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- Observed and modeled suspended-sediment dynamics and its bottom boundary layer
- Effects of mangroves and tidal flats reclamation on suspended-sediment dynamics
- Impact of human activities on suspended-sediment dynamics

Supporting Information:

- Readme
- Figure captions and figures

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Effects of mangroves and tidal flats on suspended-sediment dynamics: Observational and numerical study of Darwin Harbour, Australia

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Abstract The suspended-sediment dynamics in Darwin Harbour, Australia were investigated using field measurements and numerical modeling. The model suspended-sediment concentration (SSC) agreed well with observation; the root-mean-square error was less than 0.02 kg m^{-3} and the anomaly correlation coefficient greater than 0.6. Model results indicate that the tide is the dominant forcing for suspended-sediment transport: total sediment transport was seaward in the channel and landward at the East and Middle Arm entrances, dominated by the *Eulerian residual* current. Further numerical experiments indicate that mangroves and tidal flats play key roles in redistributing suspended sediment and affecting total sediment transport by modulating the tides and the tidal asymmetry. In Darwin Harbour, if these areas were reclaimed, there would be a significant transport of sediment into the inner harbor. However, the water in East Arm would be less turbid, with about 70% lower bottom SSC during spring tides. The landward sediment flux at its entrance would decrease by 99%, because of reduced currents in the Arm due to a weakened tidal choking effect. Tidal pumping would then dominate sediment transport in the channel and at the entrances of East and Middle Arms. Dredging for the East Arm Wharf affected the SSC upstream in East Arm. According to the model, material from dredging disposed of at a location outside the harbor will be transported back into the outer harbor, generating higher SSC values there. Although this study is site-specific, the findings may be applicable to suspended-sediment dynamics in other harbors and estuaries with extensive tidal flats and mangroves.

1. Introduction

Coastal management and development of marine industries require an accurate prediction of the sediment dynamics of harbors [Toorman, 2001]; an understanding of the sediment dynamics is fundamental to wharf planning and harbor construction. Suspended-sediment dynamics in estuaries determine the fate of particle-bound nutrients and harmful materials, the rate of erosion or accretion of mudflats and sand beaches, the speed of siltation of navigation channels, and the generation of high-turbidity zones [Mehta, 1988; van Leussen, 2011]. High turbidity is harmful to a harbor's ecosystem; for example, the recruitment rate of corals is negatively correlated with sediment deposition rate [e.g., Dikou and van Woessik, 2006]. Therefore, suspended-sediment research has received widespread and increasing attention worldwide [Allen et al., 1980; van Kessel et al., 2011; Manning et al., 2010; Margvelashvili et al., 2003].

Darwin Harbour ($12^{\circ}28'S$, $130^{\circ}51'E$), Northern Territory, Australia (Figure 1a), is a tropical estuary characterized by extensive mangroves and some delicate coral areas. The Northern Territory Government has paid particular attention to the aquatic and terrestrial environment of the harbor [e.g., Fortune and Drewry, 2011]. Many studies have been conducted on the harbor's biological systems [e.g., McKinnon et al., 2006; Metcalfe and Glasby, 2008; Michie, 1987; Sinclair Knight Merz Pty Ltd., 2011]; pollution and nutrients [e.g., Metcalfe et al., 2011; Peerzad et al., 1990; Peerzada and Dickinson, 1988; Peerzada and Kozlik, 1992; Peerzada and Ryan, 1987; Smith and Haese, 2009]; and on the harbor's hydrodynamics [e.g., Andutta et al., 2013; Karimi et al., 2013; Li et al., 2012; Williams et al., 2006] and seabed materials [Fortune, 2006]. However, studies of suspended sediment in Darwin Harbour (DH) are limited to Williams [2009], which examined the effect of the

Figure 1. (a) Model domain and the field measurement stations. Cross-sections: 1 in the channel; 2 at the East Arm entrance; 3 from the outer harbor to Middle Arm; 4 at the Middle Arm entrance. A—Charles Point; B—Lee Point; C—Mandorah Point; D—East Point; E—Darwin City and old wharfs; F—East Arm Wharf; G—Nightcliff; H—outer harbor; I—inner harbor; J—Channel Island; L—offshore dumping ground. Seven measuring stations are labeled on the map: MA1 and MA2 in Middle Arm; EA1 and EA2 in East Arm; WA1 in West Arm; CL and CR on the west and east coast, respectively, in the outer harbor. The depth contour is relative to Mean Surface Level in meters, with positive downward. The purple color indicates the dredging areas. (b) The initial fine-sediment thickness distribution on the seabed. (c) The assumed removal scheme of the tidal flats and mangroves in numerical experiments 4–6: zones a1 and a2 are removed in numerical experiment 4; zones a1–a3 are removed in numerical experiment 5; zones a1–a4 are removed in Experiment 6. The blue lines are the boundaries between mean surface water level and tidal flats, and between the removed zones.

sandbar removal in East Arm on the harbor's sediment dynamics [e.g., *Water Research Laboratory*, 2010], and to an INPEX study concerning dredging and dumping as part of its Ichthys Project [e.g., *Asia-Pacific Applied Science Associates*, 2010a, 2010b; *HR Wallingford*, 2010a, 2010b]. These studies were using only two-dimensional model (in the x-y domain), so that the sediment bottom boundary layer and the effect of

mangroves and tidal flats on suspended-sediment transport have not been well-examined. The objectives of the current study are: first to build a three-dimensional suspended-sediment dynamics model, calibrated using observed suspended-sediment concentration (SSC) data in the bottom boundary layer; second to understand the effects of mangrove areas and tidal flats on the suspended-sediment dynamics in DH, including sediment distribution and fluxes; and third to discuss the impacts of human activities, in particular dredging and disposal, on the suspended-sediment dynamics. The methodology is described in section 2. Model calibration and results are presented in sections 3 and 4. Section 5 discusses the effects of mangrove areas and tidal flats on the suspended-sediment dynamics, and the effects of dredging and dumping on the SSC. Conclusions are provided in section 6.

2. Methodology

2.1. Model Development

A two-way coupling was applied between the finite volume coastal ocean model (FVCOM) [Chen *et al.*, 2003] and the estuarine suspended-sediment model (ESSed) of Wang [2002], thus allowing the sediment concentration to affect water density, and consequently water circulation. FVCOM uses a 3-D unstructured mesh, which is well-suited to the complex geometry of DH. The Coriolis term in the momentum equations of the hydrodynamics model was simplified using the f-plane approximation. This simplification is justified by the small spatial scale of Darwin Harbour (a few kilometers), and its geographical location (12.5°S). The ESSed model focuses on suspended sediment, and includes the sediment bottom boundary layer. The basic equations of ESSed were incorporated into FVCOM (M. Bao, personal communication, 2010), including calculations of density, the bottom drag coefficient, and the Richardson number.

This study considers only suspended sediments and the bottom boundary layer. Sediment processes are parameterized following the Wang [2002] model. The sediment transport is described by:

$$\frac{\partial C}{\partial t} + \frac{\partial(uC)}{\partial x} + \frac{\partial(vC)}{\partial y} + \frac{\partial(w-w_s)C}{\partial z} = \frac{\partial}{\partial z} \left(K_h \frac{\partial C}{\partial z} \right) + F_c, \quad (1)$$

where x , y , and z are the east, north, and vertical coordinates, respectively, and u , v , and w the corresponding velocity components. w_s is the settling velocity of the sediment, and C the suspended-sediment concentration. The vertical eddy diffusivity for suspended sediment was set equal to K_h in the momentum equation, which employs the Mellor-Yamada level 2.5 turbulence closure scheme for vertical mixing [Mellor and Yamada, 1982]. F_c is the horizontal diffusion term, parameterized according to the Smagorinsky diffusion scheme [Smagorinsky, 1963].

The density of clear seawater without sediment is determined by the equation of state [Mellor, 1998]; when the contribution of the suspended sediments is considered, the density of seawater ρ is given by a volumetric relationship,

$$\rho = \rho_w + \left(1 - \frac{\rho_w}{\rho_s} \right) C, \quad (2)$$

where ρ_w is the clear seawater density and ρ_s the sediment density. The bottom drag coefficient in a sediment-laden bottom boundary layer is given by:

$$C_d = \left[\frac{1}{\kappa / (1 + AR_f)} \ln \left(\frac{h + z_b}{z_0} \right) \right]^{-2}, \quad (3)$$

where z_0 is the bottom roughness length, z_b is the thickness of the bottom layer ($\sigma = -0.991$ in this study), $\kappa = 0.4$ is the von Karman constant, and h is the water depth. The effect of stratification is specified by a stability function, $1 + AR_f$, where A is an empirical constant and R_f is the flux Richardson number. Adams and Weatherly [1981] determined that $A = 5.5$ for a sediment-laden oceanic bottom boundary layer.

The vertical sediment flux, E ($\text{kg m}^{-2} \text{s}^{-1}$), on the seabed due to erosion/deposition processes is, according to Ariathurai and Krone [1976],

$$E = \begin{cases} E_0 \left(\frac{|\tau_b|}{\tau_c} - 1 \right), & |\tau_b| > \tau_c \\ C_b w_s \left(\frac{|\tau_b|}{\tau_d} - 1 \right), & |\tau_b| < \tau_d \end{cases}, \quad (4)$$

where E_0 is the erosion coefficient, τ_c and τ_d ($\text{kg m}^{-1} \text{s}^{-2}$) is the critical stresses for resuspension and deposition, respectively, and C_b (kg m^{-3}) is the sediment concentration in the model's bottom layer. The continuous bottom exchange of sediment between the seabed and the water column through erosion and deposition is a function of spatial shear stress, which varies in both space and time.

The sediment model sensitivity was tested to examine the variation in the model results with realistic variations in the main parameters: critical erosion and deposition stress, erosion rate, and bottom fine-sediment thickness. This is described briefly in the following.

The bottom fine-sediment thickness plays the principal role in determining the SSC values in the water column: it determines the fine-sediment availability on the seabed, and consequently limits the amount of suspended sediment in the water column. If the bottom fine-sediment thickness is not limited, i.e., there is an infinite amount of fine sediment on the seabed, the SSC in the water column varies in a similar manner to the erosion rate.

Increasing the critical erosion stress reduces the SSC in the water column: doubling this critical erosion stress reduces the SSC to less than half. Increasing the critical deposition stress also reduces the SSC in the water column, but by how much is not clear, as the amount of sediment deposited is determined not only by the critical deposition stress, but also by the bottom SSC and the settling velocity (equation (4)).

More information on the sediment model sensitivity is provided in Wang [2002], Wang *et al.* [2005], and Wang and Pinardi [2002].

2.2. Model Configuration

2.2.1. Model Setup and Initial Conditions

This study examines the suspended-sediment dynamics of Darwin Harbour during the dry season from Charles Point to Lee Point (Figure 1a), with the model domain expanded to include an area outside the mouth of the harbor. All the mangrove areas are included in the domain in order to investigate the effect of mangrove areas and tidal flats on sediment transport in the harbor. Wetting-drying processes are included in the model as follows: if the total water depth (including tides) is less than a critical depth of 0.5 m, the node is considered as dry by the sediment module, and the SSC value in the water column is accordingly not updated from the previous step. The sediment on the seabed remains there to keep mass balance. Advection, erosion, and deposition do not occur at dry nodes. When the node becomes wet again, the SSC value is the summation of the SSC values at the previous wet time step of this node, the sediment from bottom erosion and deposition, and the sediment from advection and diffusion.

The model bathymetry and grid configurations are shown in Figure 1a. The unstructured grid, which consists of 9666 elements and 5205 nodes, ranges in size from 18 m near the wharfs to 3300 m at the ocean open boundary. Twenty vertical layers are employed in the model, with higher vertical resolution near the bottom and the surface. The model is forced by the following tides at the ocean open boundary, with constant temperature and salinity: four diurnal components (K1, O1, P1, Q1); four semidiurnal components (M2, S2, N2, K2); three shallow-water components (M4, MS4, MN4); and two long-period components (Mf, Mm). River discharges are not considered, as according to field data from telemetered gauging stations of the Bureau of Meteorology in Darwin, the discharges of the Elizabeth River (Station Number G8150018) and

Table 1. Model Initial Conditions and Constants

Parameter	Description
Number of seabed layers	1
Sediment type	Cohesive
Erosion rate	$5 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$ in water areas $10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ in tidal flats
Critical erosion stress	$0.1 \text{ kg m}^{-1} \text{ s}^{-2}$ in water areas $1.0 \text{ kg m}^{-1} \text{ s}^{-2}$ in tidal flats and mangrove areas
Critical deposition stress	$0.08 \text{ kg m}^{-1} \text{ s}^{-2}$

Berry Creek (Station Number G8150028) in the dry season (e.g., November 2012) are very low (nearly zero). More-detailed information can be found in *Li et al.* [2012].

The sediment model began after the hydrodynamic model had run for 12 (model) h. Only cohesive suspended sediments were included, as they constitute the bulk of the

suspended sediment and are more easily transported around the harbor [Brenon and Le Hir, 1999]. An effective approximation is to treat suspended sediments as a single group of particle size 0.002 mm [Wang, 2002], as this group represents most of the fine sediments found in the harbor [Fortune, 2006]. Accordingly, the settling velocity was set at an average value of 10^{-4} m s^{-1} . This constant settling velocity is suitable for Darwin Harbour, which has low SSC, because flocculation only becomes significant when the SSC values rise to about 1 kg m^{-3} [van Rijn, 1993]. The critical resuspension and deposition stresses were set to 0.1 and $0.08 \text{ kg m}^{-1} \text{ s}^{-2}$, respectively, according to field experience; these have been observed in the range $0.02\text{--}5.0 \text{ kg m}^{-1} \text{ s}^{-2}$ for erosion and $0.06\text{--}0.1 \text{ kg m}^{-1} \text{ s}^{-2}$ for deposition [HR Wallingford, 2010b]. The tidal flats and mangrove areas are complicated by the presence of runnel networks and plants, acting as traps for sediments when currents are reduced in these areas [Le Hir et al., 2000/2000]. Therefore, a smaller erosion rate (about 1/50 of that in water areas) and a larger critical erosion stress value (about 10 times of that in water areas) were assigned to the tidal flats. The mangrove areas were treated as a sink for suspended sediment in the model: deposition was allowed, but no resuspension. The model was run for 40 days, from 1 November 2012 to 10 December 2012; its initial conditions and model constants are listed in Table 1.

2.2.2. Sensitivity Tests

Nine numerical experiments were conducted to simulate the suspended-sediment dynamics. Experiment 0 assumed an initially uniform fine-sediment thickness, and was run for 40 days. The erosion and deposition patterns on the seabed obtained from it were used as input for the thickness of the fine-sediment layer for Experiments 1–6. The thickness at the grid location was taken to be the sum of the deposition and erosion thicknesses from Experiment 0. Furthermore, the thickness at the grid location with the greatest erosion was set to zero with no fine sediment on the seabed. The thickness at other grid locations was set according to their erosion or deposition values.

In some areas, the thickness was adjusted according to the findings of Fortune [2006] and our own field observations. The thickness of the fine-sediment layer in the channel and at the entrance to Middle Arm were set to zero, because the water there has low turbidity; the seabed there experienced high erosion in Experiment 0. The thicknesses in the outer and inner harbor were set to low values, following Experiment 0. This was also because the sediments there are coarser than those in the arms. The detailed initial conditions for the sediment thickness on the seabed are shown in Figure 1b.

In Experiment 1, the simulation was over the entire model domain; it is the reference model for the remaining experiments. In order to examine the effects of the mangrove areas and tidal flats on suspended-sediment transport, Experiments 2 and 3 were conducted using the same settings as Experiment 1, but with the mangrove areas, and the mangrove areas plus tidal flats, respectively, removed from the model domain. The removed areas were converted to land in the numerical experiments 2–6. Experiments 2 and 3 were designed to test the effect of mangrove areas and tidal flats on suspended-sediment distribution and total fluxes. To examine the effect of mangrove areas and tidal flats on suspended-sediment transport in more detail, in Experiments 4–6 the mangrove areas and tidal flats were progressively removed from the model (Figure 1c): in Experiment 4, about 30% of the total mangrove area and tidal flats were removed, from around East Arm (zones a1 and a2); in Experiment 5, about 50%, from around East Arm and the east side of Middle Arm (zones a1–a3); and in Experiment 6, about 70%, from around East Arm and Middle Arm (zones a1–a4). These removal scenarios are in accordance with those that may occur in the development of Darwin Harbour, because almost all the

Table 2. Details of the Numerical Experiments

Experiment	Description
0	Uniform seabed thickness
1	Whole domain; initial seabed thickness from Experiment 0
2	No mangrove areas; initial seabed thickness from Experiment 0
3	Water areas only; initial seabed thickness from Experiment 0
4	Experiment 1, but with 30% of the total mangrove area and tidal flats removed from around East Arm
5	Experiment 1, but with 50% of the total mangrove area and tidal flats removed from around East Arm and the east side
6	Experiment 1, but with 70% of the total mangrove area and tidal flats removed from around East Arm and Middle Arm
7	Experiment 1, but with dredging included; no resuspension; sediment release rate of $10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$
8	Experiment 1, but with disposal of dredging material included; no resuspension; surface sediment release of 50 kg m^{-3} over 10 min every 6 h at slack water

social and economic activity of Darwin takes place near East Arm. Descriptions of these experiments are given in Table 2.

According to field data, the SSC at Stations EA1 and EA2 (Figure 1a) were obviously affected by dredging (more discussion later). Experiment 7 (Table 2) was conducted to model the effect of dredging on sediment distribution in the harbor. According to *HR Wallingford* [2010b], the berthing area and the offloading zone of the East Arm Wharf, indicated by the purple area in Figure 1a, were dredged during the observation

time. This dredging phase, Phase 3, lasted for 3 months from mid-September to mid-December 2012.

Experiment 7 was the same as Experiment 1, but with the dredging process included. An erosion rate of $10^{-6} \text{ kg m}^{-2} \text{ s}^{-1}$ throughout the simulation period was assigned to the dredging area to model sediment release during dredging. This value corresponds approximately to the total sediment release rate reported in *HR Wallingford* [2010b]. The same deposition algorithm as in Experiment 1 was applied. In the harbor model, deposition was allowed, but no erosion.

As there is an offshore disposal zone outside the harbor (Figure 1a), the SSC at Station CR may also have been affected by the dumping of dredging material (more discussion later). Experiment 8 was designed to test the effect of this dumping on the SSC at Station CR. Experiment 8 (Table 2) was the same as Experiment 1, but with disposal of sediment at Location L in Figure 1a included. In the model, only deposition was allowed to focus on sediment advection from the disposal area; there was no resuspension. In the model, suspended sediment at a concentration of 50 kg m^{-3} was released at the surface over 10 min every 6 h at slack water throughout the simulation period to model the actual sediment disposal. This concentration is lower than the average of the actual discharge values, because Location L is arranged to the grid point, not exactly at the center of the disposal ground; the magnitude of the suspended-sediment concentration is not important in this test.

2.3. Physics of Sediment Flux Decomposition

According to the method of mass transport flux of *Dyer* [1997], if short-period turbulence is neglected, the velocity u and sediment concentration c at any depth can be written as $u = \bar{u} + u_v$ and $c = \bar{c} + c_v$, where u_v and c_v are the deviations at any depth z from the mean values $\bar{u} = \frac{1}{h} \int_0^h u dz$ and $\bar{c} = \frac{1}{h} \int_0^h c dz$, respectively, and h is the water depth.

As $\bar{u}$ and $\bar{c}$ will vary over tidal cycles with tidal fluctuations, they can be expressed as the sum of a tidally averaged value and a deviation as $\bar{u} = \bar{u}_0 + \bar{u}_t$ and $\bar{c} = \bar{c}_0 + \bar{c}_t$, respectively, where $\bar{u}_0 = \frac{1}{T} \int_0^T \bar{u} dt$ and

$\bar{c}_0 = \frac{1}{T} \int_0^T \bar{c} dt$, T is the tidal period, $\bar{u}_0$ and $\bar{c}_0$ the mean vertically averaged velocity and sediment concentration over the tidal cycle, respectively, and $\bar{u}_t$ and $\bar{c}_t$ the corresponding deviations of the vertically averaged values from the means.

The instantaneous sediment flux through a unit width of a section perpendicular to the mean flow is given by $F = \int_0^h u c dz = \int_{-1}^0 h u c d\sigma$, where σ is the relative depth: at the seabed $\sigma = -1$, at the water surface $\sigma = 0$.

The total sediment flux over a tidal cycle is partitioned into seven major fluxes as:

$$\begin{aligned}
 \langle F \rangle &= \frac{1}{T} \int_0^T \int_{-1}^0 h u c d\sigma dt \\
 &= h_0 \bar{u}_0 \bar{c}_0 + \bar{c}_0 \langle h_t \bar{u}_t \rangle + \bar{u}_0 \langle h_t \bar{c}_t \rangle + h_0 \langle \bar{u}_t \bar{c}_t \rangle + \langle h_t \bar{u}_t \bar{c}_t \rangle + h_0 \langle \bar{u}_t \bar{c}_t \rangle + \langle \bar{h}_t \bar{u}_t \bar{c}_t \rangle \\
 &= T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7,
 \end{aligned} \tag{5}$$

where the brackets $\langle \rangle$ denote the tidally averaged value of a vertically integrated variable, the overbar the vertically averaged value and $h = h_0 + h_t$, where h_0 and h_t are the tidally averaged water depth and its deviation, respectively. T_1 is the flux due to the nontidal drift, the Eulerian velocity, and T_2 the flux due to Stokes drift. $T_3 + T_4 + T_5$ is the tidal pumping term that is produced by the tidal phase differences: T_3 is the correlation term between the tidal level and sediment concentration; T_4 arises mainly from the consequence of the sediment erosion threshold and lags, which result from sediment resuspension and deposition; T_5 is the correlation term between the tidal level, velocity, and sediment concentration, which expresses the role of tidal trapping; T_6 the vertical gravitational circulation, arising from the correlation between the landward (e.g., upstream of the estuary) bottom mean flow with a high near-bed sediment concentration and the seaward mean surface flow with a lower concentration; and T_7 arises from the changing forms of the vertical profiles of velocity and concentration in the tide, due mainly to the lags between scouring and settling activities [Wai *et al.*, 2004]. This method is used to identify the different sediment-transport mechanisms in Darwin Harbour.

3. Model Calibration

The hydrodynamic model was calibrated by Li *et al.* [2012]. Sediment-model calibration was conducted in the current study to obtain a set of parameters to set up the model and improve model accuracy using observed suspended-sediment concentrations at the bottom level at seven stations (Figure 1a). The root-mean-square error (RMSE) was used to measure the model errors:

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^T (f_t - o_t)^2}{T}}, \tag{6}$$

where f_t and o_t are the predicted and observed values of SSC at time t . A value of RMSE near zero indicates a close match between the observed and model values.

In addition to the RMSE statistics, the anomaly correlation coefficient (ACC) was used to quantify the temporal and spatial correlation between model and observed SSC based on the method of Krishnamurti *et al.* [2003]:

$$\text{ACC} = \frac{\sum_{m=1}^M (f_m - ct_m)(o_m - ct_m)}{\left(\sum_{m=1}^M (f_m - ct_m)^2 \sum_{m=1}^M (o_m - ct_m)^2 \right)^{\frac{1}{2}}}, \tag{7}$$

where f_m , o_m , and ct_m are the model values, observed values, and climatology mean values of SSC, respectively, and the summation m is over time or spatial location. The climatology mean of the SSC is the observed mean SSC value in the lunar month of November 2012. The ACC measures pattern similarities, considering the error and bias. A value of 0.6 is the limit below which the prediction is thought to be less valuable.

As shown in Figure 2, the sediment model reproduced the observed SSC reasonably well, matching both the observed concentrations and their variation with the tides at almost all of the seven stations. However, there were large discrepancies at Stations EA1 and CR. At Station EA1, the model SSC values did not match the high observed values in the second spring tidal cycle (Figure 2c), as evidenced by the largest RMSE values of all stations, 0.02 kg m^{-3} , occurring at Station EA1 (Figure 3a).

The lowest ACC value from the seven stations, 0.5, also occurred at Station EA1 (Figure 3b). The abnormally large SSC values measured at Station EA1 were caused by harbor dredging near East Arm Wharf during the observation period.

Figure 2. Comparison of model and observed time series of bottom suspended-sediment concentrations at the seven stations.

Figure 3. Error statistics: (a) RMSE for the model suspended-sediment concentrations at the seven locations; (b) ACC at the seven locations, averaged over time; and (c) time variation in ACC, averaged over the locations; all during the simulation period.

Station CR is located near an offshore dumping zone for dredging materials from the Ichthys Project [HR Wallingford, 2010a, 2010b]. The significant mismatch, shown by the low ACC value of 0.53, between the model and observed SSC at Station CR during the first spring tidal cycle (Figure 2g) was caused by advection of the dumped sediments by the flood currents. Further discussion on the effect of these dredging and dumping activities on the SSC distribution in the harbor is presented in section 5.

About 75% of the ACC values during the simulation time were larger than 0.6 (Figure 3c), with values smaller than 0.6 occurring when the model and observed values had different signs relative to the lunar monthly mean. These lower ACC values were mostly caused by the abnormally high SSC values at Stations EA1 and EA2. If the Station EA1 and EA2 data are not included, about 80% of the ACC values were larger than 0.6, indicating an acceptable spatial similarity between model and observation.

Therefore, the sediment model is sufficiently accurate for an analysis of the suspended-sediment dynamics in the harbor, including time and spatial variations in the distributions of suspended sediments and total sediment fluxes.

4. Results

4.1. Sediment Bottom Boundary Layer Measurements

The SSC in the bottom boundary layer was measured at seven stations, MA1, MA2, EA1, EA2, WA1, CL, and CR, in the outer harbor and the arms (Figure 1a). These stations were selected to cover all of the harbor, but avoiding strong currents and a shipping lane with heavy traffic. Seven nephelometers were deployed about 0.4 m above the seabed [Ridd *et al.*, 2001; Thomas *et al.*, 2003]. Each nephelometer contained a pressure sensor, a deposition sensor, a turbidity sensor, a light sensor, and a temperature sensor. Measurements were taken at 10 min intervals from early November 2012 to early February 2013. However, after mid-December 2012, the dredging activities for the East Arm Wharf expansion compromised the SSC records and reduced the data quality. For this reason, only the data from early November to early December in 2012 were used to calibrate the sediment model.

As the SSC measurements from 7 November to 7 December 2012 at the seven stations show (Figure 2), the bottom SSC varies with the spring and neap tides, with larger SSC values during spring tides. The SSC on the harbor bottom during spring tides can be up to 100 times larger than during neap tides, but is still only of the order of 10^{-3} to 10^{-4} kg m^{-3} . Turbidity was greatest at Station CL, with SSC values of more than 0.1 kg m^{-3} , followed by Stations WA1 and EA1.

Abnormally high or low SSC records were smoothed using a Gaussian low-pass filter before the data were used for model calibration: these abnormally high or low values only occurred over short time periods, and were largely the result of special events, e.g., construction or the failure of instruments, rather than the natural suspended-sediment dynamics.

The SSC values in the second spring tidal cycle were normally no more than 50% of those in the first spring tidal cycle. This is because of the larger bottom-current speeds induced by the larger tidal range in the first spring tidal cycle compared with the second.

Station EA1 in East Arm had relatively high turbidity throughout the entire measurement period, especially during the second spring tidal cycle (Figure 2c), with the SSC as high as 0.09 kg m^{-3} . This variation was abnormal compared with the SSC at the other six stations, where the second spring tidal cycle had lower SSC values than the first. At Station EA2, spikes of high SSC values appeared in the spring tidal cycle.

As observed during field work, the abnormally high SSC values at Station EA1 were caused by dredging near the East Arm Wharf. This dredging had a greater effect in the second spring tidal cycle because at that time more sediment was lifted into water column than in the first. These suspended sediments at Station EA1 were further advected to Station EA2 by strong flooding currents during the spring tide, and caused large peaks in the SSC values there. This effect was reproduced in this study (see section 5.1).

In the outer harbor, obvious spikes of high SSC in the spring tidal cycle occurred at both Stations CL and CR, as shown in Figures 2f and 2g. These high SSC values were also related to the disposal of sediment from the dredging: sediment was transported from the offshore disposal area outside the harbor to Stations CR

Figure 4. Model suspended-sediment concentration at: (a) the bottom level and (b) the surface level in the spring tidal cycle on 16 November 2012; (c) the bottom level and (d) the surface level in the neap tidal cycle on 7 December 2012.

and CL. This effect was also modeled, and is further discussed in section 5.2, supplementing the 2-D simulation of *HR Wallingford* [2010b].

4.2. Suspended-Sediment Dynamics in Darwin Harbour

4.2.1. Horizontal Distribution

In Experiment 1, the reference experiment, the bottom SSC was high in the outer harbor, the inner harbor, East Arm and West Arm during the spring tidal cycle (Figure 4a), as a result of the strong currents coupled with the availability of erodible fine sediment in the harbor. The SSC near the west coast in the outer harbor was higher than near the east coast because the currents are stronger near the west coast, which is near the deep navigation channel. This phenomenon was also evident in the field data, as shown in Figure 3. The turbid zone in the outer harbor, which was basically formed by bottom fine-sediment erosion, moved landward and seaward with the flood and ebb tidal currents, respectively. The SSC in the turbid zone in the outer harbor was as high as about 0.1 kg m^{-3} at peak flood currents. This turbid area had higher SSC values at low slack water than at high slack water, because the suspended sediment was diluted by the larger water volume during high slack water, during which the water was about 6 m deeper. The SSC in East Arm was always high all through the spring tidal cycle, because East Arm has an erodible muddy seabed and relatively strong currents. The suspended sediment in the inner harbor came from both bottom sediment erosion and sediment advection from East Arm. The very high SSC values over the tidal flats were generated by wetting-drying processes. During low water, these areas were dry, and the model SSC was zero; during high water, these areas were under water, and the SSC was high due to the high bottom drag caused by the shallow water. The water in the channel and Middle Arm was clear due to low sediment availability, in

Figure 5. Model vertical profiles of suspended-sediment concentration along Cross-section 3 (Figure 1) in: (a) the spring tidal cycle on 16 November 2012; (b) the neap tidal cycle on 7 December 2012. "A" indicates the Middle Arm entrance.

accordance with our field observations. The water was also clear near Channel Island in Middle Arm, where the coral reefs are well developed [Fortune and Drewry, 2011].

The suspended sediment had a distribution at the surface level similar to that at the bottom level (Figure 4b). However, the SSC values at the surface were less than 0.07 kg m^{-3} , which is only about 50% of those at the bottom. The SSC along the navigation channel in the outer harbor was lower than in the surrounding waters, e.g., in the area outside the channel indicated by "A" in Figure 4b, because the sediment was transported away by strong currents in the channel.

In contrast to the spring tides, the less energetic neap tides did not erode much sediment in the upper part of the harbor, and the bottom SSC in the inner harbor and the arms was mostly less than 0.005 kg m^{-3} (Figure 4c). Although the turbid zone in the outer harbor still existed during the neap tidal cycle, its SSC was less than 0.02 kg m^{-3} as a result of the relatively strong currents. This was less than 20% of the SSC during the spring tidal cycle. The turbid zone moved landward and seaward with flood and ebb current cycles, respectively, as a result of current advection. At the surface level, the suspended sediment had a similar distribution to that at the bottom level (Figure 4d), but the surface SSC was only one-third of that at the bottom.

Figure 6. Model vertical profiles of current magnitude along Cross-section 3: (a) spring peak flood currents; (b) spring peak ebb currents; (c) neap peak flood currents; (d) neap peak ebb currents.

4.2.2. Vertical Suspended-Sediment Concentration Profile

Figure 5 shows the vertical SSC profile along Cross-section 3 (Figure 1) from the outer harbor to Middle Arm during the spring tidal cycle. The turbid zone in the outer harbor had a higher SSC than near the entrance to Middle Arm, indicated by “A” in Figure 5a. The turbid zone in the outer harbor outside the channel (the deepest area in Figure 5) moved landward (to the right) and seaward (to the left), respectively, with current cycles, as shown in Figures 6a and 6b. The turbid zone near the entrance to Middle Arm similarly moved up and down along its channel.

During the spring tidal cycle, sediments tended to be well-mixed throughout the water column due to the strong currents. The bottom SSC values at peak flood currents were higher than at low slack water because of resuspension.

During the neap tidal cycle, although the water was still turbid in the outer harbor, the SSC values were high only at the bottom level, as the current speeds there were low (Figures 6c and 6d); the SSC values were only one-third of those during the spring tidal cycle. As a consequence, the turbid zone at the entrance to Middle Arm disappeared, and vertical mixing was weaker than during the spring tidal cycle. Consequently, a vertical SSC gradient developed during the neap tidal cycle (Figure 5b).

4.2.3. Total Sediment Transport in the Channel and the Arms

Figure 7 shows the vertical profiles and time series of residual currents and total sediment fluxes along Cross-section 1 (Figure 1). Averaged over 1 lunar month, the mean residual current along the cross section was almost zero (Figure 7a). The total sediment flux was approximately 107,263 t/month seaward (Figures 7c, 7d and Table 3). The total net sediment flux magnitude and direction are in accordance with the observations of Williams *et al.* [2006]. The largest seaward sediment fluxes were near Mandorah Point and the bottom near East Point (Figure 1a). In the middle of Cross-section 1, the sediment fluxes at the surface were slightly seaward, at the bottom slightly landward. The total sediment transport through Cross-section 1 was

Figure 7. Residual current and sediment flux distribution along Cross-section 1 (Figure 1), averaged over 1 lunar month: (a) residual-current distribution; (b) water-volume flux time series; (c) sediment flux distribution; (d) sediment flux time series. Positive indicates seaward.

dominated by residual currents; the distributions of seaward and landward sediment transport were in accordance with those of the residual currents.

In the East Arm and Middle Arm entrances (Cross-sections 2 and 4), the mean residual current averaged over 1 lunar month was also nearly zero, and the total sediment flux 18,542 t/month and 25,359 t/month landward (Table 3), respectively. The sediment transported landward was trapped in the upper arms, as observed by Williams *et al.* [2006]. Therefore, in the dry season, most of the outgoing sediment through Cross-section 1 did not come from East Arm and Middle Arm.

4.2.4. Time Variation of SSC and Seabed Thickness

In order to check the time variation of the SSC and bed thickness with the tides, the time series of elevation, surface and bottom SSC, and fine-sediment thickness on the seabed were examined (Figure 8) at Location K (Figure 1), selected because of the importance of the East Arm Wharf. Here, the SSC had an obvious spring and neap variation, in accordance with the tides, both at the surface and bottom levels. The SSC values during the second spring tidal cycle were much smaller than during the first. The peak SSC only reached about 25% and 43% of that in the first spring tidal cycle at the surface and bottom levels, respectively. This trend is in accordance with the tides, as the second spring tidal cycle is weaker than the first, as indicated by its smaller tidal magnitude. A similar phenomenon appeared in the field data. The peak SSC near East Arm Wharf was 0.08 kg m^{-3} at the bottom level, double that at the surface level (0.04 kg m^{-3}).

The model time variance of the fine-sediment layer thickness near Location K is shown in Figure 8d. This layer was eroded throughout the spring-neap tidal cycle, losing a total thickness of about $3 \times 10^{-3} \text{ m}$ of fine sediment in 1 month.

Table 3. Total Sediment Transport (t/month) Through the Cross-Sections^a

Experiment	Cross-section 1	Cross-section 2	Cross-section 4
1	107,263	−18,543	−25,359
2	81,158	−17,980	−22,359
3	−5601	−248	−3572

^aPositive values indicate seaward.

4.3. Effect of Mangroves and Tidal Flats on Suspended-Sediment Distribution and Fluxes

4.3.1. Changes in the Suspended-Sediment Distribution

The removal of the mangroves and tidal flats changes the tides in the

Figure 8. Time series of: (a) elevation; (b) suspended-sediment concentration at the surface; (c) suspended-sediment concentration at the bottom; (d) fine-sediment layer thickness; all at Location K near East Arm Wharf.

Figure 9. Model suspended-sediment concentration at the bottom level in the spring tidal cycle on 16 November 2012 and the neap tidal cycle on 7 December 2012, respectively, in: (a) and (b) Experiment 2; and (c) and (d) Experiment 3.

harbor [Li *et al.*, 2012], and consequently generates a different SSC distribution. In Experiment 2, with the mangrove areas removed from the model, the water was still turbid in the outer harbor, as in Experiment 1, during both spring tides (Figure 9a) and neap tides (Figure 9b); however, the maximum SSC at the bottom level was about 20% larger than in Experiment 1. In the inner harbor, a new turbid zone was formed near Darwin City, with higher SSCs of about $0.08/0.01 \text{ kg m}^{-3}$ at the bottom level during spring/neap tides, respectively. This turbid zone was formed by the reduced advection of suspended sediment to the arms and the surrounding mangrove areas. The water was less turbid in the arms during both the spring and neap tides in Experiment 2, compared with Experiment 1, as the current was decreased due to the reduced tidal choking effect.

In Experiment 3, although the turbid zone in the outer harbor was still present during spring tides (Figure 9c), its SSC values at the bottom level were approximately 50% less than those in the turbid zone in Experiment 1. Water near Nightcliff in the outer harbor (Figure 1a) became turbid in Experiment 3. This turbid zone was formed by the headland (indicated by "A" in Figure 9c), which is actually an area of tidal flats in Experiment 1, but reclaimed in Experiment 3. This turbid zone disappeared if the headland was removed from the model domain. This can be explained by an eddy formed near the headland in Experiment 3, trapping sediments there. As the current speeds in the arms were weakened due to a reduced tidal choking effect, the bottom stress was reduced. Therefore, compared with Experiment 1, less sediment was resuspended in the arms, which led to reduced SSC values in the inner harbor and arms in Experiment 3.

During neap tides, the suspended sediment exhibited similar distributions in both Experiments 1 and 3. As the currents during neap tides were weak and only large in the outer harbor and near the channel, turbidity only appeared in the outer harbor, but SSC values at the bottom level in Experiment 3 were about 70% less than those in Experiment 1 (Figure 9d). Again this was due to reduced currents in the channel caused by a dampened tidal choking, when the mangrove areas and tidal flats were removed.

4.3.2. Changes in Total Sediment Fluxes

4.3.2.1. Total Sediment Fluxes in the Channel and the Arms

The total sediment fluxes in the channel and at the entrances to East Arm and Middle Arm were examined to determine the effect of the mangrove areas and tidal flats on suspended-sediment transport. In Experiment 2, with no mangroves, the total sediment flux through Cross-section 1 in the channel was still seaward, but reduced by 24% compared with Experiment 1. In Experiment 3, with no mangroves or tidal flats, the total sediment flux through Cross-section 1 in the channel was about 5601 t/month but now landward rather than seaward as in Experiment 1 (Table 3). Over 1 lunar month, total sediment transport was upstream through Cross-section 1 and into the inner harbor when the mangroves and tidal flats were removed, consistent with Li *et al.* [2012], who found that flood dominance will be increased in the harbor if the mangrove areas and tidal flats are removed from the model domain.

In Experiment 3, the total sediment fluxes through the East Arm and Middle Arm entrances (Cross-sections 2 and 4) were, respectively, 248 t/month and 3572 t/month landward, in the same direction but with reduced magnitudes ($\sim 99\%$ and $\sim 86\%$ smaller, respectively) than those in Experiment 1. This was due to the reduced currents in the inner harbor and the arms caused by weakened tidal choking when the mangroves and tidal flats were absent.

Therefore, mangrove and tidal-flat reclamation or coastal construction may cause more sediment to move into the inner harbor through the channel. However, less sediment will be transported upstream into the East Arm and Middle Arm branches. This decreased onshore sediment flux in the arms is in accordance with Winterwerp *et al.* [2013], who concluded that the onshore sediment flux would be reduced if coastal lands were reclaimed.

4.3.2.2. Factors Controlling Suspended-Sediment Transport

In order to examine the mechanisms that influence the total sediment transport before and after the removal of the mangrove areas and tidal flats, the factors controlling sediment transport in Experiments 1 (entire domain), 2 (without mangroves), and 3 (without mangroves and tidal flats) were compared. The components of the tidally averaged sediment transport fluxes through Cross-sections 1, 2, and 4 were decomposed using the method of Dyer [1997].

The sediment-transport components at the three cross sections in Experiments 1–3 are listed in Table 4. In the channel (Cross-section 1), the total sediment flux was mostly determined by the Eulerian velocity (T_1) in

Table 4. Sediment Transport Components (kg/s) at the Cross-Sections 1, 2, and 4^a

Component	Experiment 1			Experiment 2			Experiment 3		
	CS 1	CS 2	CS 4	CS 1	CS 2	CS 4	CS 1	CS 2	CS 4
T_1	32.2	-5.3	-6.8	22.5	-5.0	-4.9	-0.5	-0.1	-0.8
T_2	0.8	0.3	-1.1	0.7	0.0	-0.4	0.6	0.0	-0.1
T_3	0.4	-0.1	-0.4	1.0	-0.2	-0.6	0.0	0.0	0.0
T_4	7.5	-2.6	-1.2	4.5	-1.2	-2.0	-2.0	-0.1	-0.8
T_5	-0.3	0.2	-0.6	0.2	-0.3	-0.8	0.5	0.0	0.0
T_6	0.0	0.0	-0.1	-0.4	-0.1	-0.1	-0.2	0.0	0.0
T_7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	40.7	-7.5	-10.3	28.5	-6.8	-8.8	-1.6	-0.2	-1.7
Landward	-0.3	-8	-10.3	-0.4	-6.8	-8.8	-2.7	-0.2	-1.7
Seaward	41	0.5	0	28.9	0	0	1.1	0	0

^aPositive values indicate seaward.

Experiment 1, but by tidal pumping ($T_3 + T_4 + T_5$) in Experiment 3. The direction of the Eulerian residual changed from seaward in Experiment 1 to landward in Experiment 3, while the second largest flux, in Experiment 1, caused by tidal pumping, was seaward. However, in Experiment 3, in which the mangrove areas and tidal flats were removed, the effects of tidal pumping on sediment transport were greater due to the increased flood dominance. At the East Arm and Middle Arm entrances (Cross-sections 2 and 4), the Eulerian velocity and tidal pumping both transported sediment landward in all experiments. The tidal-pumping effect increased to a similar level as the Eulerian velocity when the mangrove areas and tidal flats were removed in Experiment 3 because of increased flood dominance.

According to the landward and seaward sediment flux rates in Experiments 1–3, the landward sediment flux at Cross-section 1 increased, and the seaward sediment flux decreased in Experiments 2 and 3, compared with Experiment 1 (Table 4). At Cross-sections 2 and 4, the landward sediment fluxes decreased because the currents were reduced due to the reduced tidal choking effect.

Figure 10 displays the cross-sectional variations in the seven components in Experiments 1 and 3. In Experiment 1, the Eulerian velocity dominated sediment transport in the channel through Cross-

Figure 10. Components of total sediment fluxes at Cross-sections 1 (first column), 2 (second column), and 4 (third column). (a), (d), and (g) Experiment 1. (b), (e), and (h) Experiment 3. (c), (f), and (i) The depths of the cross sections. Positive indicates seaward. T_1 Eulerian velocity; T_2 Stokes drift; T_3 , T_4 , and T_5 tidal pumping; T_6 gravitation circulation; and T_7 changing forms of the vertical profiles of velocity and concentration in the tide. Note that the scale is not the same for each figure.

Figure 11. Total sediment flux through cross-section 1 as a function of percentage removal of mangrove areas and tidal flats. Positive values indicate seaward.

section 1. Sediment was transported landward at the deepest point (Figure 10c) of Cross section 1 with the removal of the tidal flats and mangrove areas (Experiment 3), instead of seaward as in Experiment 1. The overall sediment-transport dynamics was in accordance with the residual-current distribution shown in Figure 7a.

The Eulerian velocity component T_1 dominated landward sediment transport through Cross-

section 2 in Experiment 1, followed by tidal pumping ($T_3 + T_4 + T_5$) (Figure 10d). However, the effect of tidal pumping overtook the Eulerian advection component near East Arm Wharf (Figure 10f, right-hand side) when the mangroves and tidal flats were removed (Figure 10e), due to reduced tidal choking and increased flood dominance. Similar effects appeared in the Middle Arm entrance (Cross-section 4), as shown in Figures 10g–10i.

Figure 12. Comparison of the time series of suspended-sediment concentration near the bottom from the dredging simulation (blue lines), dumping simulation (purple lines), and the observed data (black dots) at the seven measurement sites.

Similar to *Li et al.* [2012], the combined mangrove areas and tidal flats were removed incrementally by 30%, 50%, and 70% in Experiments 4–6 to further examine their impact on total sediment flux in the harbor. The total sediment flux at Cross-section 1, seaward in Experiment 1 with the mangrove areas and tidal flats present, decreased in Experiment 4 (30% removal), then slightly increased in Experiment 5 (50% removal) (Figure 11). The total sediment flux decreased further in Experiment 6 (70% removal), and finally changed to landward in Experiment 2 in which 100% of the mangroves and tidal flats were removed. Therefore, there is an obvious trend in total sediment flux at Cross-section 1: increasing landward/decreasing seaward with increasing percentage removal of the mangrove areas and tidal flats in the harbor.

5. Discussion

5.1. Effects of Dredging in East Arm on Sediment Distribution and Flux

As shown by the field data in Figure 3, the SSC at Stations EA1 and EA2 were affected by dredging. This dredging effect was well-reproduced by Experiment 7. A comparison of the SSC values from the model with dredging and the observed values at the seven stations is shown in Figure 12. The SSC modeled in Experiment 7 was higher during the neap tides than during the spring tides at EA1 (Figure 12c), because the suspended sediment from dredging was transported away from EA1 by the strong currents during the spring tides. The discrepancy between model and observation during neap tides is probably due to the fact that the actual dredging intensity was reduced during neap tides, whereas the model assumed a constant dredging rate through the entire period. The spikes in the model values at EA2 (Figure 12d) were in phase with the field measurements, demonstrating that the suspended sediment at Station EA1 was transported to EA2 during the spring tides. The SSC at EA1 during the second spring cycle was higher than during the first, probably because less sediment was advected away from this location due to a weaker tidal current. It should be noted here that we only compared phases, as resuspension was not included in this experiment in order to highlight the effect of dredging. Also note that, after 1 month the suspended sediment from the dredging site had been transported to all seven stations.

5.2. Effects of the Disposal of Dredging Material on Sediment Distribution and Flux

As was shown in Figure 3, the SSC from Experiment 1 at Station CR did not match the field data, if only local sediment resuspension was considered. However, the SSC values at Station CR may also have been affected by the dumping of materials in the offshore disposal zone outside the harbor (Figure 1). Experiment 8 was designed to test the effect of this dumping on the SSC at Station CR. The time series of SSC values at the bottom level from Experiment 8 are shown in Figure 12. The model SSC peaks at Station CR were in phase with those in the field data (Figure 12g). This indeed demonstrates that the SSC at Station CR was affected by the dumping activity, and the observed spikes observed there were caused by advection of the material dumped offshore. Model SSC spikes were also seen at Station CL, as shown in Figure 12f; these were also in phase with the observed SSC spikes. The SSC at the other stations in the inner harbor and the arms was not affected by this disposal activity.

6. Conclusions

The suspended-sediment dynamics of Darwin Harbour in the dry season were simulated by ESSed, a sediment model [Wang, 2002], coupled with FVCOM. The FVCOM-ESSed model focuses on suspended sediment and its bottom boundary layer. The suspended-sediment concentration (SSC) was coupled into the water-density calculation. Various bathymetry types were considered, with the initial fine-sediment layer varied to distinguish between different geomorphologic situations.

The field data show that the SSC at seven stations in the harbor (Figure 1) varies with the spring-neap tidal cycle. The SSC values in the second spring tidal cycle were less than 50% of those in the first, due to stronger currents in the first spring tidal cycle caused by the larger tidal range. The abnormally high SSC values at Station EA1 were caused by dredging for the East Arm Wharf expansion. This dredging also affected the SSC values at Station EA2, about 7 km upstream, generating large spikes during the spring flood currents. Offshore dumping of the dredging materials also affected SSC values at Stations CR and CL about 20 km away in the outer harbor.

The model results agreed with the field data, with RMSE values smaller than 0.02 kg m^{-3} and ACC values larger than 0.6. Therefore, this sediment model is well suited to modeling the suspended-sediment dynamics in the harbor.

According to the model results, there was a turbid zone in the outer harbor, with bottom SSC about 0.1 kg m^{-3} during the spring tides. The water was also turbid in the inner harbor, and in the East Arm and West Arm channels during the spring tidal cycle. The turbid zone in the outer harbor was still present during the neap tides, but the bottom SSC values were less than about 0.07 kg m^{-3} . Water in the inner harbor and the arms was less turbid during the neap tidal cycle due to weaker currents. These turbid zones were formed by strong currents and the ready availability of sediment. Flood and ebb currents moved the turbid zone in the outer harbor landward and seaward, respectively, by advection. Vertically, sediments were well mixed during the spring tides. Weak vertical gradients of suspended sediment were formed in the channel during neap tides. Total sediment transport was seaward in the channel and landward in the East Arm and Middle Arm entrances, dominated by the Eulerian residual current.

The numerical experiments indicated that mangroves and tidal flats play key roles in redistributing suspended sediment and affecting total sediment transport by modulating the tides and tidal asymmetry. In Darwin Harbour, when the tidal flats and mangrove areas were removed from the model domain, the turbid zone in the outer harbor was still present during the spring tide, but the SSC values were reduced by 50% at the bottom level. The water in the inner harbor and the arms was less turbid because of a reduction in tidal current speeds due to a dampened tidal choking effect. The net sediment flux was landward in the channel (through Cross-section 1; Figure 1), due to the increased effect of flood dominance. The net landward sediment flux was reduced at Cross-sections 2 and 4 in the East Arm and Middle Arm entrances as a result of reduced currents in the arms when the mangroves and tidal flats were removed, and tidal pumping dominated suspended-sediment transport near the entrances of East and Middle Arm. Therefore, special attention should be paid to suspended-sediment dynamics when constructions are planned in a harbor, as inappropriate construction could cause siltation.

The dredging increased not only the local SSC, but also affected the SSC upstream in East Arm (about 7 km away from the dredging), as indicated by the SSC spikes observed there. Sediment from the offshore disposal area clearly increased the SSC at Station CR, where the SSC was more affected by advection of this sediment than local resuspension. The sediment was also transported to Station CL on the opposite side of the outer harbor, generating large SSC spikes there. Hence, dredging or dumping needs careful planning, as these activities could significantly change the suspended-sediment dynamics in a harbor.

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