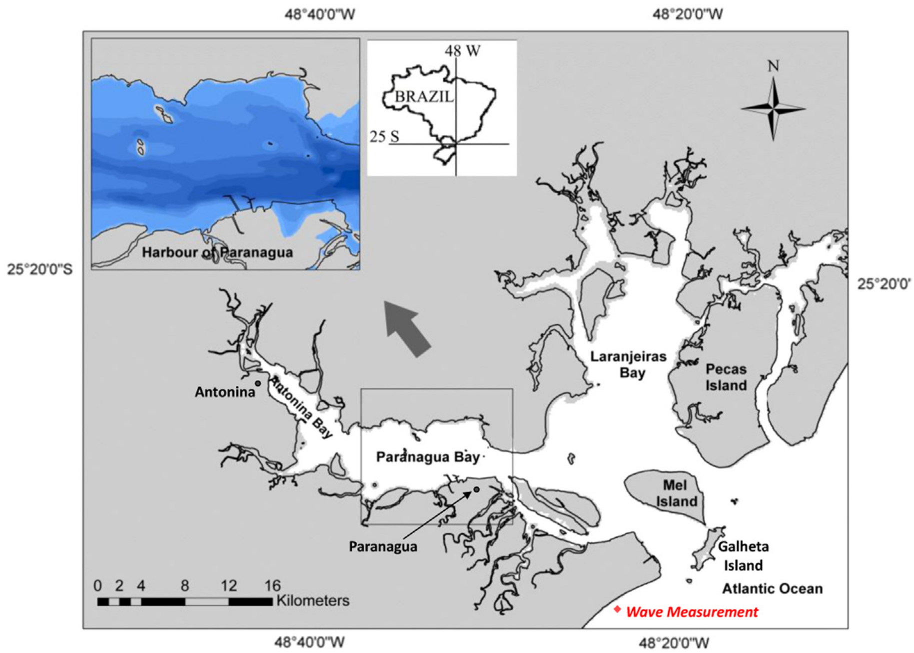


**Fig. 1.** Map showing the Paranaguá Estuarine Complex (PEC). Insets: locations of PEC on the coast of Brazil and Paranagua Harbour in the PEC.

Pinheiros bays. The other in the south along the East–West direction is about 50 km long and 7 km wide containing the Paranaguá and Antonina bays. The overall area of the PEC is about 612 km$^2$. The mean water depth in the PEC is about 5 m but along the navigation channel it can be as much as 20 m.

Tides are semi-diurnal with diurnal inequalities up to six especially for neap tides. The mean neap and spring tidal ranges are about 1.3 m and 1.7 m respectively at the mouth of the estuary. They are 2.0 m and 2.7 m respectively in Antonina in the upper reaches of the PEC (Marone and Jamiyana, 1997). The tidal range in the navigation channel is less than 2.0 m and the hydrodynamics in this region of the PEC are governed essentially by a micro-tidal regime. Numerical studies of flow field show that the depths and currents in the PEC are determined basically by the tides. The effects of waves generated locally by wind are negligible with respect to currents when the wind speed is less that 6.0 m/s. The estuarine system is classified as partially mixed. The period of the waves at the coast is between 6 s and 10 s, and the significant wave height is between 0.5 m and 1.5 m. Wave heights of about 2–3 m have been observed during extreme weather conditions at the southern inlet (Marone and Camargo, 1994). The tidal prism is estimated as 1.3 km$^3$ (Camargo and Harari, 2003). The direction of waves offshore is essentially the same as the main wind direction from the southeast. The presence of Mel Island and Galheta shoals at the mouth of the estuary reduce the severity of waves that enter the estuary from the ocean (Lamour et al., 2004).

The sediments in the PEC consist mainly of sand and fine silt in the area in the vicinity of the river mouths and very fine sand at the mouths of the PEC. In the inner area the sediments may be categorised as muddy (Angulo et al., 2006). Fig. 2 displays the sediment size distribution in the PEC according to Lamour et al. (2004) confirmed by the observations of Angulo et al. (2006). As can be seen in Fig. 2, fine silt occupies the PEC extensively including the area of Paranagua Bay where the harbour is located (see also Fig. 1).

Most of the investigations that have been made so far, relating to sediment motion in the PEC are qualitative. According to Angulo et al. (2006) the dredging of the navigation channel of the PEC has been interfering with the natural sediment transport to cause accelerated morphological changes. The study of coastal morphology by Lamour et al. (2004) concludes that the beach along the south of the PEC is most vulnerable to erosion while the area north of the PEC is free from erosion. Using the measurements of velocity vectors in a channel at 3.5 km from the coast, Noernberg et al. (2007) deduce that the bed load of sediments transported by tidal currents is essentially normal to the coast. They find that the offshore high-energy waves are responsible for the sediment motion along the coast. By means of a hydrodynamic-morphological model coupled to a wave model Dahlem et al. (2008) investigated the sediment transport along the beach and the resulting sedimentation in the navigational channel.

## 3. Purpose and methodology of the present study

Studies of sediment transport in the PEC so far have been exploratory and detailed study is required for the functioning of the harbour and the conservation of the estuary. This paper presents a three-dimensional model for cohesive sediment transport based on Delft3D modelling system. The concentrations of suspended matter at several locations in the PEC were measured during neap and spring tidal cycles. The validation procedure shows that the model is capable of computing sediment concentrations in the PEC satisfactorily. The results obtained from the field measurements and the numerical set up are useful to quantify the sediment transport in the PEC.

The Delft3D flow model was used to compute current velocities, water levels and salinities at various locations in the PEC. The flow, the wave and the sediment transport models of Delft3D were coupled together and they were calibrated and validated using relevant field measurements at different locations in the PEC. This paper confines itself to the presentation of results relevant to sediment transport in the PEC. Information regarding measured water depths and computed current velocities are also provided. Some field observations of the morphological changes along the navigation channel are included in this paper to relate them to the sediment activity. The model for sediment transport presented here and the morphology model when it is completed should be useful to the operators of the harbour in arriving at

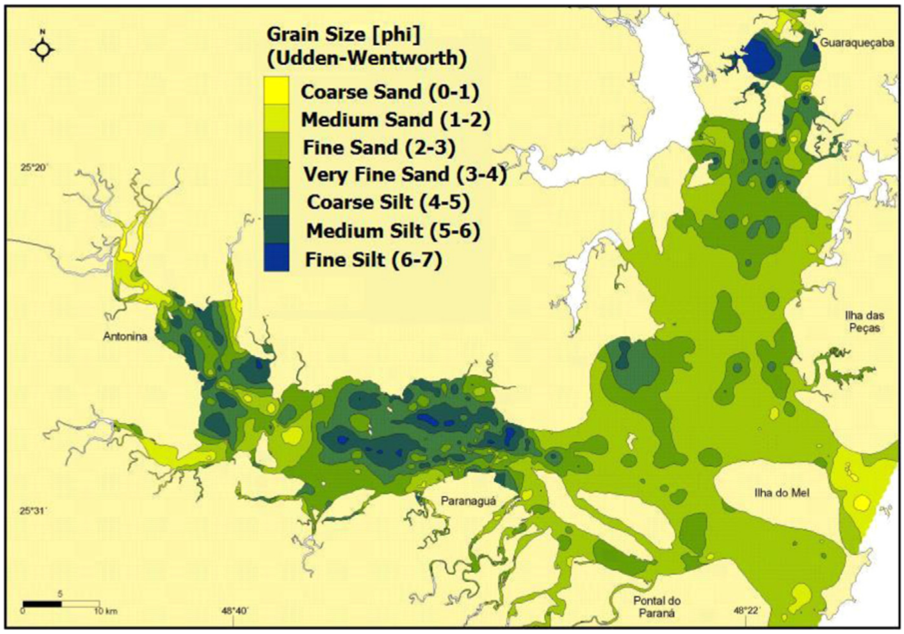


**Fig. 2.** Sediment size distribution in the PEC (Lamour et al., 2004).

decisions pertaining to the maintenance and dredging of the navigation channel.

## 4. Field measurements

In this paper only a brief review of the measurements carried out in the PEC is presented. From a moving vessel measurements of current velocities and sediment concentrations were made simultaneously at key cross-sections (Fig. 3). Velocities were measured by acoustic profilers and sediment concentrations were obtained by direct water sampling. Data were collected at stations at L1 to L10 and $L_*$. Detailed measurements were made across cross-sections along T1 and T2 near the harbour basin and T3 at the southern mouth of the estuarine complex. The locations of T1, T2 and T3 and their cross-sectional shapes are shown in Fig. 3. T1 is over 3000 m wide with water depths between 5 m and 15 m across the section. T2 is about 2000 m wide with a sand bar in the middle with water depths varying from about 5 m to 15 m. T3 is about 3000 m wide and the water depths there are up to 20 m. Transects were run obliquely to the axis of the navigation channel and continuously over entire tidal cycles. A large number of water samples for sediment concentration were collected during each measurement campaign.

To account for the seasonal variability, measurements were made to cover the neap and spring tidal cycles in September 2007 in winter and February 2008 in summer. Water samples for suspended sediment concentration were collected at about 1.0 m below the free surface and at about 1.0 m above the bed. The tidal range during the measurements in September 2007 was about 0.9 m during neap tides and about 1.7 m during spring tidal conditions. The wind speeds were below 6 m/s. At these wind speeds, the significant wave heights were quite small, and their effects on current velocities and sediment transport were found to be negligible. Table 1 presents the field conditions during measurements and the range of measured suspended material concentration. More detailed description of the flow conditions during the measurements is available from Marone et al. (2012).

Observations showed that the suspended sediment concentrations were generally low and less than about 0.22 kg/m$^3$ with very little variation throughout the tidal cycles (See Table 1). The observed concentrations during spring tides were generally greater than those during neap tides. The concentrations near the bed can be much larger than those at the free surface. In Figs. 4 and 5 are shown the variations in water levels measured at stations L5, L6 and $L_*$. In the same figures are also shown the computed current velocities and measured suspended sediment concentrations near the bed and below the free surface. Fig. 4 is for the neap tidal cycle during 4–6 of September 2007, and Fig. 5 is for the spring tidal cycle during 11–13 of September 2007. For station $L_*$, Fig. 6 displays the measured water levels, and sediment concentrations at 1.0 m above the bed and 1.0 m below the free surface for the neap tidal cycle on 14–15 of September 2008. In Fig. 6 are also shown the computed velocities near the bed and below the free surface. In Fig. 7, for station $L_*$ are plotted the measured water levels and sediment concentrations, and computed velocities for the spring tidal cycle on 21 February 2008.

## 5. Sediment transport model

### 5.1. *The numerical model*

The 3-D model of sediment transport for the PEC is based on the Delft3D Modelling Suite developed by Delft Hydraulics in the Netherlands. Delft3D consists of process-based models for simulation of flow, waves and sediment transport. The model takes account of the density gradients, wave generation and propagation, and sediment transport of cohesive and non-cohesive fractions. For a more detailed description of the model, reference is made to Lesser et al. (2004).

The model domain considered in this paper is shown in Fig. 8. The model area of 700 km$^2$ covers the PEC including the part of the coastal area adjacent to the river mouths. The bathymetry adopted in the model is based on the nautical chart published in 1995 by the Brazilian Navy. Further information is added using remote sensing images from thematic mapper Land Sat. Along the navigation channel, echo-sounding measurements were taken between 2004 and 2006, and used in the details of bathymetry. It should be pointed out that the bathymetry of substantial part of the PEC adopted in the numerical model is not up to date.

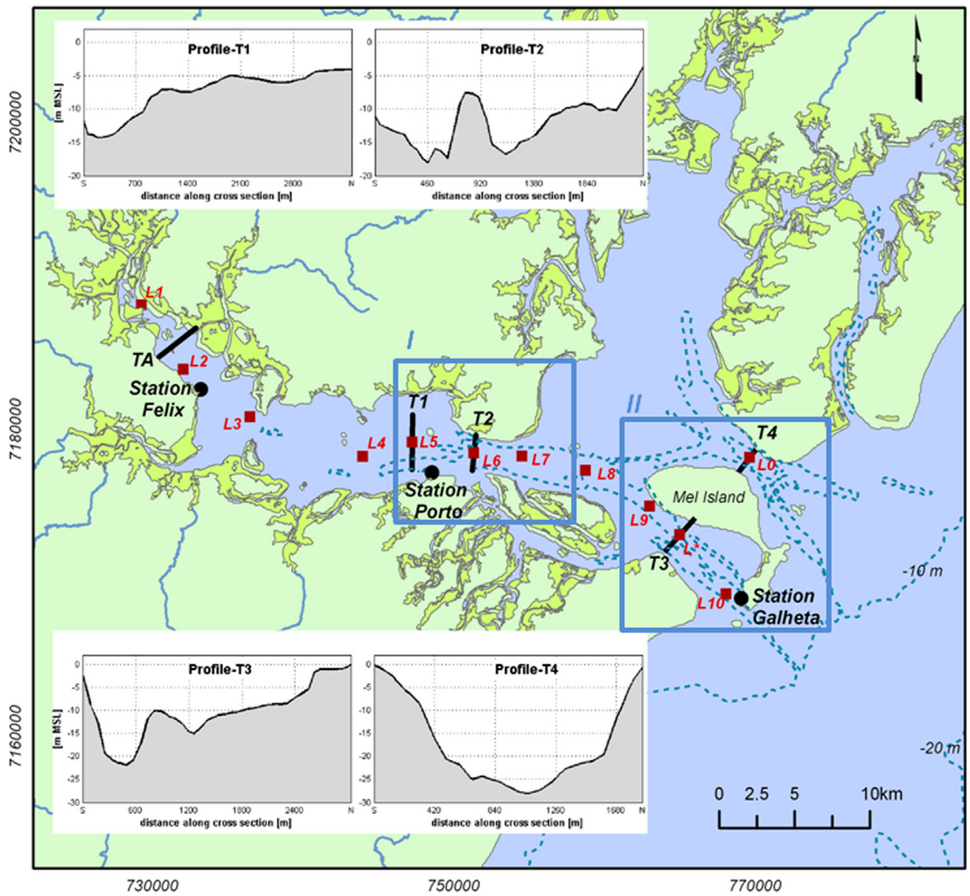


**Fig. 3.** Study area of the PEC showing measurement stations L1 to L10 and L*, the transects T1, T2, T3 and T4, and the bed profies along T1, T2 and T3.

**Table 1**
Overview of the field data sets based on measurements from moving vessels.

| Station | | Date | Tidal range (m) | No. of samples per station | Wind velocity (m/s) | | Range of salinity (PSU) | Max. Point velocity (m/s) | Range of suspended sed. Conc. (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Max | Mean | | | |
| Calibration | T1 | Neap tide 05–06.09.07 | 1.3 | 7 | 3.8 | 1.9 | – | – | 0.004–0.046 |
| | | Spring tide 11–12.09.2007 | 1.5 | 10 | 4.9 | 1.9 | 24–25 | 1.56 | 0.004–0.091 |
| | T2 | Neap tide 05–06.09.07 | 1.3 | 7 | 3.8 | 1.9 | – | – | 0.002–0.184 |
| | | Spring tide 11–12.09.2007 | 1.5 | 11 | 4.9 | 1.9 | 25–26 | 1.90 | 0.003–0.124 |
| | T3 | Neap Tide 04–05.09.07 | 1.3 | 13 | 3.8 | 2.0 | – | – | 0.005–0.054 |
| | | Spring tide 12–13.09.2007 | 1.6 | 14 | 4.9 | 2.2 | 28–29 | 2.90 | 0.004–0.217 |
| Validation | T3 | Neap tide14–15.02.2008 | 0.9 | 15 | 6.2 | 2.7 | – | – | 0.005–0.023 |
| | | Spring tide 20–21.02.2008 | 1.72 | 6 | 6.0 | 3.3 | – | – | 0.014–0.040 |

The sediment transport in the PEC is computed for the tidal flow including waves. The flow model was calibrated and validated with respect to field data concerning water depths and current velocities at various locations in the study area. The sediment transport model is calibrated and validated as discussed later. The model settings for calibration and validation of the flow model are presented in Table 2.

### 5.2. *Suspended sediment transport*

In Delft3D the amounts of sediment transported in suspension for mud and sand fractions are obtained by solving the advection-diffusion equation. A distinction is made between “mud” and “sand” to account for the different formulations necessary for bed-exchange with the water column and for the settling

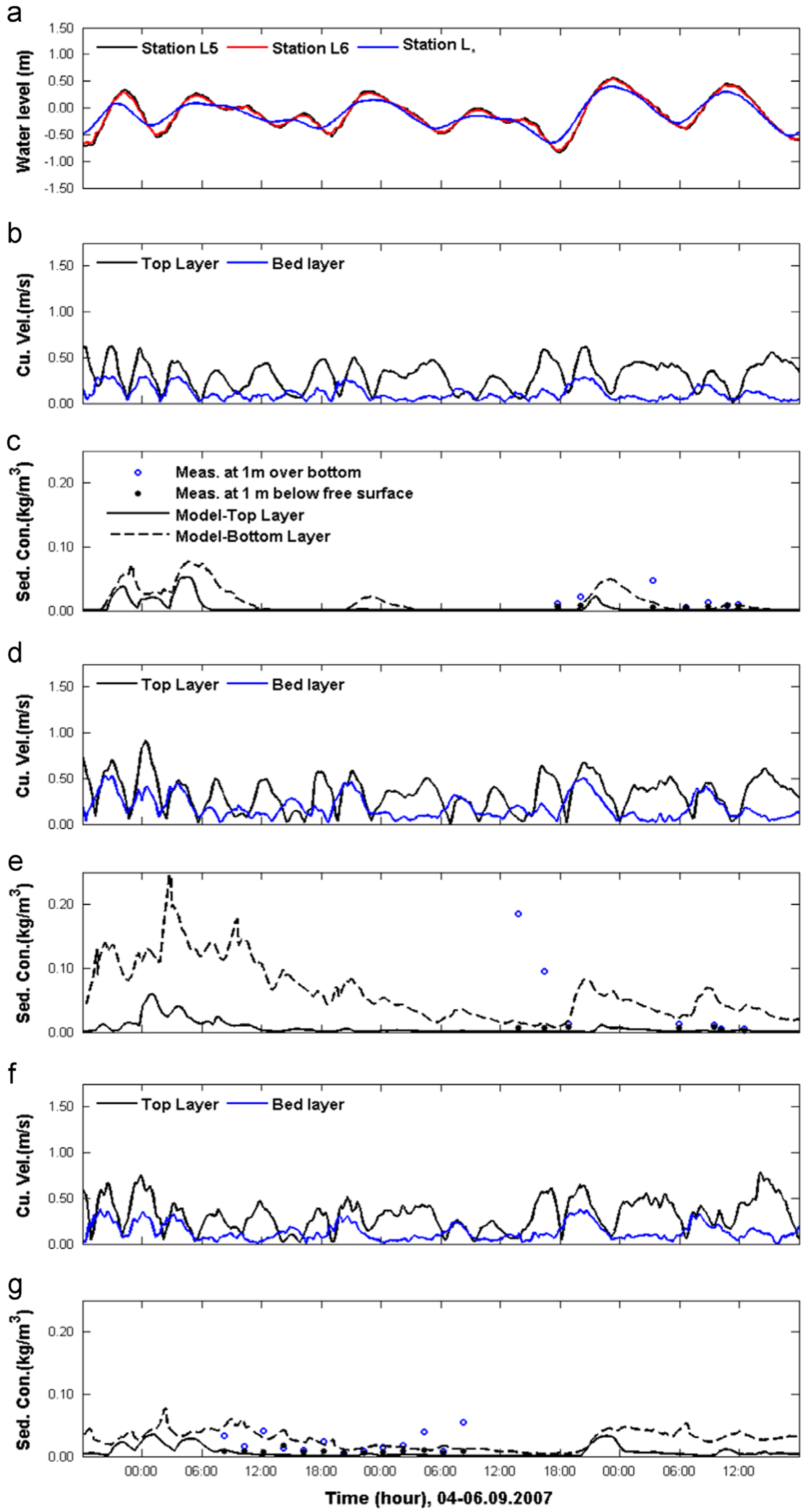


**Fig. 4.** Computed and measured sediment concentrations near the bed and below the free surface at Stations L5, L6 and L* for neap tidal cycle from 4 to 6 September 2007. Also shown are measured depths and computed velocities.

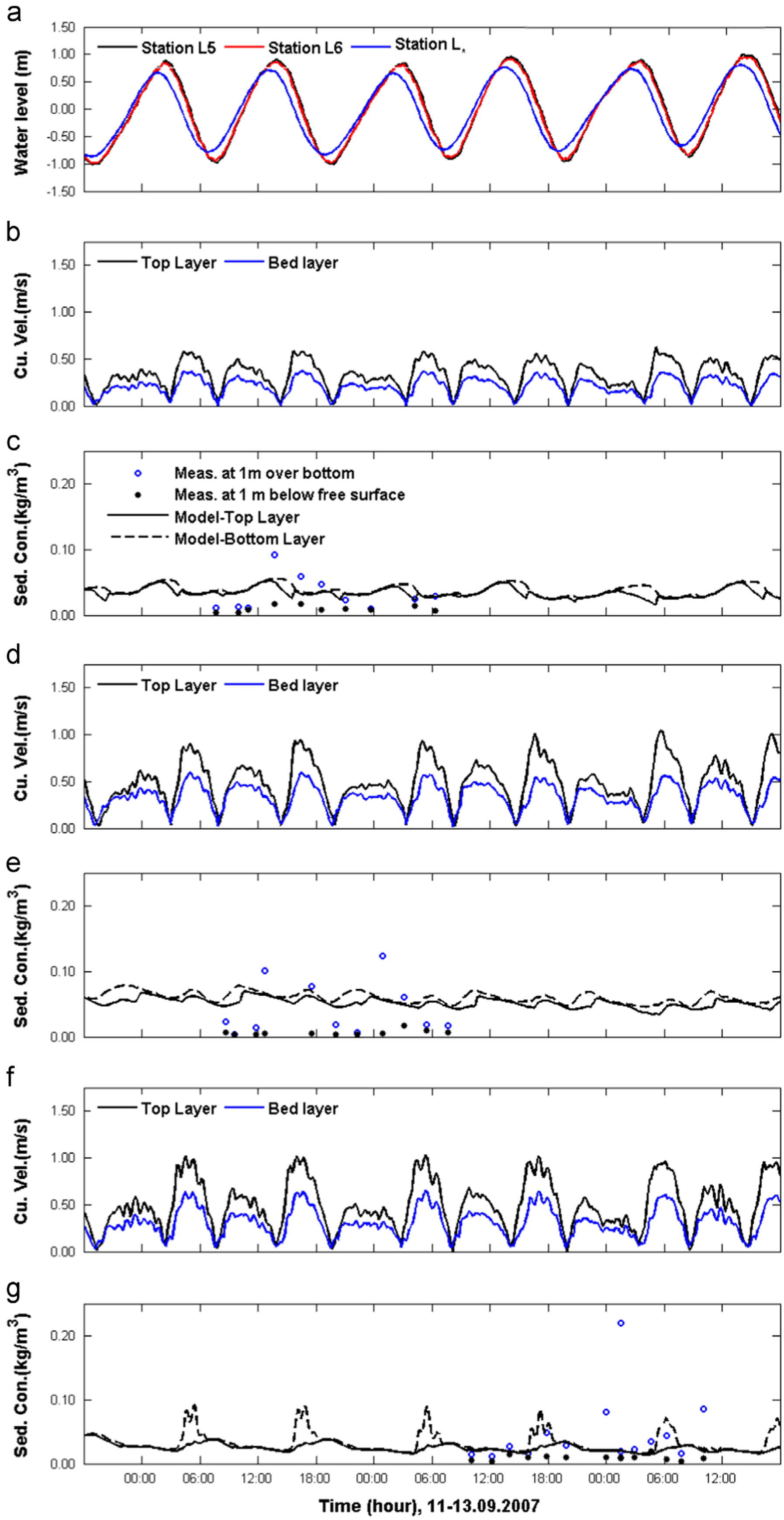


**Fig. 5.** Computed and measured sediment concentrations near the bed and below the free surface at Stations L5, L6 and L* for spring tidal cycle from 11 to 13 September 2007. Also shown are measured depths and computed velocities.

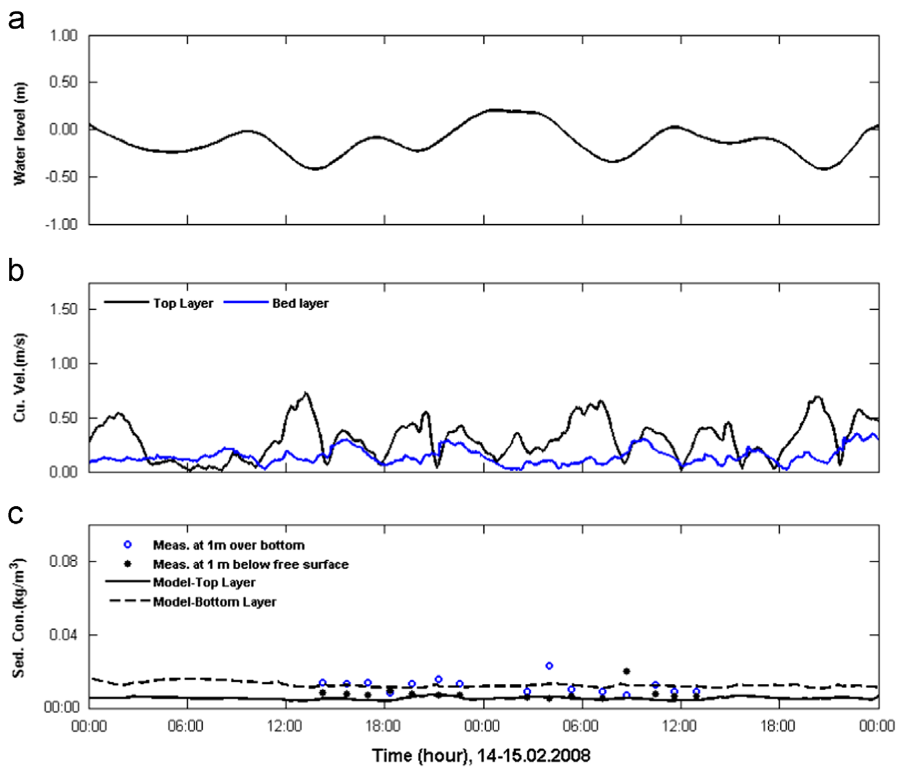


**Fig. 6.** Computed and measured sediment concentrations near the bed and below the free surface at Stations $L_*$ for neap tidal cycle from 14 to 15 February 2008. Also shown are measured depths and computed velocities.

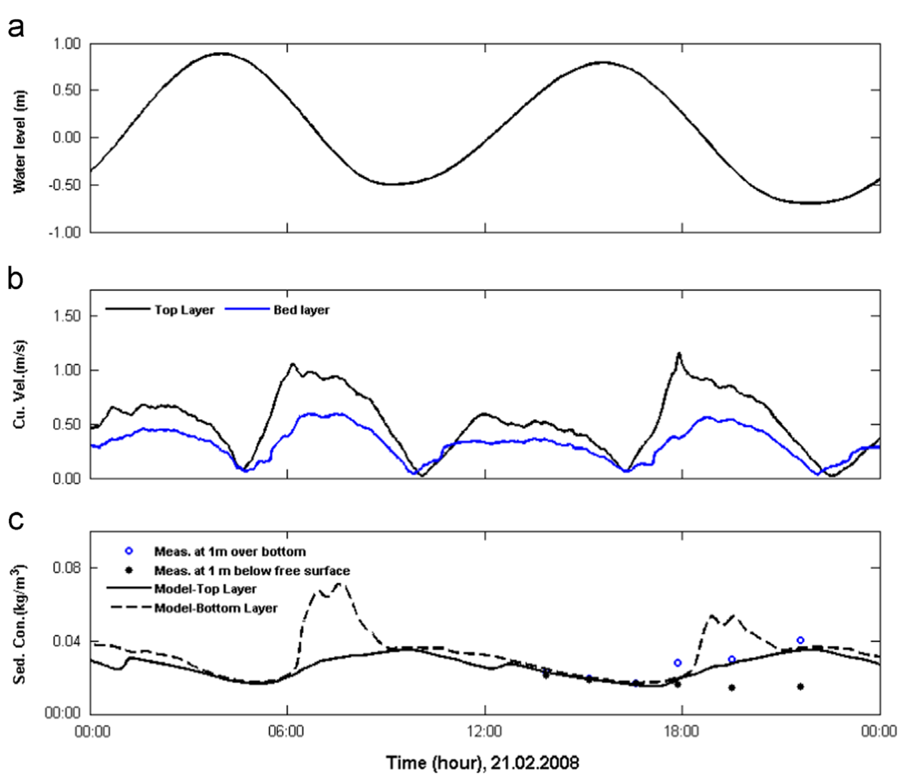


**Fig. 7.** Computed and measured sediment concentrations near the bed and below the free surface at Station $L_*$ for spring tidal cycle from 21 February 2008. Also shown are measured depths and computed velocities.

velocities. The effects of suspended sediments on density fields are included by incorporating the weight of each sediment class in the equation of state for sea water density. The settling velocities of the sandy fractions are calculated following the method proposed by Van Rijn (1993). The exchange of sediments with the bed is taken care of by means of separate sources and sinks for each fraction placed near the seabed (Van Rijn, 1993). Calibration factors are introduced to control the magnitude of suspended sediment transport. A reference height close to the bottom is defined at which sediment concentration is specified. For the mud fraction the vertical flux between the bed and the water column for erosion or deposition, and the flocculation of particles under the action of currents are based on the formulation due to Partheniades and Krone (see Partheniades, 2009). The erosion rate depends on the erosion parameter, and the ratio of the bed shear stress to the critical shear stress for erosion. The deposition rate is a function of the settling velocity, sediment concentration and the ratio of the bed shear stress to the critical shear stress for deposition. In this study, neither field nor laboratory data are available for critical shear stress etc., for the cohesive sediment fractions in the PEC. The required values have been chosen, guided by the studies of previous investigators (Whitehouse et al., 2000; Lumbor and Pejrup, 2005; Lopes et al., 2006; Van der Harm and Winterwerp, 2001). Table 3 presents the range of values due to different investigators. The model of the present study is fine-tuned to obtain appropriate values for the critical shear stresses for erosion and deposition, settling velocities and sediment erosion rates. The properties related to cohesive sediments are given in the Table 3. Note that in Table 3 two different sets of values, one for neap tides and the other for spring tides are given in the last two columns. The turbulent mixing and the bottom roughness during more energetic spring tides manifest themselves in values different from those during relatively calm neap tides.

Waves are capable of agitating sediments near the bed and make it possible for the prevailing currents to transport sediment load more than that without waves. The effect of waves is taken account through the vertical diffusion coefficient for the sediments at the bottom of the reference cell.

### 5.3. Bed load

Bed load sediment transport for sandy fractions is calculated following Van Rijn, 1993. The direction of the bed load transport is taken to be parallel to the flow in the bottom computational layer.

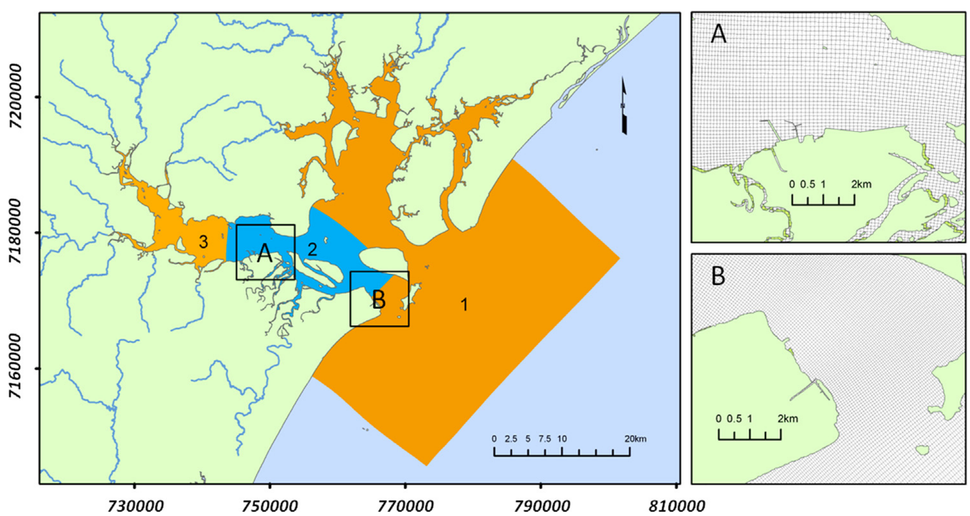


**Fig. 8.** Model domain. Insets: areas A and B.

**Table 2**
Flow model settings.

| Model | Parameter | Value | Description |
|---|---|---|---|
| Flow | $\Delta t$ | 60 | Computational time step (s) |
| | $\rho_w$ | 1025 | Water density (kg/m$^3$) |
| | $\rho_{air}$ | 1 | Air density (kg/m$^3$) |
| | $g$ | 9.81 | Gravitational acceleration |
| | $K$ | 1 | Horizontal eddy diffusivity (m$^2$/s) |
| | $k_s$ | Map | Equivalent roughness size (m) |
| | Threshold depth | 0.1 | Threshold depth for exposure and flooding (m) |
| | $\nu$ | 0.1 | Horizontal eddy viscosity (m$^2$/s) |

**Table 3**
Properties of the cohesive sediment fraction used in the model set up.

| Parameters | Ranges adopted in previous studies* | Calibrated values for the PEC | |
|---|---|---|---|
| | | Neap tides | Spring tides |
| Critical shear stress for erosion [N/m$^2$] | 0.1–3 | 0.1 | 1 |
| Critical shear stress for deposition [N/m$^2$] | 0.05–0.3 | 0.2 | 0.5 |
| Settling velocity [mm/s] | 0.01–0.1 | 0.5 | 0.1 |
| Sediment erosion rate [kg/m$^2$s] | 0.000005–0.0001 | 0.00025 | 0.00 01 |

* Whitehouse et al. (2000), Van der Harm and Winterwerp (2001), Lumbor and Pejrup (2005), Lopes et al. (2006).

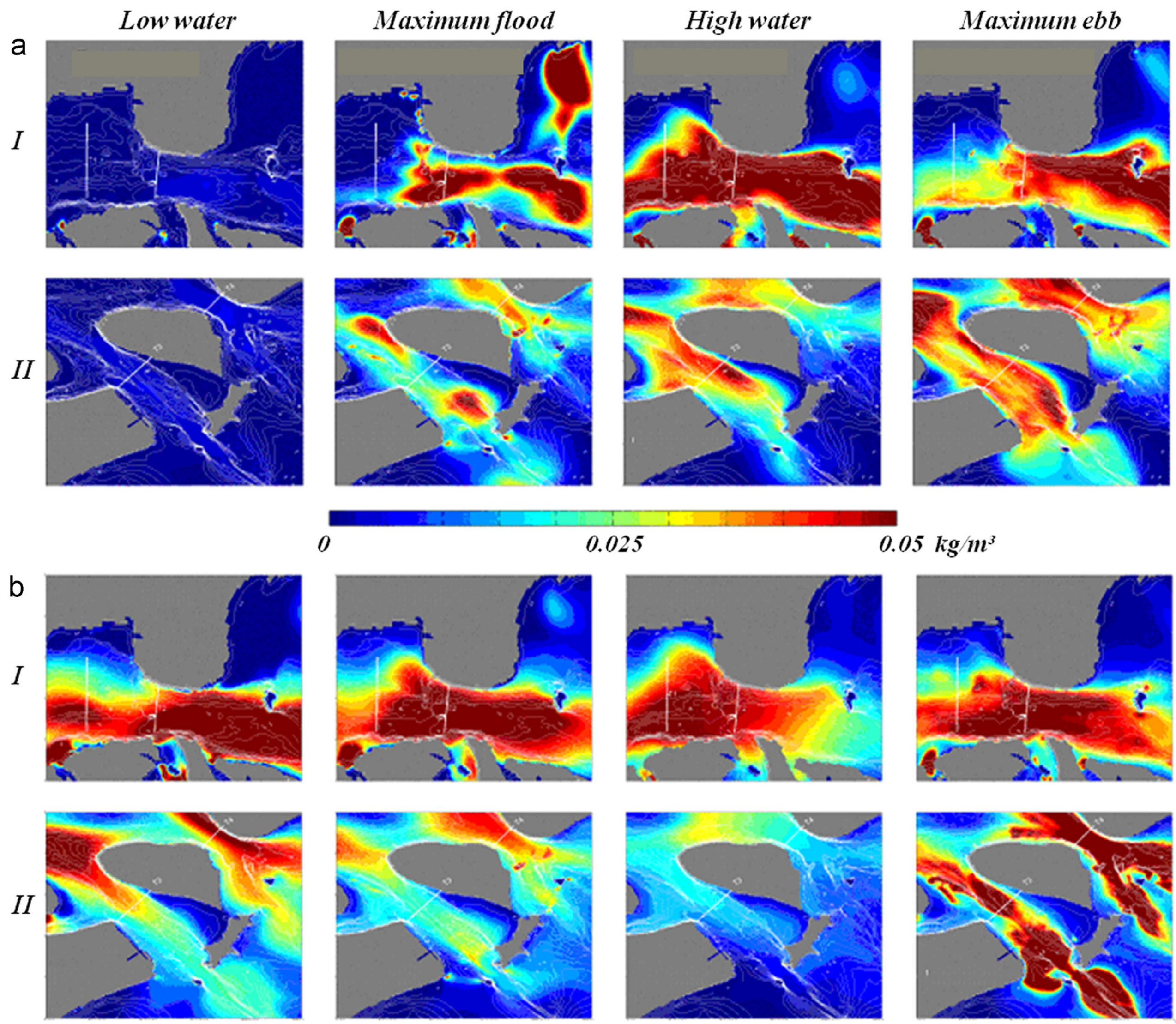


**Fig. 9.** Distribution of suspended sediment concentration at the *bottom layer* of depth during neap and spring tides.

For simulation including waves, the magnitude and direction of bed load on a horizontal bed are estimated initially using an approximation that accounts for the effects of wave orbital asymmetry on bed load. The direction of bed load in the presence of waves is determined considering two contributions, one induced by the currents in the direction of the near-bed velocities and the other due to waves in the direction of wave propagation. A third contribution included in the bed load transport vector is an estimate of the suspended sediment transport due to the effect of wave asymmetry within about 0.5 m of the sea bed. These three separate contributions are added to determine the bed load. The effects on the bed load due to the longitudinal and lateral bed slopes are also taken into account.

### 5.4. Domain boundaries

Along the sea boundaries in the Atlantic Ocean, measured water levels and salinities are imposed. At these open sea boundaries, the rates of sediment transport were assumed to be in equilibrium and they are computed using the method of Van Rijn (1993). The sediment rates thus obtained are prescribed at the open sea boundaries. At the boundaries where rivers bring fresh water into the PEC, equilibrium sediment loads calculated by the method of Van Rijn (1993) are used and the salinities are also specified there.

Sensitivity studies show that river discharges affect the sediment concentration in the PEC. The sediments carried by the rivers into the PEC contain much coarser elements than those within the PEC. According to Soares et al. (2012) and Fig. 2, sediments in the navigation channel are muddy. It is found that fresh water discharges affect the salinity and current velocities within the PEC. Therefore, the sediment transport is expected to be affected by the fresh water inflow. At present it is not possible to evaluate the river discharges with accuracy. However, sensitivity studies showed that the motion of river sediments which are mostly sandy, are very much limited to areas close to the river mouths because sand settles on the bed in those areas (Fig. 2).

### 5.5. Bed roughness

A numerical procedure due to Escobar and Mayerle (2006) that estimates the bed roughness has been used in the present study. Bed roughness has been found to influence current velocities. Sensitivity studies show that the effect of bed roughness in the PEC is not very significant as far as the cohesive sediments are

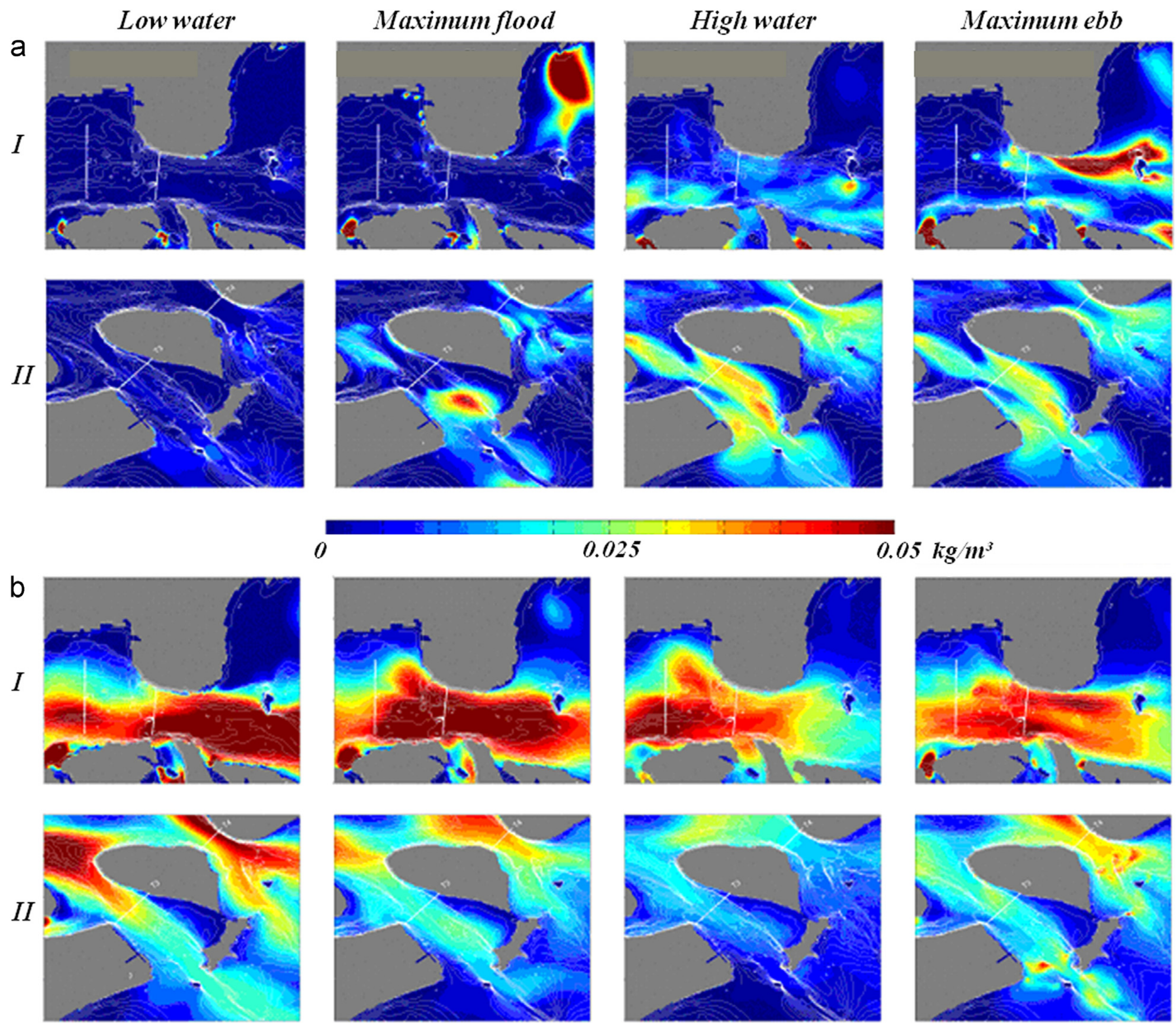


**Fig. 10.** Distribution of suspended sediment concentration at *top layer* of depth during neap and spring tides.

concerned because they are transported primarily in suspension in areas along the navigation channel.

### 5.6. Cohesive sediment transport

The effect of calibration factors to control the magnitude of suspended and bed load sediment transport of non-cohesive sediment fractions was investigated. Simulations were carried out for various amplification factors in the formulations of bed load and pick-up functions. It was found that the effects of calibration factor on the suspended load were noticeable at the southeastern and southern mouths of the PEC, at the river mouths and during short periods of spring tides. Near the mouths of the estuary at the Atlantic and the river mouths, the sediments are mostly non-cohesive. As mentioned before, the sediments transported in the middle part of the PEC from the harbour to the mouth at the Atlantic Ocean are muddy in character.

### 5.7. Calibration and validation

Calibration of the sediment transport model was carried out with respect to field data for suspended sediment concentration. The field conditions based on measurements from moving vessels for calibration and validation are given in Table 1. The calibration covered the neap and spring tidal cycles respectively during 4–6 of September 2007 and 11–13 of September 2007 (Figs. 4 and 5). Comparisons of the measured and computed values at the bottom and below the free surface were carried out for the sampling stations $L_5$, $L_6$ and $L_*$ at cross-sections T1, T2 and T3 respectively. Since most of the sediments in suspension within the PEC are of cohesive nature, emphasis was given to the tuning of parameters controlling the cohesive sediment fractions. Figs. 4 and 5 respectively show the measured and computed suspended sediment concentrations for the neap and spring tides. In these figures, the water levels are plotted. Current velocities below the free surface and near the bed are also shown.

In Fig. 6 are displayed the measured and computed suspended sediment concentrations at station $L_*$ for the neap tidal cycle on 14–15 February 2008, and in Fig. 7 for the spring tidal cycle on 21 February 2008. In the same figures the measured water levels and the computed current velocities at the top and bed layers at $L_*$ are also included. This validation exercise shows that the model set up represents the sediment transport in the PEC reasonably well both for neap and spring tides. The verification of the model in capturing the temporal variation encompassing the whole tidal cycle was not possible due to very low sampling rates.

As already mentioned, measurement of sediment concentration in flowing water in the field is prone to errors as observed by many investigators (see for example Van Rijn et al., 2003 and

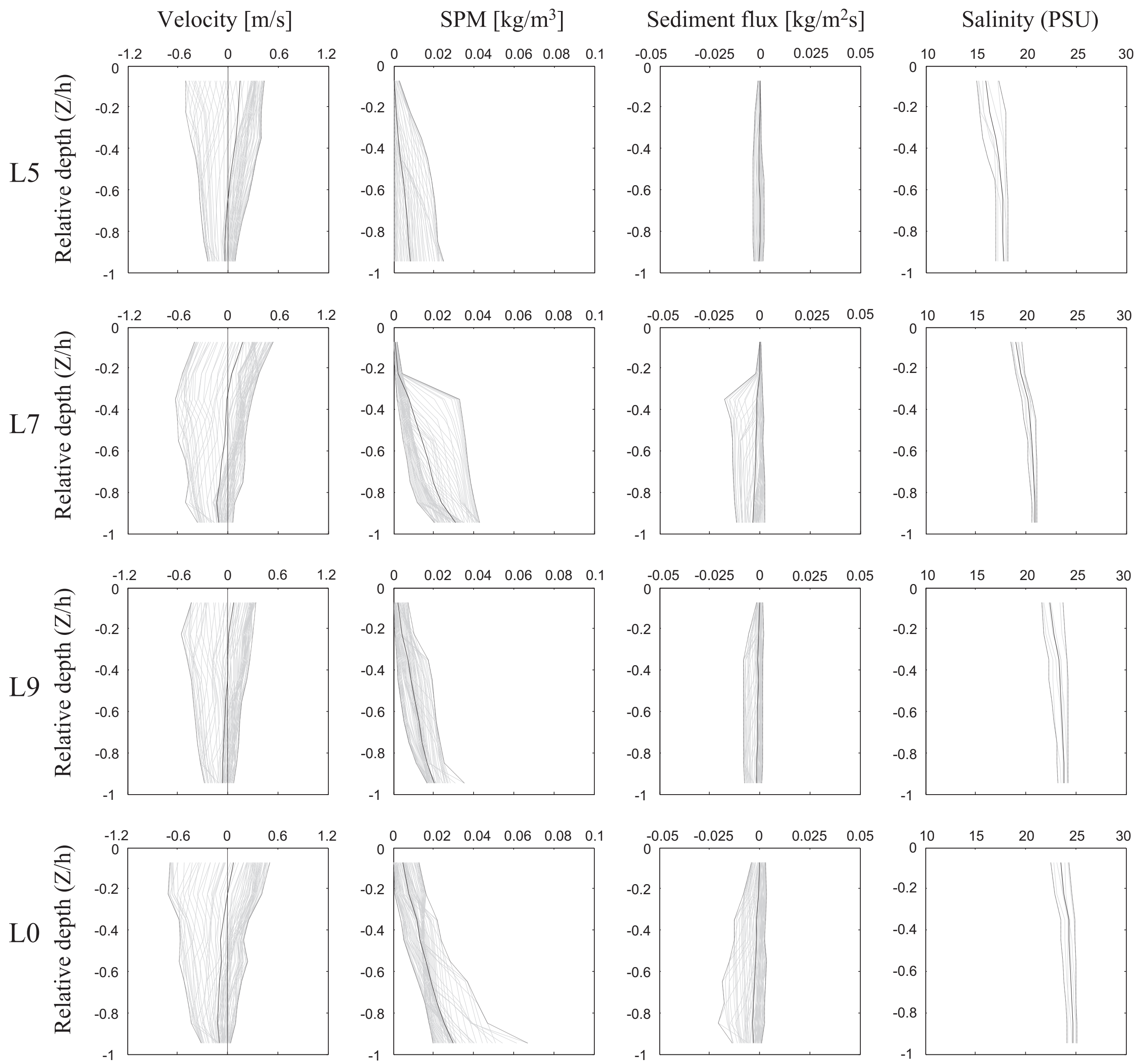


**Fig. 11.** Depthwise variations of computed velocity, suspended sediment concentration and salinity along the navigation channel for neap tidal cycle on 5th of September 2007.

Marone et al., 2012). In the present study, measurements were carried out from moving vessels and it was not always easy to place the water sampler at the precise point in the field below the free surface. It was particularly difficult to position the sampler near the bed due to the presence of bed forms. The computed and measured sediment concentrations at 1.0 m below the free surface and 1.0 above the bed as shown in Figs. 4–7 are generally in reasonable agreement. However at certain times at location L6, there are marked discrepancies between the field and computed results near the bed; these field data could have been affected by measurement errors.

Some of the difficulties encountered in the sediment transport modelling are discussed in Section 1. The equations that are developed in the technical literature to calculate the sediment load are not always accurate when they are applied to field conditions. It is known that there can be large differences between the measured and computed results. It is also found in the present study that the bed roughness has significant influence on the flow field and hence the sediment transport. Correct bed roughness in the tidal flows is difficult to determine especially when the bathymetry is not accurate to start with. The bathymetry used in the present model is not up-to-date. For all these reasons the computed results of sediment transport are also prone to some errors.

## 6. Results of the investigations

### 6.1. Sediment concentration along the navigation channel

The distribution of suspended sediment concentration in the PEC is computed by the model and is shown in Figs. 9 and 10. The area covered is along the entire navigation channel from the harbour to the southern mouth of the PEC. In Figs. 9 and 10 are

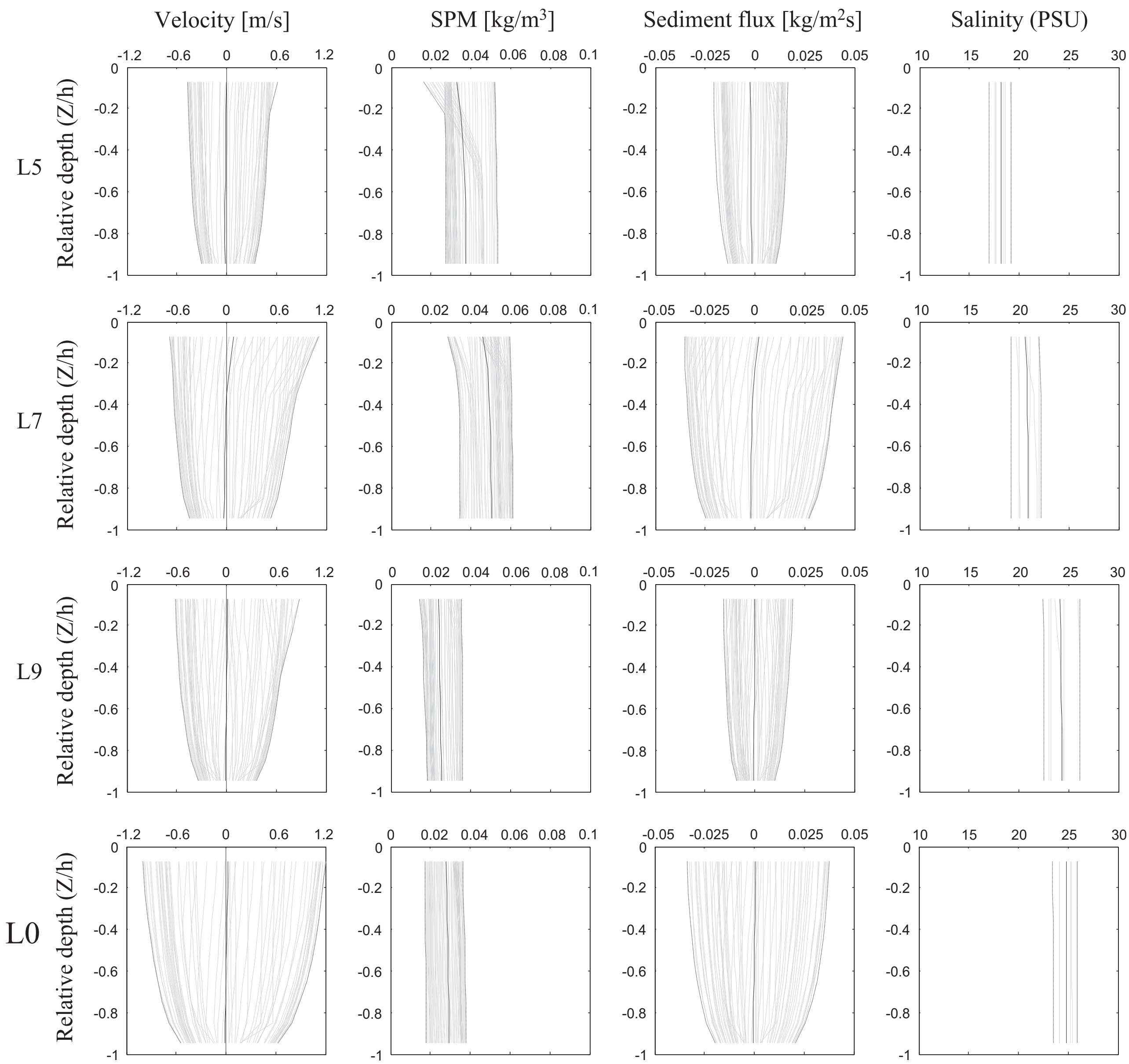


**Fig. 12.** Depthwise variations of computed velocity, suspended sediment concentration and salinity along the navigation channel for spring tidal cycle on 13 September 2007.

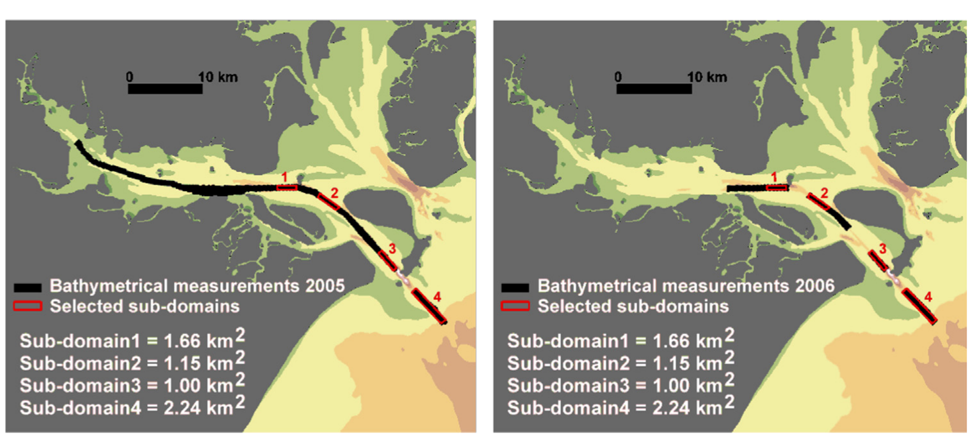


**Fig. 13.** Location of bathymetrical surveys and selected sub-domains – 2005 (left) and 2006 (right).

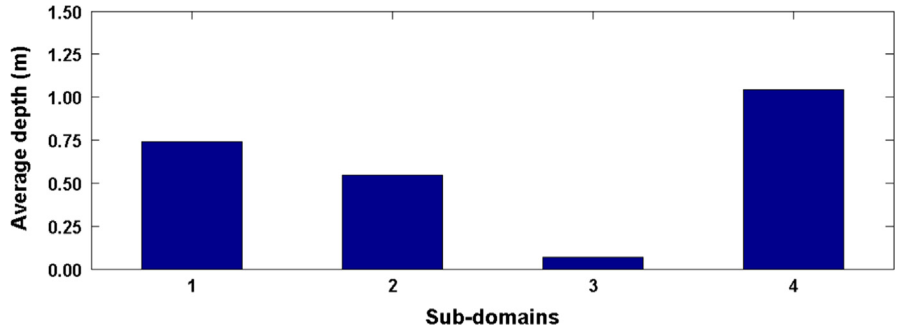


**Fig. 14.** Mean bed elevation changes from 2005 to 2006 at Stations 1 to 4.

shown respectively the sediment concentration at the bottom and top layers of the numerical grid. These figures relate to the conditions for neap and spring tides. Model results are shown at low water, maximum flood current, high water and maximum ebb current for both neap and spring tides. The higher mixing during spring tides leads to larger suspended sediment concentrations and quasi-uniform sediment concentration profiles. During the neap tides, lower concentration of sediments distributed non-uniformly over the vertical are observed. Different patterns of sediment concentration and transport in the upper and lower regions of the PEC are also identified. The sediments fed into the estuary by the rivers contain coarser fractions, which settle down to form deposits upstream of the harbour (Dahlem et al., 2008).

In the lower parts of the PEC between the coastal area and the Paranaguá Harbour, sediments containing cohesive and non-cohesive fractions are in motion. This result is consistent with the observations of Angulo et al. (2004) and the inference of Dahlem et al. (2008). In the lower part of the PEC sediment concentration in suspension of cohesive material is generally much greater especially during spring tides (Figs. 9 and 10). Fig. 9 shows suspended sediments close to the bed transported during neap and spring tides adjacent to the mouth of the PEC. Fig. 10 pertains to the top layer during neap and spring tides. The deposition of sediments near Galheta is essentially from the longshore sediment transport along the coast caused by the southeasterly waves in the Atlantic Ocean (Lamour et al., 2004; Noernberg et al., 2007; Dahlem et al., 2008). The deposited sediments are fine to coarse sand that requires regular dredging for the navigation channel to be operational.

### 6.2. Variations over the vertical

The distributions of suspended sediment concentration over the vertical at various stations L1 etc. were investigated using the numerical model. The results are presented typically at stations L5, L7 and L9 along the navigation channel and at station L0 situated north of Mel Island (see Fig. 3). Computed values of current velocities, suspended sediment concentrations, sediment transport rates and salinity values are plotted against the dimensionless height ($z/h$) for all the stations L5, L7, L9 and L0 as shown in Figs. 11 and 12. $z$ is the distance from the free surface and h is the depth of water. Fig. 11 shows respectively the results for neap tidal cycle on 5 September 2007 and the results for spring tidal cycle on 13 September 2007 are shown in Fig.12. The tide averaged values are shown as bold lines in the figures. There are clear differences between the results concerning spring and neap tides. Due to higher energetic conditions during spring cycle, suspended sediment concentration profiles tend to be nearly uniform across the depth. On the other hand, during neap tides the relatively small current velocities exhibit non-uniformity across the depth. Low sediment concentrations are also distributed non-uniformly across the depth. As a result of low sediment concentration, the rates of sediment transport are smaller. In most of the stations there is a net sediment transport towards the inner parts of the PEC. Large suspended sediment concentration is observed at station L6 located in the vicinity of the harbour. In the inner sections of the navigation channel at stations L5–L8 net sediment flux is towards the Paranaguá harbour.

### 6.3. Bathymetry

Bathymetric measurements along the navigation channel were made in 2005 and then in 2006 along Stretches 1, 2, 3 and 4 as shown in Fig. 13. The areas of each of the Stretches are also given in the Figure.

From Figs. 3 and 13, it is seen that Stretch 1 is the area east of station L6, Stretch 2 is the area south east of L8, Stretch 3 includes L10 and Stretch 4 is offshore of Galheta at the southern mouth. The changes in the mean bed elevations from year 2005 to 2006 were measured in the field and are shown in Fig. 14. The sediment deposition is large at the southern mouth of the estuary and near the Paranagua harbour; it is small along Stretch 2. Along Stretch 3 of the navigation channel, the siltation is very small. At the southern mouth of the estuary, the bed level increased by about 1.1 m in the year 2005–2006 while the increase was about 0.7 m near the harbour. The field observations give confidence in the computation of distribution of sediment concentration during neap and spring tides as shown in Figs. 9 and 10.

Sediment transport is more during spring tides along regions close to the harbour and estuary mouth than that during neap tides. During calmer conditions, the sediments settle down in these regions. The area of sediment deposition observed in the field corresponds to that experiencing significant sediment concentration. As mentioned before, wave induced longshore current is established along the southern coast (Angulo et al., 2004; Noernberg et al., 2007; Dahlem et al., 2008). Deposition of sediments south of the Galheta is essentially from the sediment load transported by the longshore currents.

Fig. 14 shows the deposition of sediments along the navigation channel showing regions of large deposition. For the channel to be navigable, the channel requires periodic dredging in areas of deposition of sediments. The next step of the present study is to set up the morphological model of Delft3D for the PEC in combination with the flow and sediment transport models. The results thus obtained should help engineers estimate the extent, depth of deposition, the nature of sediments deposited and the frequency of dredging needed.

## 7. Conclusions

The three-dimensional process-based model of Delft3D was set up in conjunction with the field measurements for the sediment motion due to fluid and tidal processes in the Paranagua Estuarine

Complex in Brazil. The 3D simulation account for wind, waves and tides to compute sediment transport of cohesive and sandy fractions in the PEC. The effect of waves on sediment concentration and transport is found to be insignificant during normal weather conditions when wind speeds are below 6 m/s. Sensitive studies show that away from the bed the effect of the bed roughness on suspended sediment concentrations and transport is not very important. Results of the validation of the model on a medium term showed that the sediment transport model is capable of predicting suspended sediment concentrations agreeably with the observations. Due to the low sampling frequency during the tidal cycles, it was not possible to test the ability of the model in predicting the temporal variations properly over the whole cycle.

The nature of sediment transport gives insight into the morphological behaviour along the navigation channel of the estuary. The areas where significant bathymetry changes were measured in the PEC coincide with those where large sediment concentrations are predicted. Human interactions like dredging the navigation channel will affect the flow regime and sediment transport. Further work is necessary to study the impact of dredging and the disposal of the dredged sediments with respect to the morphological behaviour in PEC.

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