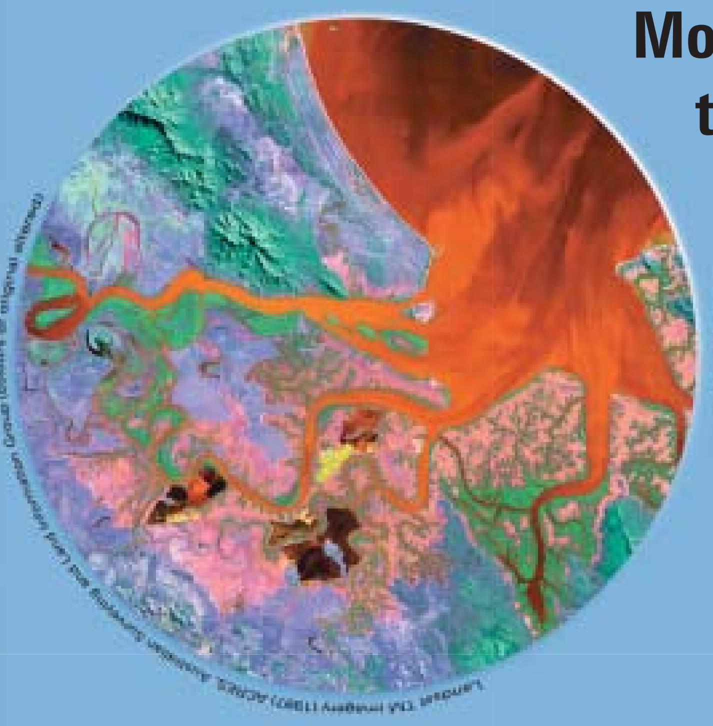
Cooperative Research Centre for Coastal Zone, Estuary & Waterway Management

Technical Report 39



Modelling of fine-sediment transport in the Fitzroy Estuary and Keppel Bay

N. Margvelashvili
M. Herzfeld
I. T. Webster

June 2006

CSIRO
Central Queensland University
Where Students Come First.
Queensland Government
Natural Resources, Mines and Water
Australian Government
Geoscience Australia
Griffith University
CRC for Coastal Zone Estuary & Waterway Management

Modelling of fine-sediment transport in the Fitzroy Estuary and Keppel Bay

Nugzar Margvelashvili, Mike Herzfeld and Ian Webster

June 2006

CRC for Coastal Zone
Estuary & Waterway Management

Modelling of fine sediment transport in the Fitzroy Estuary and Keppel Bay

Written by:

N. Margvelashvili
M. Herzfeld
I. Webster

Published by the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (Coastal CRC)

Indooroopilly Sciences Centre
80 Meiers Road
Indooroopilly Qld 4068
Australia

www.coastal.crc.org.au

National Library of Australia Cataloguing-in-Publication data
Modelling of fine sediment transport in the Fitzroy Estuary and Keppel Bay
QNRM06357
ISBN 1 921017 76 7 (online)

Acknowledgments

The work described in this report was funded by the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management and relied on extensive inputs of data and ideas from members of other components of the Fitzroy contaminants subproject (described in Coastal CRC technical reports 34 to 37). Particular thanks are due to Lynda Radke, Phillip Ford, Ian Atkinson, and Peter Verwey for data support and helpful advice, Barbara Robson for helpful discussions pertaining to sediment model performance and scenario modelling, Uwe Rosebrock and John Andrewartha for programming support, Brendan Brooke and David Ryan for helpful discussions on sediment dynamics. The sediment model also relies on the hydrodynamic modelling work described in Technical Report 38.

Nugzar Margvelashvili conducted the sediment modelling and analysis, Mike Herzfeld designed the hydrodynamic model components, Ian Webster provided field data and contributed to the analysis. This report was written and compiled by N. Margvelashvili.

Contents

List of figures

List of tables

Executive summary

Increased rates of sediment and nutrient loads from catchments to ocean in recent years have raised concerns about the potential impact of these loads on the Great Barrier Reef ecosystem. The role of coastal areas in mediating material fluxes between catchments and ocean is still poorly understood. The Fitzroy catchment is the largest Queensland catchment (144 000 km^2) draining to the east coast; it delivers significant amounts of sediment with high levels of nutrients and some pesticides to the Fitzroy Estuary and Keppel Bay.

To provide a better understanding of the sediment dynamics in the Fitzroy Estuary, a coupled, one-dimensional (1-D), vertically and laterally averaged model of hydrodynamics and sediment transport was developed and applied to the main channel of the estuary during the first phase of the Coastal CRC (Margvelashvili *et al*., 2003). The work highlighted a strong coupling between the Fitzroy Estuary and Keppel Bay and revealed the complex dynamics of sediments associated with flocculation and an upstream tidal pumping of sediments. However the 1-D model constraints precluded accurate assessment of sediment delivery to the ocean.

In phase 2 of the Coastal CRC, these limitations were eliminated by using 3-D fine-resolution hydrodynamic and sediment transport models and extending the modelling domain into Keppel Bay. The modelling objectives were to provide a better understanding of the sediment transport in a coupled estuary–bay system and to assess sediment loads to the ocean by developing a calibrated 3-D fine-resolution model and running ‘what if’ scenarios that would assist regional planning. The scenarios involved modelling of the sediment transport under low, moderate, and high river flow regimes with sediment loads from catchments also altered by varying land use practices.

The calibration study, followed by validation tests, revealed large uncertainties in the model predictions. These were attributed to limited understanding of the fundamental processes involved in sediment transport, as well as model constraints and uncertainties in input data. While the model did not predict every individual measurement, it was capable of reproducing general trends of suspended sediment distribution over the modelling domain and a typical range of sediment concentrations. Combined with data analysis, the modelling results provided useful insights into the sediment dynamics in the study area.

The simulations demonstrated two distinct mechanisms of the sediment delivery to the ocean, operating at different time-scales. One is associated with a pulsed discharge of sediments during flood events, and another with a subsequent, relatively long-term, tidal flushing of the deposited particles from the coastal areas into the deep ocean. During moderate and high flow years, the model predicts that sediments accumulating in the estuary and Keppel Bay develop a sedimentary pool that is sufficient for maintaining elevated export of fine particles to the ocean throughout the year.

The sediment discharge to the ocean varies with the river flow regime and the sediment loads from catchments. Increasing freshwater flows from moderate (peak discharge of 700 m^3/s) to high (peak discharge of 4000 m^3/s), increases fine-sediment delivery to the ocean from 163 to 1143 kT/year. Varying sediment loads from catchments, during years having low or moderate flood events, has a less pronounced impact on the annual loads to the ocean.

The modelling results have the following implications for catchment management practices. If the years following high flood event have only low and moderate flows, then any alterations in land-use practices may have a minor impact on the sediment delivery to the ocean, as the loads would be maintained by the background fluxes associated with the past deposits. Significant changes in sediment delivery from the Fitzroy Estuary and Keppel Bay to the ocean, due to altered land use practices, in this case can be expected to occur during the years having another high flood event, when fresh sediments from catchments dominate net annual loads to the ocean.

Introduction

The Fitzroy is a shallow, macrotidal estuary in eastern Australia (Figure 1), which discharges into the marine environment at the southern end of the Great Barrier Reef (GBR). The major freshwater inflow to the estuary is from the Fitzroy basin, which is the largest catchment in north-eastern Australia (Rochford, 1951; Connell *et al.*, 1981). Limited data indicate average annual sediment delivery to the Fitzroy Estuary is four million tonnes, with high levels of nutrients and some pesticides (Taylor & Jones, 2000). Increasing discharge rates of sediments and nutrients in recent years have raised concerns about the potential impact of these loads on the GBR ecosystem (Wolanski & De'ath, 2005; Wolanski *et al*., 2005; Neil *et al*., 2002; Larcombe & Woolfe, 1999).

In order to reduce sediment and nutrient loads from catchments to the GBR, substantial effort has in recent years gone into developing and implementing management scenarios, including altered land-use practices, under the Australian and Queensland Governments' Reef Water Quality Protection Plan (http://www.deh.gov.au/coasts/pollution/reef/). However the role of coastal areas in mediating material fluxes from catchments to ocean is still poorly understood and additional studies, aiming at better understanding of coastal processes, are required for realistic prediction of the sediment delivery to ocean.

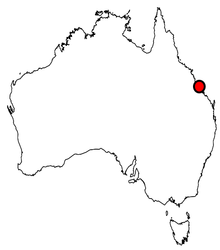


Figure 1. Fitzroy Estuary and Keppel Bay, central Queensland

To provide better understanding of the sediment dynamics in the Fitzroy Estuary, a coupled one-dimensional, vertically and laterally averaged model of hydrodynamics and sediment transport was developed and applied to the main channel of the Fitzroy Estuary during the first phase of the Coastal CRC (Margvelashvili *et al*., 2003). The work demonstrated a strong coupling between the Fitzroy Estuary and Keppel bay and highlighted the complex dynamics of sediments associated with flocculation and an upstream tidal pumping of sediments. However the modelling constraints associated with limitations of the 1-D model and the close proximity of the modelling domain boundaries to the estuary precluded accurate assessment of sediment delivery to the ocean.

In phase 2 of the CRC, these limitations were eliminated by implementing 3-D fine-resolution hydrodynamic and sediment transport models and extending the modelling domain into Keppel Bay. The modelling objectives were to provide a better understanding of the sediment transport in a coupled estuary–bay system and to assess sediment loads to the ocean by developing a calibrated 3-D fine-resolution model and running ‘what if’ scenarios that would facilitate regional planning. It is anticipated that the biophysical understanding and model capability derived here for tropical macrotidal estuaries will be transferable to other similar systems, which are widespread throughout northern Australia but relatively poorly studied.

This report gives brief description of the sediment model, outlines the results from the calibration study and presents discussion on scenario modelling results.

The model

Hydrodynamics

The flow and mixing in the Fitzroy Estuary and Keppel Bay are most strongly controlled by the freshwater flows—mainly from the Fitzroy River—discharging into the estuary through the Rockhampton barrage and by the tides. Other potential influences on the hydrodynamics of such systems are the wind, and evaporation and precipitation, which affect the water balance within the system. River discharge is characterised by large interannual variability and a marked seasonal variation due to rainfall, usually with strong flows from November to May, and dropping almost to zero at other times (Rochford, 1951). The tides are a mixed, dominant semidiurnal type with a two-weekly cycle of spring tides and neap tides. During spring tides the daily tidal excursion at Port Alma may reach 5 m, reducing to about half this during neap tides. The wind climate over the Fitzroy Estuary and Keppel Bay is dominated by the southeast trade winds.

Water circulation in the Fitzroy estuary and Keppel Bay was modelled by a 3-D non-linear, non-stationary, z-coordinate hydrodynamic model (Walker & Sherwood, 1997; Herzfeld *et al.*, 2003), which solves Reynolds' equations with a free surface boundary condition and utilises the Boussinesq approximation and the hydrostatic assumption. The model's governing equations include equations for momentum, continuity and salinity/temperature transport. Detailed description of the application of the model to the Fitzroy Estuary and Keppel Bay can be found in the hydrodynamic modelling report of Herzfeld *et al*. 2005.

Sediment transport model

This study is primarily concerned with the understanding and prediction of fine sediment transport, as those particles being resuspended can be carried by currents over much longer distances than the heavier sand grains. Consequently, if the sediment loads from catchments have substantial impact on the GBR, then fine particles are likely to play a major role in these processes. Furthermore, fine sediments are instrumental to the ecology of the Fitzroy Estuary and Keppel Bay (Turner & Millward, 2002; Ambrose *et al*., 1993). Suspensions of fine silts or clays can be very effective at reducing the light necessary for the growth of phytoplankton or benthic primary producers. Nutrients (phosphorus) and pesticides adsorb to the surfaces of mineral particles. Having a larger surface area to volume ratio, fine particles can adsorb and carry much larger quantities of these contaminants than can suspensions of particles of the same concentration but greater grain sizes (Onishi *et al*., 1981). Transportation of nutrients and pesticides in adsorbed form is regarded as likely to be a major delivery mechanism for these substances between the catchment of the Fitzroy River and the mouth of the estuary (Webster *et al*., 2003).

Historically, the modelling of fine-grained, cohesive sediments and sand fractions has been developed separately, as the physics associated with transport of those two classes of particles varies considerably (USACE 1999). The following section gives a brief description of the fine-sediment model that was developed and implemented during this study.

Mass balance equations

The hydrodynamic model drives the sediment transport model, which solves advection-diffusion equations for the mass conservation of suspended and bottom sediments, taking into account bottom exchanges due to resuspension and deposition. The model's governing equations include 3-D equations for the suspended sediment concentration (S_i ,):

$$\frac{\partial S_i}{\partial t} + \frac{\partial}{\partial x}(uS_i) + \frac{\partial}{\partial y}(vS_i) + \frac{\partial}{\partial z}\left[(w - w_{gi})S_i\right] = = \frac{\partial}{\partial x}\left(K_h \frac{\partial S_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h \frac{\partial S_i}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial S_i}{\partial z}\right), \quad z_{bot} < z < z_{top} \qquad \text{(Eqn 1)}$$

1-D equations for the bottom sediment concentration

$$\frac{\partial S_i}{\partial t} = \frac{\partial}{\partial z}\left(K_z \frac{\partial S_i}{\partial z}\right) \qquad z_{deep} < z < z_{bot} \qquad \text{(Eqn 2)}$$

and equations for the top sediment layer coordinate (z_{bot})

$$\frac{\partial z_{bot}}{\partial t} = F_{solid} + F_{liquid} . \qquad z = z_{bot} \qquad \text{(Eqn 3)}$$

Here F_{solid} and F_{liquid} are volumetric fluxes of solid and liquid phases through the 'sediment–water' interface, respectively; S_i [kg/m^3] is the concentration of the *i*-th fraction of the suspended or bottom sediments; K_z is the diffusion coefficient associated with either turbulent mixing in the water column or local bioturbation in the sediment bed; K_h is the horizontal diffusion coefficient in the water column.

In equations 1–3, the modelled seabed is represented by a number of vertically resolved columns with no direct horizontal exchange between adjacent numerical cells. Any exchange between sediment columns is associated with resuspension or deposition events and horizontal displacement of the suspended sediments. In the water column, the numerical grid for sediments is identical to the numerical grid of the hydrodynamic model, and the sediment model utilises the same high-order numerical schemes for advection and diffusion as are used for salinity and temperature variables.

Boundary conditions

At the open lateral boundaries, either zero-gradient boundary conditions or observed sediment concentrations are specified. There are no fluxes of sediments through the solid lateral boundaries, the estuarine surface ($z = z_{top}$) and through the bottom of the deepest sediment layer ($z = z_{bot}$):

$$\left(w_{gi} - K_z \frac{\partial}{\partial z} \right) S_i = 0 \qquad z = z_{top} \qquad \text{(Eqn 4)}$$

$$K_z \frac{\partial S_i}{\partial z} = 0 \qquad z = z_{bot} \qquad \text{(Eqn 5)}$$

At the water–sediment interface ($z = z_{\text{int}}$) solid fluxes are prescribed taking into account sediment resuspension and deposition:

$$\left(w_{gi} - K_z \frac{\partial}{\partial z} \right) \cdot S_i = Q_i \qquad z = z_{\text{int}} \qquad \text{(Eqn 6)}$$

Here Q_i [kg/(m^2 s)] represents either resuspension or deposition flux of sediment.

Sediment fluxes and settling velocities

The volumetric solid and liquid fluxes across the water–sediment interface shown in Equation 3 are defined as:

$$F_{solid} = \sum_{i=1}^{n} \frac{Q_i}{\rho_i}, \qquad F_{liquid} = \sum_{i=1}^{n} \varepsilon_i \frac{Q_i}{\rho_i}. \tag{Eqn 7}$$

Here ρ_i [kg/(m^3)] is the density of the sediment grains; and ε_i is the void ratio of the *i*-th fraction of the sediment deposits.

Resuspension and deposition of fine sediments are parameterised using the Ariathurai-Krone (1976) formula:

$$Q_i = w_{g\,i} S_i f_d + \left(\frac{S_i / \rho_i}{1-\varphi} \right) M f_e, \tag{Eqn 8}$$

where the probabilities for deposition and erosion are given by

$$f_d = \begin{cases} 0: & \tau_b \geq \tau_{cd} \\ \left(1 - \dfrac{\tau_b}{\tau_{cd}}\right): & \tau_b < \tau_{cd} \end{cases} \qquad f_e = \begin{cases} 0: & \tau_b < \tau_{ce} \\ \left(\dfrac{\tau_b}{\tau_{ce}} - 1\right): & \tau_b \geq \tau_{ce} \end{cases} \tag{Eqn 9}$$

The formulation (Equation 9) depends on the specification of bottom stress τ_b, which is calculated from the hydrodynamic model. Critical shear stresses for resuspension (τ_{ce}) and deposition (τ_{cd}) are empirical constants. The resuspension rate M (kg m^2/s) is specified using the formulation suggested by Delo (1988) (cited in Uncles & Stephens, 1989):

$$M = 0.002 * \tau_{ce} \ (\text{kg m}^2 \text{ s}^{-1}), \tag{Eqn 10}$$

The settling velocity of fine-grained sediment in estuarine water is influenced by flocculation effects. Following field observations and laboratory studies, the settling velocity of sediments during simulations varied with salinity and fine sediment concentration:

$$w_{gi} = \begin{cases} w_{0i}, & Salinity < 0.1\,(PSU) \\ \max\left(w_{0i},\, aC^b\right), & Salinity \geq 0.1\,(PSU) \end{cases} \tag{Eqn 11}$$

where *a* and *b* are empirical constants (Dyer, 1989; van Leussen, 1999) and w_{0i} is the settling velocity of disaggregated particles.

Although this study was concerned primarily with fine sediment dynamics, the sediments in the Fitzroy Estuary and Keppel Bay contain a mixture of particles with different grain size and physical and chemical characteristics. On a mixed seabed consisting of fine and coarse particles, heavier particles can limit the depth from which finer grains are available for resuspension and, conversely, consolidated mud can form a layer that arrests further entrainment of sand. To take account of such interactions, the model has been extended by incorporating capabilities for simulating resuspension and deposition of non-cohesive sediments. The formulation is based on the concept of the near-bed equilibrium sediment concentration (USACE, 1999) and utilises Smith and McLean's (1977) formula for resuspension and deposition fluxes.

Numerical grid, initial and boundary conditions

Figure 2 illustrates the bathymetry of the study area and the location of the modelling domain, which extends downstream from the barrage along the estuary to Keppel Bay. The estuary has a relatively deep upper channel (up to 12 m deep), and a shallower lower section with a number of islands at the estuarine mouth.

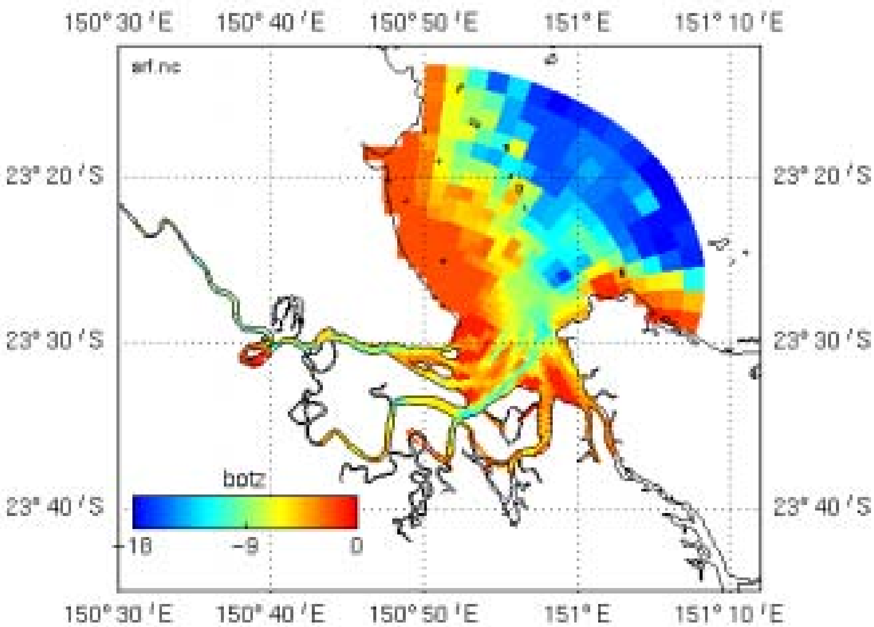


Figure 2. Bathymetry of the Fitzroy Estuary–Keppel Bay study area

The main channel of the estuary is the primary source of fresh water to Keppel Bay, with minor or no contribution from the smaller creeks that infringe the land masses at the southern end of the modelling domain. The water depth in Keppel Bay gradually increases seaward, with relatively broad, shallow areas allocated along the north-west coasts.

The lateral spacing of the numerical grid (Figure 3) varies from ~100 m in the upper estuary to ~ 2000 m at the seaward end of the modelling domain. The vertical coordinate is resolved by 16 layers with 0.5 m resolution in the top 5 m, and the vertical resolution gradually increasing with depth in deeper water. Horizontal resolution in sediments is identical to the resolution in the water column. In the vertical direction, bottom sediments are resolved by three layers with the total initial thickness of sediments of 30 cm, and the thickness of the top and the underlaying layers of 0.5 cm and 1 cm, respectively.

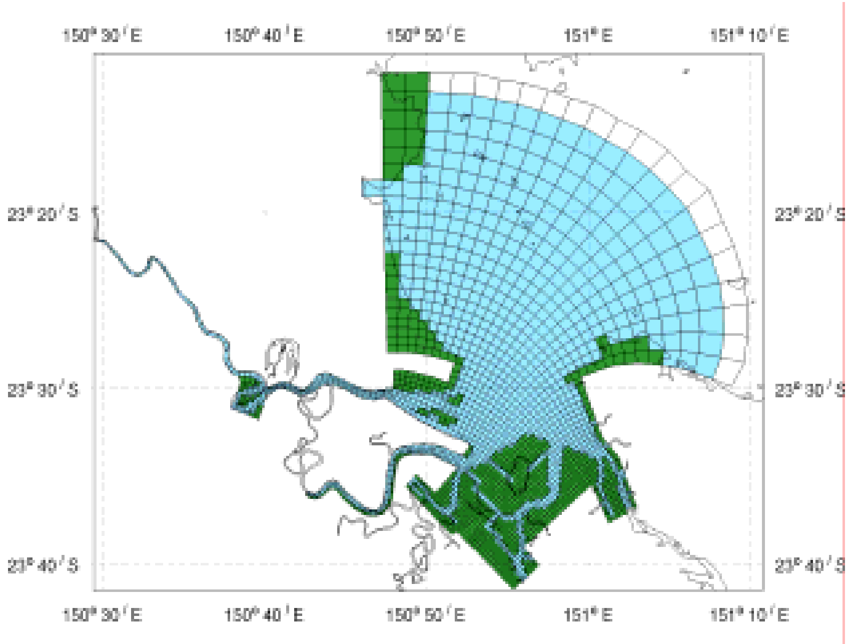


Figure 3. Plan view of the 3-D numerical grid

The hydrodynamic model is forced at the barrage with the observed river flow, temperature and salinity. At the seaward end of the modelling domain, temperature, salinity and surface elevation are specified by nesting inside large-scale model simulations (not shown in this report). More details on the hydrodynamic model set up and forcing are available from the accompanying report by Herzfeld *et al*. (2005).

The sediment model was initialised with the observed distribution of gravel, sand and mud deposits in the seabed (Figure 4 a,b,c; Radke *et al*., 2005b).

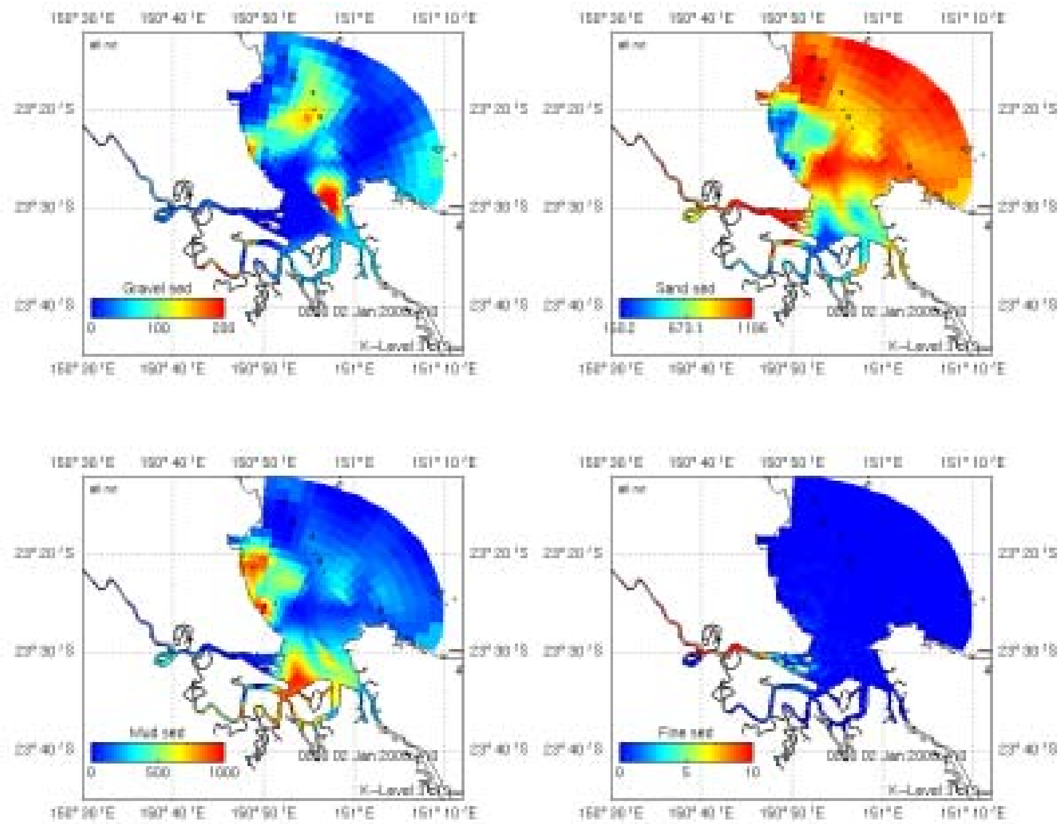


Figure 4. Initial distribution of gravel, sand, mud and clay fractions of sediment, as used in the model

The mud fractions were originally represented by a single class of sediments corresponding to medium silt. The settling velocity for this fraction was estimated by testing the model against data collected in Keppel Bay. However, even though with these settings the model reproduced sediment concentrations in Keppel Bay, it underestimated suspended sediment concentrations in the upper and middle estuary. Limited data indicate that suspended sediments in the estuary are typically represented by small particles with the modal grain size ranging from 3.5 µm to 9.3 µm (Webster *et al*., 2003; Radke *et al*., 2005a). These observations have led to incorporation into the model of the additional class of sediments representing fine silt and clay fractions. The initial bottom deposits for this fraction were evaluated by simulating the 2004 flood event. In the water column, initial concentration of all sediment fractions was set to zero.

In the following sections, for the sake of convenience, we will refer to these two classes of fine sediments, one representing coarse and moderate silt and another fine silt and clay, as coarse silt and fine silt respectively.

During the simulations the gravel was considered as an immobilised porous medium, providing a basis from which finer particles were resuspended.

Furthermore, due to limitations imposed by the z-coordinate numerical grid, sand fractions were simulated in a 1-D vertical mode, assuming no horizontal advection in the water column and in sediments. Only fine sediment fractions, representing silt and clay, were allowed to move with currents in horizontal directions.

At the barrage, the input concentrations for the gravel, sand and coarse silt fractions were set to zero and the concentration of the fine silt was scaled with river flow, using linear regression between river flow and monthly sampled TSS at the barrage of S = (0.1*Flow+15). This relationship is based on data from July 2001 to June 2002 – a year having a peak flood discharge comparable to the discharge during the model calibration period (2004–2005). Note that the relationship between TSS concentration and discharge in the Fitzroy estuary is highly irregular and variable, changing from one year to another with the catchment in which the flow event originates and with the stage of the hydrograph (Webster *et al*., 2003).

Apart from sediment concentration, the grain size of particles delivered to the estuary from catchments is also likely to change from one year to another and with river flow. However, the understanding of these changes is poor and, during the modelling, sediments entering the modelling domain through the barrage were represented by a single fraction corresponding to fine silt.

At the seaward boundary, a free-flow boundary condition is applied to all sediment fractions when the water flow is directed out of the modelling domain. During the inflow events, the concentration of coarse silt is specified using a zero-gradient boundary condition, and the concentration of fine silt is set to zero.

Sediment data

Figure 5 shows an example of depth-averaged currents and suspended sediment concentrations as measured at the surface and near-bottom layer of two sites in Keppel Bay (Radke *et al*., 2005b), with the measurements coinciding with neap tide conditions. The site location map is shown in Figure 6.

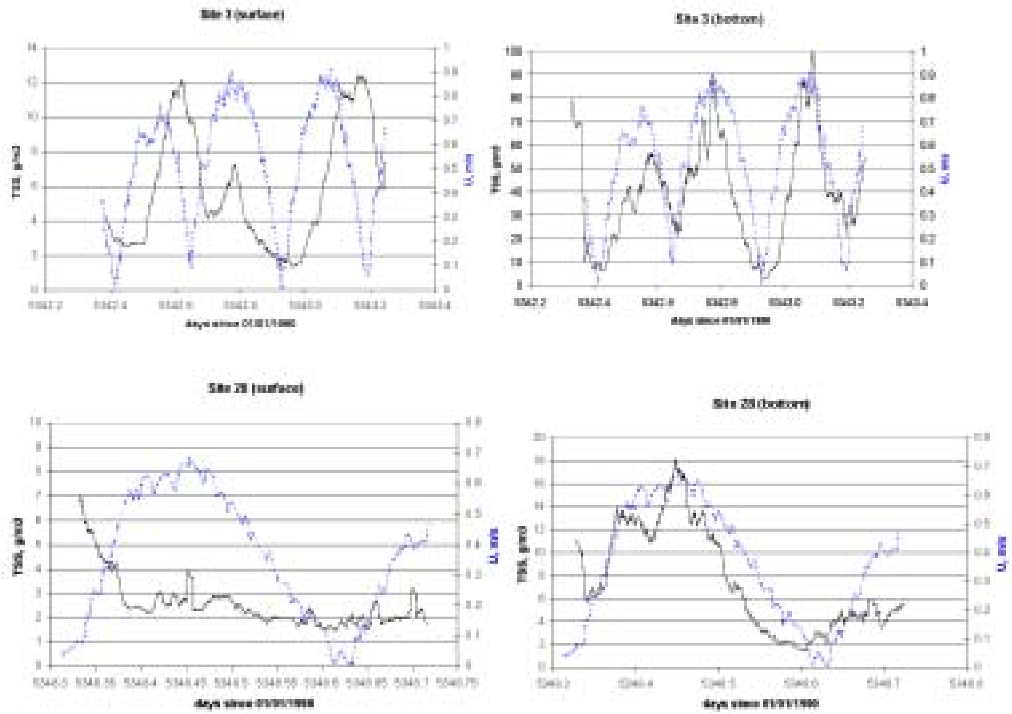


Figure 5. Measured TSS versus measured velocity, August 2004

According to the data demonstrated in Figure 5, the near-bottom concentrations are in phase with local velocity, suggesting that local resuspension and deposition are the major drivers of sediment variability near the seabed. At the surface layer, a phase lag between sediment concentration and velocity could be attributed either to horizontal transport of the sediment plume or/and to vertical mixing of sediments.

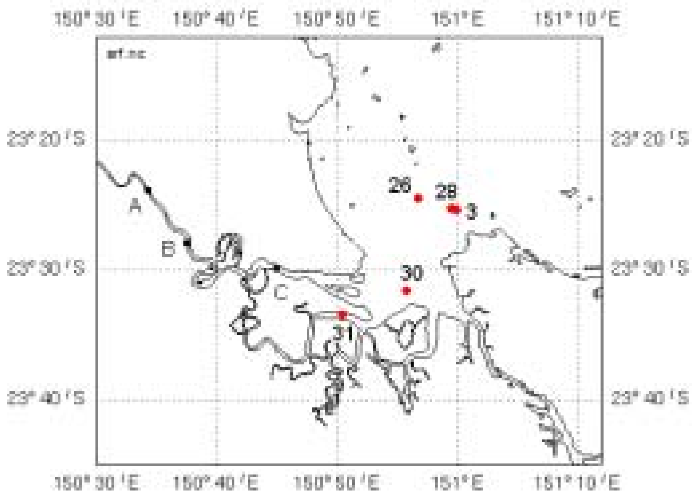
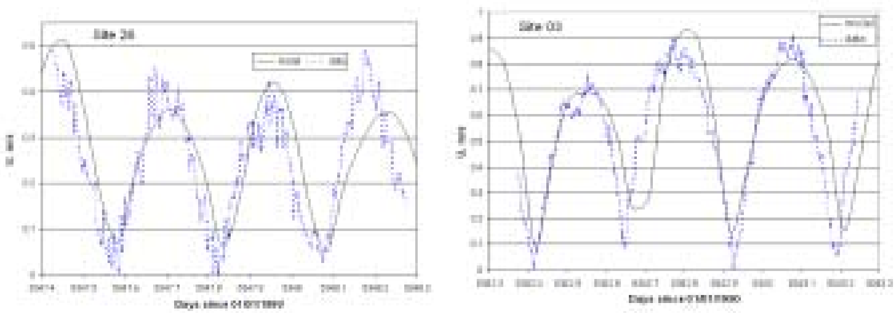


Figure 6. Location of sampling stations, August 2004

Since the sediment model is driven by simulated currents, uncertainties in the hydrodynamic model may constrain an accuracy of the sediment model predictions. To evaluate the accuracy of the modelled currents, the simulated velocities were compared with measurements, showing, in general, good agreement between model and data in open deep-water areas such as Sites 26 and 28 (Figure 7). In shallow confined areas such as Casuarina creek, and in a close proximity to the coastline, there are more discrepancies between model and data, attributed to lack of resolution in these areas and uncertainties in the local bathymetry data. It is worthwhile mentioning here that the resuspension rate of fine sediments is a nonlinear function of bottom friction, which in turn, in the simplest approximation, is proportional to the squared velocities. Such a highly nonlinear relationship between resuspension and velocities suggests that the errors in the predicted sediment concentrations are likely to disproportionally exceed the velocity errors.



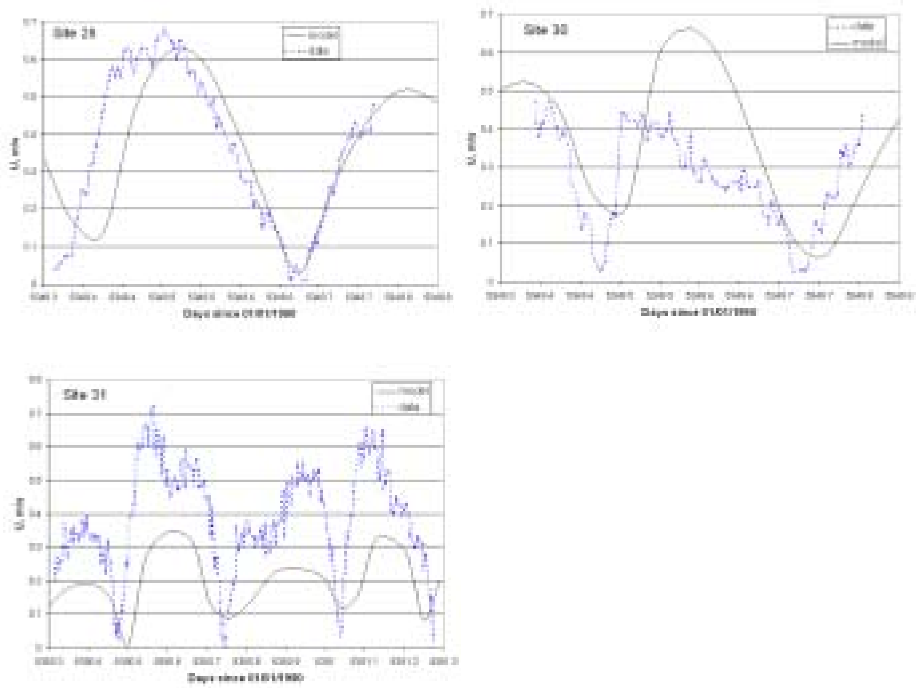


Figure 7. Modelled velocity versus measurements, August 2004

Calibration of the sediment model

The sediment model was calibrated against suspended sediment data recorded at Buoy 4 (station 28) in February 2004. The performance of the calibrated model was tested then against data collected during an August 2004 field trip, and data obtained from the Buoy 1 (station 30) in February 2005. The model was calibrated with respect to flocculation parameters (*a* and *b* in Equation11), settling velocities of unflocculated particles and critical shear stress of the sediment resuspension. The best fit between model and measurements has been achieved with the flocculation parameters *a* = 500, *b* = 3; settling velocities for disaggregated coarse and fine silt of 7e-4 and 1e-5 m/s respectively; and critical shear stress of resuspension of 0.05 N/m^2.

The calibration was based on trial and error and involved more than 100 scenario runs. Apart from changing the calibration parameters, a number of model runs have been executed with an altered formulation of the modelled processes (added sediment consolidation and thus introducing time-dependent critical shear stresses; changed formulation for the flocculation processes; and changed initial settings).

Figure 8 illustrates the scenario run that produced the best fit between model and data. The model predicts the correct range of variability of the sediment concentrations between neap and spring tides and the correct range of intratidal variability during high and declining spring tide, but overestimates sediment concentrations at the beginning of the spring tide.

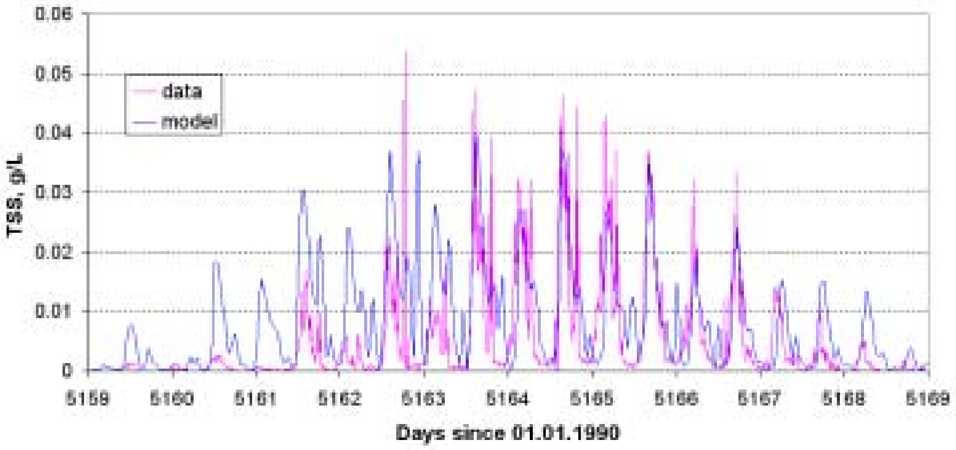


Figure 8. Modelled TSS versus data, February 2004

In the main channel of the estuary, the model performance was tested against suspended sediment concentrations measured during monthly monitoring program. While subject to large uncertainties due to small scale variability of the sediment concentrations, not captured by monthly sampling technique, monthly data reveal general trends in suspended sediment distribution along the estuary (Margvelashvili *et al.*, 2003). Under low flow conditions in the upper estuary, sediment concentrations typically do not exceed 40 g/m^3, and the maximum concentrations gradually increase downstream (up to 300 g/m^3 near the mouth) due to enhanced tidal resuspension.

Figure 9 shows the median values of the suspended sediment concentrations in the upper (10 km downstream from the barrage) and lower (20 km upstream from the mouth) estuary as predicted by the 3-D model for 2004. Since monthly data were not available for 2004, the modelled values are compared to measurements, representing 1993–1996. While underestimating suspended sediment concentrations in the lower estuary by ~27%, the model reproduces general pattern of the sediment distribution along the main channel of the estuary.

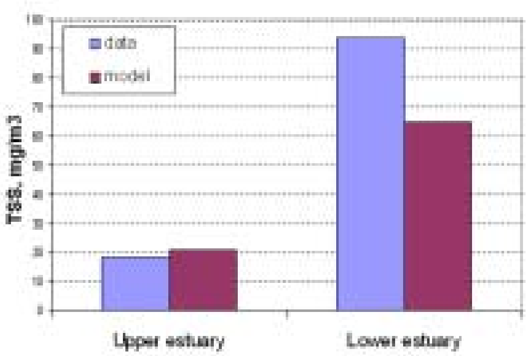


Figure 9. Median values of modelled and measured TSS in the upper and lower estuary

The performance of the calibrated model was tested against data collected during the August 2004 field trip. As seen in Figure 10, the largest discrepancies between model and data occur in the near-bottom region. These are attributed to significant small-scale variability of the benthic features which are not resolved by the model. The offshoot of the near-bottom sediment concentrations at Site 3 (Figure 10) is due to resuspension of the sand fractions which, as mentioned earlier, are simulated in a 1-D model and do not contribute to horizontal transport.

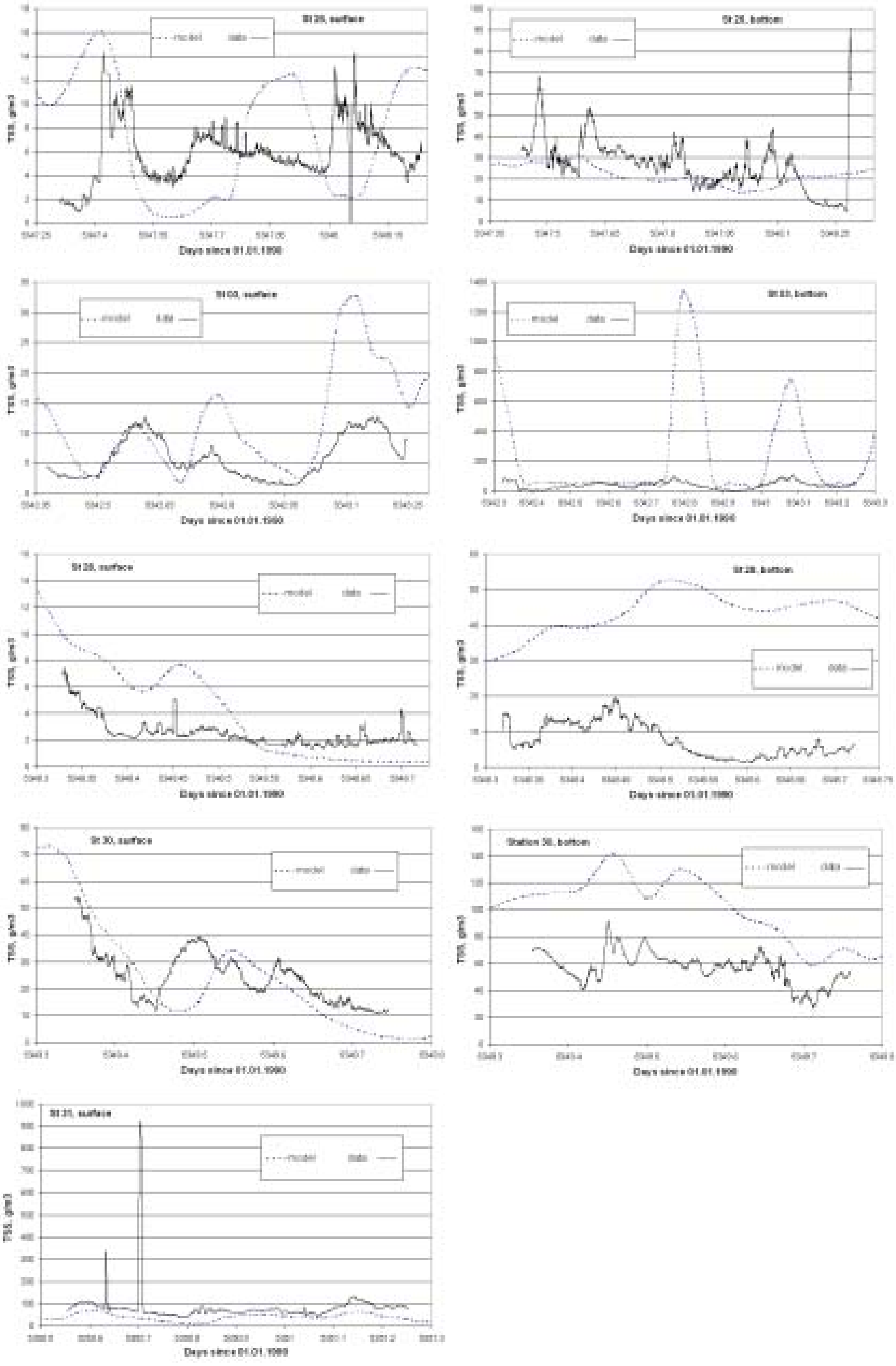


Figure 10. Modelled TSS versus data, August 2004

According to the model, sand particles tend to concentrate in the near bottom region and have little contribution to the suspended concentrations beyond ~1m layer near the seabed. Suspended sediment concentrations in most of the water column are predominantly fine fractions of sediment. The modelled and measured maximum concentrations of fine sediments at the surface layer vary by about a factor of 3, which provides the lowest limit of the potential uncertainties associated with the model predictions.

Another test of the model performance included simulation of 2005 flood. Figure 11 shows river discharge and turbidity signal (recorded at Site 30), over the three neap–spring tidal cycles. The flood event coincides with the neap tide, and causes sharp increase of the turbidity signal near the estuary mouth, attributed to downstream discharge of the turbid water.

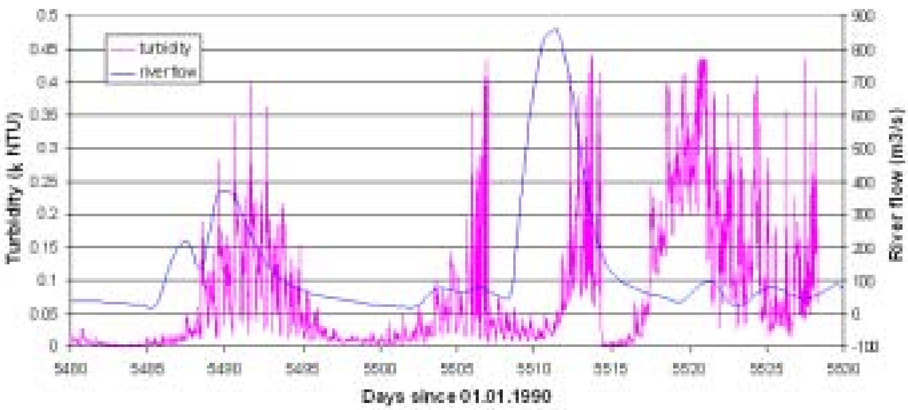


Figure 11. Measured turbidity versus river flow

At day 5514 (Figure 11) the turbidity drops within 10 minutes from 0.4 kNTU to less than 0.01 kNTU; after that the signal gradually increases with time, reaching values typical to the spring tide conditions. The data show also an episodic high turbidity event developing during the spring tide preceding the flood event (days 5506-5507).

The model comparison with data, shown in Figure 12, is based on the following relationship between turbidity and sediment concentrations: TSS = 0.65+1.13xturbidity, where TSS is given in g/m^3 and turbidity units are NTU (Radke *et al*., 2005a). According to this comparison, the model grossly underestimates the measured concentrations (turbidity) during the flood period (days 5512-5515) and during the high-turbidity event of days 5506-5507. A number of additional scenarios have been simulated to investigate the model's sensitivity to various assumptions involved in modelling, including varying sediment delivery from the barrage and simulating transport of the conservative dissolved tracer. All these simulations, however, predicted sediment concentrations during the flood event that were much lower than actual measurements.

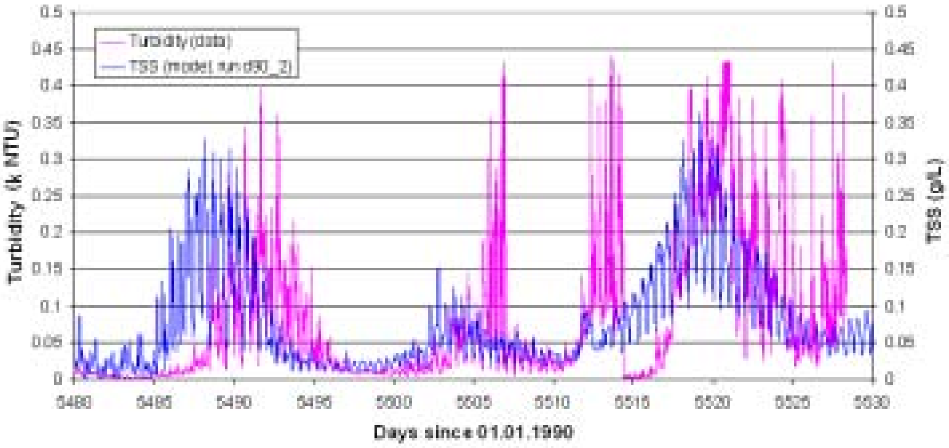


Figure 12. Modelled TSS and turbidity versus measurements, January–February 2005 (TSS = 1.13xturbidity)

Large discrepancies between model and data during the flood event could be attributed to a number of factors including failure of the instrument, an influence of the processes not accounted by the model (i.e. wave enhanced resuspension, coastal erosion, sediment loads from tidal creeks), as well as lack of understanding of the sediment transport in a macrotidal environment. Figure 13 shows a picture of the turbidity plume near the estuary mouth (Site 30), taken a few days after arrival of the turbid water to southern Keppel Bay. By the time the photo was taken, the plume had gone through a number of tidal cycles, which were expected to mix all properties in the water column. However, as Figure 13 shows, there is still a sharp transition a few metres long between clean and turbid water. Resolving and predicting such small-scale features during the regional-scale studies remains a challenge, yet to be overcome.

Figure 13. Turbidity plume near the estuarine mouth a few days after the 2004–05 flood

Modelling results

Shear stresses

High variability of simulated bottom shear velocities over the tidal cycle and under low and moderate wind conditions in the Fitzroy Estuary and Keppel Bay is illustrated in Figure 14. The red, yellow and green colours on the plots correspond to areas with high resuspension rates and blue colours represent deposition sites. The highest shear stresses over the tidal cycle tend to develop during the flooding tide in the estuarine mouth and in the central and southern parts of the Keppel Bay, while the lowest tend to occur in the upper estuary and in the estuarine loop, along the western coast of Keppel Bay and at the seaward end of the modelling domain.

Time series of the shear stresses at various locations within the estuary and bay over the neap–spring tidal cycle are illustrated in Figure 15 (a,b). The red line on these plots represents the critical shear velocity of the fine sediment resuspension, obtained from the model calibration study. The modelled period includes a moderate flood event with the peak discharge reaching 600 m^3/s.

Under low flow conditions, tidal currents in the upper estuary are fairly small, and the shear velocities only occasionally exceed the critical value. Further downstream tidal currents become more vigorous and in the lower estuary critical shear stresses are regularly exceeded. During the flood event the shear stresses within estuary increase, enhancing sediment resuspension in the upper channel however in the lower estuary the bottom stresses are still dominated by tidal currents.

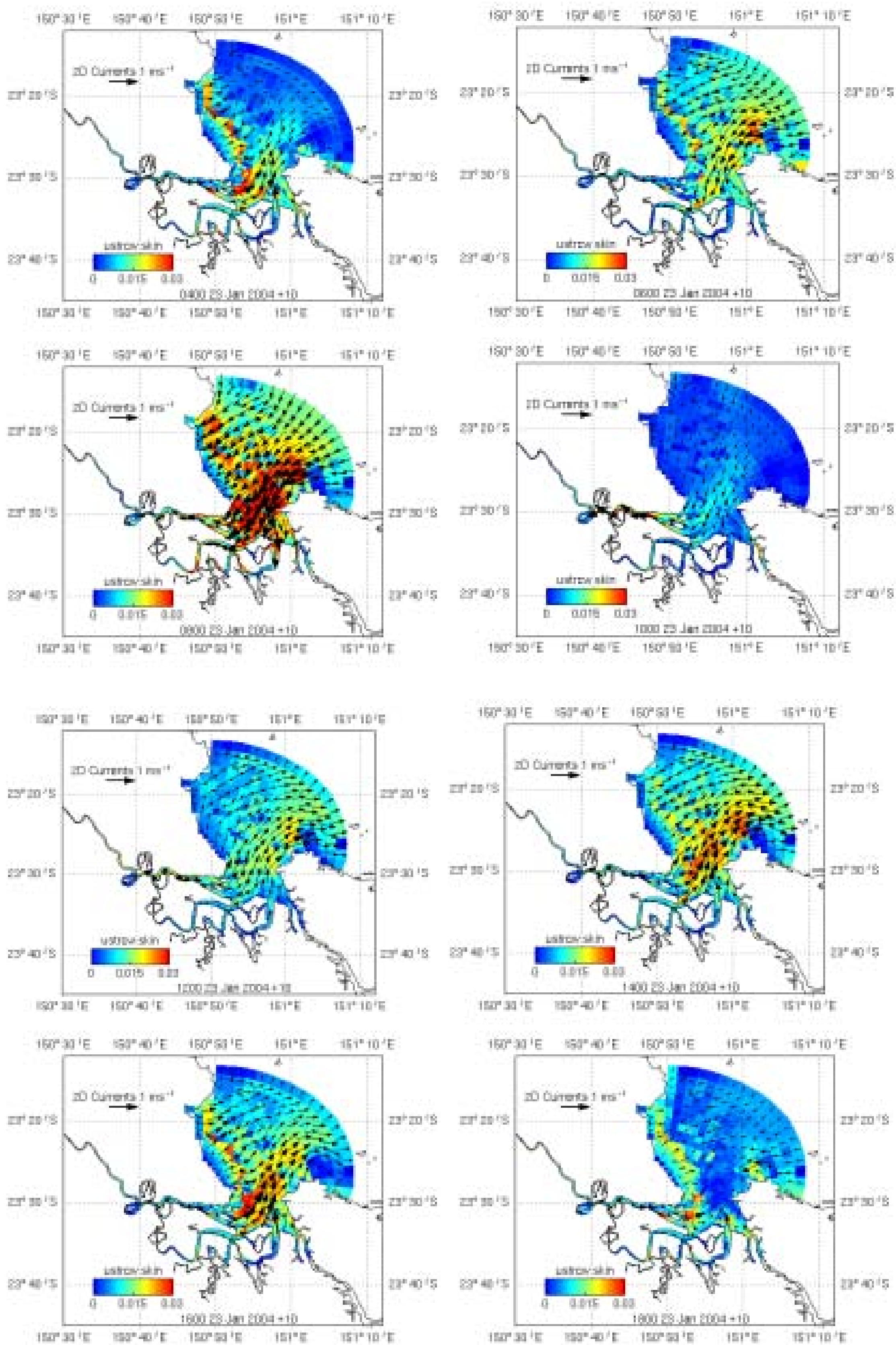


Figure 14. Simulated bottom shear velocities in the Fitzroy Estuary and Keppel Bay over one tidal cycle (spring tide)

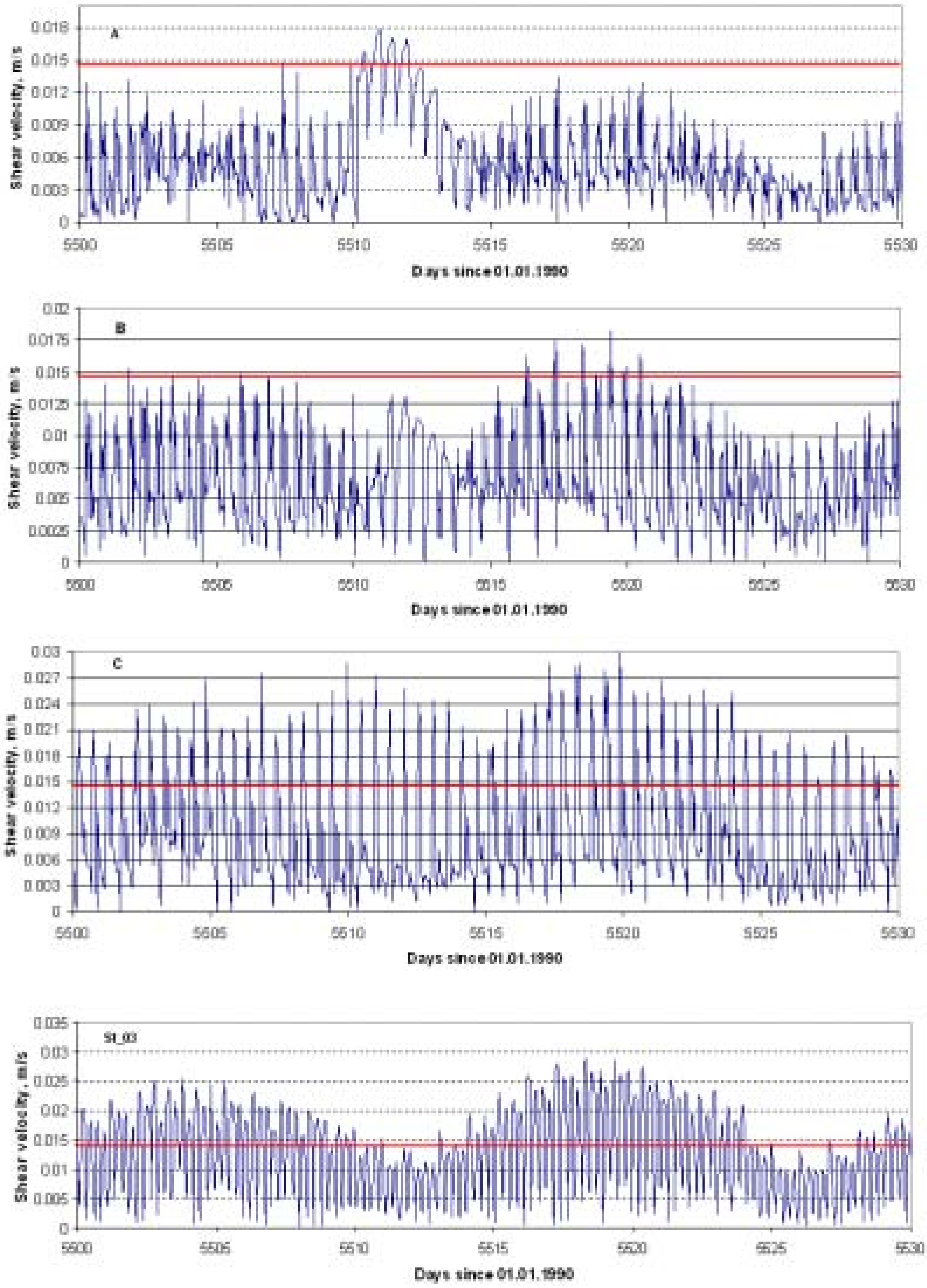


Figure 15a. Time series of shear velocities in the Fitzroy Estuary and Keppel Bay, sites A, B, C and 3

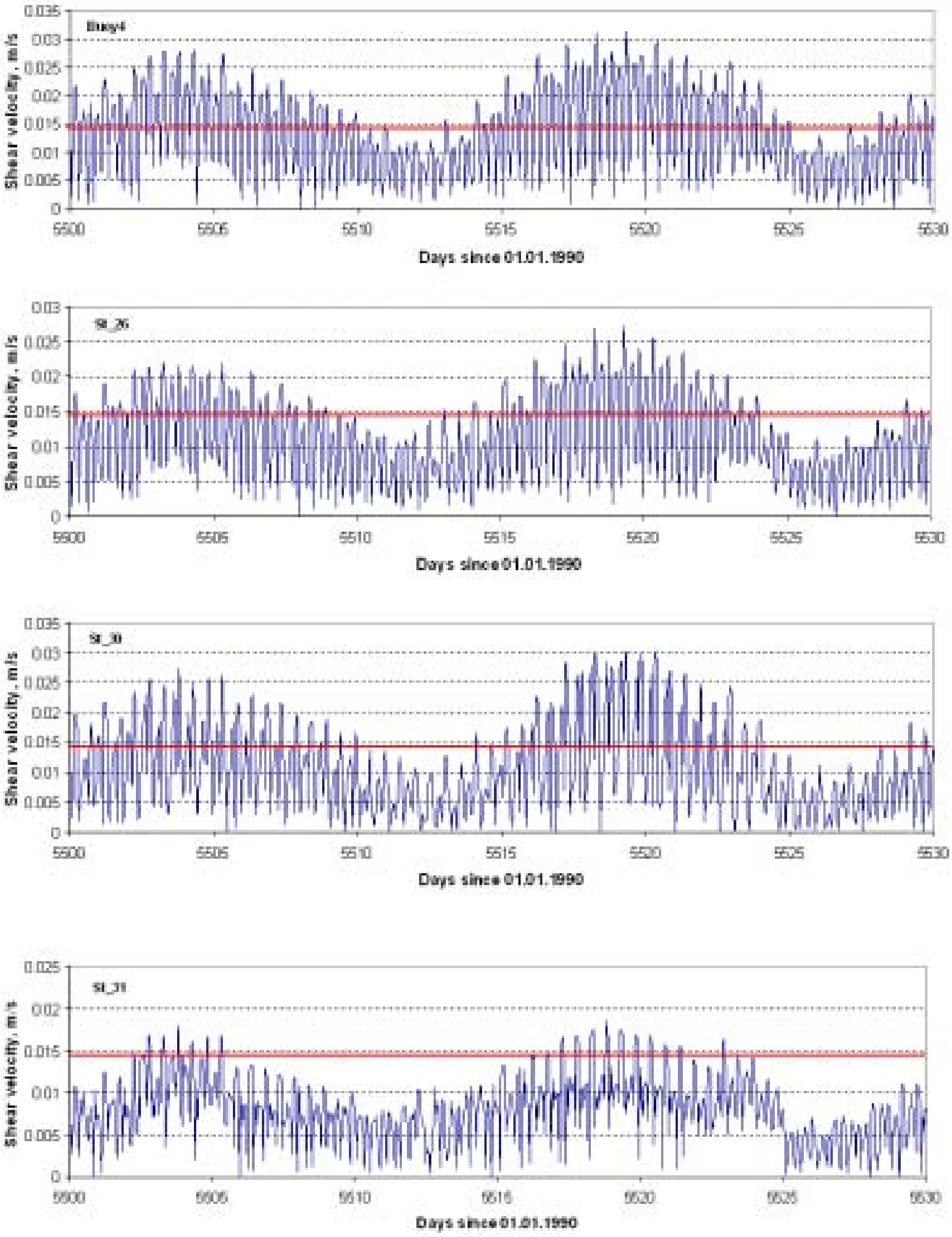


Figure 15b. Time series of shear velocities in the Fitzroy Estuary and Keppel Bay, sites 4, 26, 30 and 31

In Keppel Bay, the critical shear stress is also regularly exceeded during spring tides, while during the neap tide, the bottom friction tends to be lower than the critical value, indicating that sediments may be not resuspended from the seabed for a few days. Within a few days undisturbed cohesive particles are likely to consolidate, increasing their resistance to resuspension. During the next spring tide, the network of consolidated sediments would gradually break, starting from the top layer, and the critical shear stress of sediment resuspension would reduce with time. As mentioned earlier, the model tends to overestimate sediment concentrations at the beginning of the spring tide (Figure 8), which might be attributed to the constant values of the critical shear stresses used in modelling.

Fluxes

This section presents results from scenario runs with varying river flow regimes and land-use practices. Three simulations addressed scenarios with high, moderate and low flow regimes that would correspond to wet, baseline and dry years (Figure 16). A further two scenarios have been simulated with the baseline river flow and altered sediment loads to the estuary that would represent changes in vegetation cover at catchments due to altered land-use practices. One of the latter scenarios included simulations with doubled sediment loads (vegetation cover reduced to 30%), and the second scenario run was executed with the baseline loads reduced by a factor of 3 (i.e. vegetation cover increased to 70%). All runs covered a one-year period. The baseline scenario represented 2004 flow, the wet year – 1998 flow, and the dry year – 1993 flow.

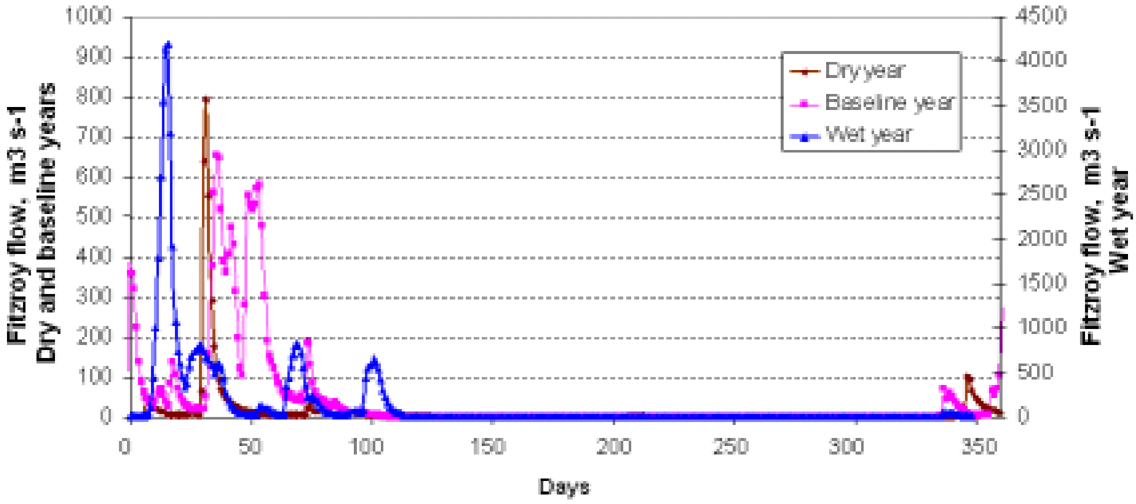


Figure 16. River flows according to scenarios with dry, baseline and wet years

The sediment fluxes and masses are calculated for the main channel of the estuary, Casuarina Creek, Connor Creek, The Narrows and Keppel Bay (Figure 17). During the analysis we discriminate between fine silt and coarse silt, as these two fractions have different transport characteristics.

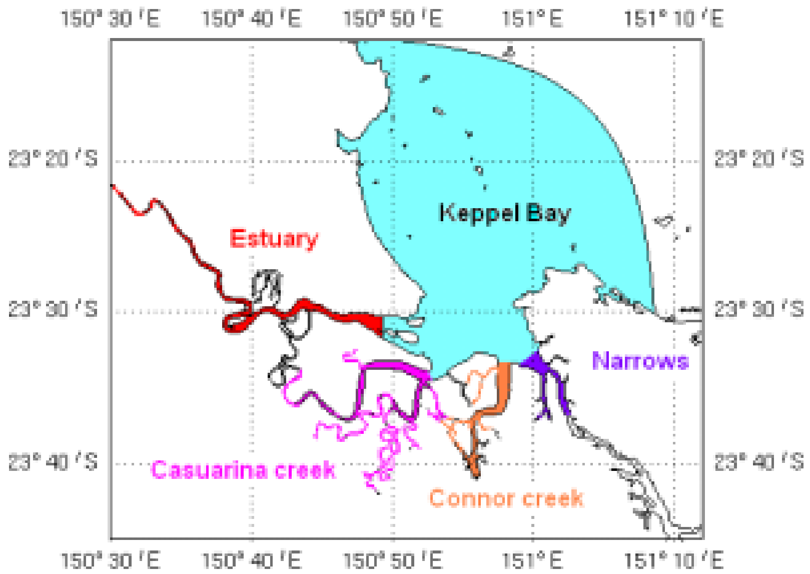


Figure 17. Modelling domain compartments

Fine silt and clay

Figure 18 shows the simulated mass balance of the fine silt after one-year modelling under scenarios with varying flow regimes. The top plot shows the results for the baseline and dry years, while the bottom plot also includes the wet year results. According to the model, during dry and baseline years there are net losses of fine particles from the estuary due to flushing by river flow and tides. These losses are lower during the baseline year as the discharge to Keppel Bay is partly balanced by elevated sediment loads from the barrage. During the wet year, the net balance between sediment loads from catchments and discharge from the estuary to Keppel Bay is an accumulation of particles in the estuary.

According to all scenarios, sediments discharged from the estuary tend to accumulate on the north-west coast of Keppel Bay, in tidal creeks and at The Narrows. The net balance of fine sediments over the whole modelling domain is an accumulation of particles during the wet and baseline flows, with a net loss of fine particles during the dry year.

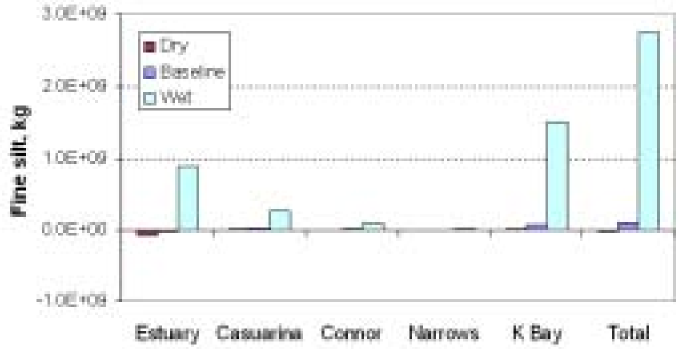


Figure 18. Mass balance of fine silt after one-year modelling (scenarios with different flow regimes)

Simulations with different land-use practices (Figure 19) predict a net accumulation of fine silt in the estuary under a scenario with elevated loads from the catchment, and a net discharge of particles from the estuary to Keppel Bay under scenarios with baseline and reduced sediments loads from the catchment.

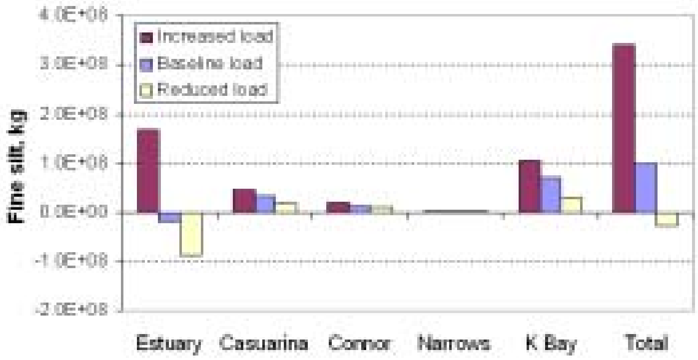


Figure 19. Mass balance of fine silt after one-year modelling (scenarios with different land-use practices)

Table 1 presents simulated annual fluxes of fine silt from the Fitzroy Estuary to Keppel Bay and from the bay to the ocean. According to this data, during the wet year about three-quarters of the river loads to the estuary have been transferred from the estuary to the bay and one-quarter remained trapped in the estuary. In Keppel Bay, about two-thirds of the sediment load from the estuary is trapped within the tidal creeks and at The Narrows and accumulates in shallow coastal areas, and only one-third of sediments delivered from the estuary is discharged to the ocean.

During the baseline and dry years historical deposits of fine particles, resuspended by river flow and tidal currents, are flushed downstream from the estuary to Keppel bay, depleting estuarine content of fine silt deposits. The sediment flux from the Keppel Bay to ocean, during the baseline year, is lower than the loads from catchments that produced a net accumulation of fine silt in the modelling domain. During the dry year the discharge to ocean is about 2 times higher than the river loads. Reducing vegetation cover at the catchment to 30% increases delivery of fine silt to Keppel Bay from 280 kT of the baseline value to 359 kT, while increasing vegetation cover to 70% reduces loads to Keppel Bay from 280 to 176 kT.

Table 1. Simulated fluxes of fine silt (kT/year) under five scenarios

Scenario	River loads	Net balance in the estuary	Discharge to Keppel Bay	Net balance in Keppel Bay and creeks	Discharge to ocean	Net balance in the whole domain
Wet	3890	+887	3003	+1860	1143	+2747
Baseline	263	-17	280	+117	163	+100
Dry	74	-70	144	+41	103	-29
Increased load	526	+167	359	+173	186	+340
Reduced load	90	-86	176	+60	116	-26

The simulated dynamics of fine silt deposits in the Fitzroy Estuary and Keppel Bay (Figures 20 and 21), suggest that after moderate- and high-flood events, it may take a few years until the deposited sediments are washed out to the ocean and the system reaches pre-flood conditions. During the wet year, the model predicts that half of the total annual amount of fine silt delivered to the ocean is associated with the long-term tidal flushing of sediments deposited in the estuary and Keppel Bay during the flood event (Figure 21).

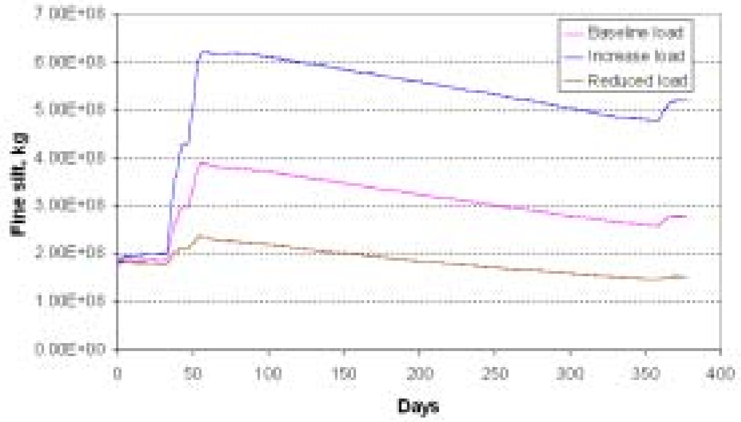


Figure 20. Mass balance of fine silt under scenarios with baseline flow and different land-use practices

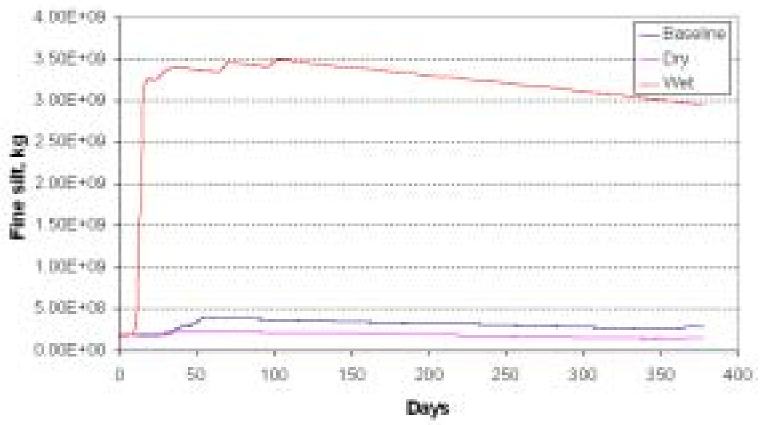


Figure 21. Mass balance of fine silt under scenarios with different flow regimes

Figure 22 illustrates the simulated redistribution of fine sediments after the baseline year, showing that fine particles tend to accumulate in the lower estuary and tidal creeks, at The Narrows and in shallow areas at the west coast of Keppel Bay.

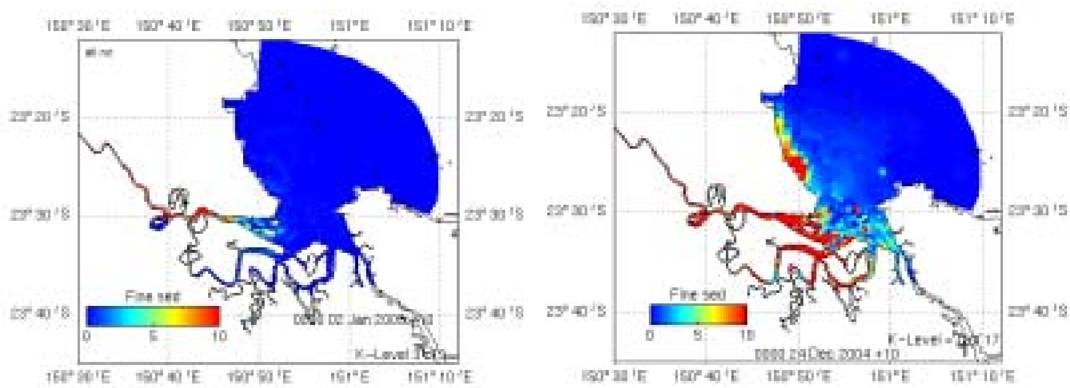


Figure 22. Simulated redistribution of fine sediments after baseline year

Coarse silt

The dynamics of heavier particles—representing moderate to coarse silt—which were initially allocated within the estuary and Keppel Bay, is very different from the dynamics of fine silt and clay particles. Regions with elevated concentrations of coarse silt deposits, allocated in the lower estuary and shallow areas of Keppel Bay (Figure 4), coincide with areas where tidal currents are the dominant feature of the local hydrodynamics. Consequently, transport of those particles is less sensitive to variations in river flow.

The model predicts a net accumulation of moderate to coarse silt in the lower estuary and tidal creeks and a net discharge of these particles from Keppel Bay (Figure 23). The discharge rates for wet, dry and baseline years are similar, indicating little impact of episodic river flows over an annual time scale on the coarse sediment fluxes.

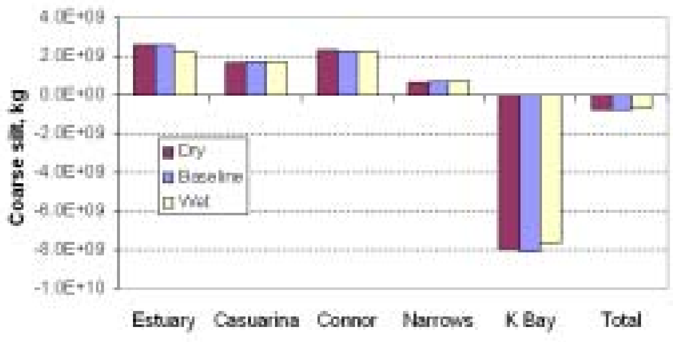


Figure 23. Mass balance of coarse silt after one-year modelling, under scenarios with different flow regimes

The model suggests that during dry and baseline years the estuary loses fine sediment (Table 1) but accumulates coarse fractions (Table 2), and an influx of coarse-grained particles substantially exceeds the discharge of fine-grained fractions, resulting in a net accumulation of sediments into the estuary and tidal creeks.

Table 2. Simulated fluxes of coarse silt (MT/year) under five scenarios

Scenario	River loads	Net balance in the estuary	Discharge to Keppel Bay	Net balance in Keppel Bay and creeks	Discharge to ocean	Net balance in the whole domain
Wet	0	+ 2.3	-2.3	-2.9	0.6	-0.6
Baseline	0	+ 2.6	-2.6	-3.4	0.8	-0.8
Dry	0	+ 2.6	-2.6	-3.4	0.8	-0.8
Increased load	0	+ 2.6	-2.6	-3.4	0.8	-0.8
Reduced load	0	+ 2.6	-2.6	-3.4	0.8	-0.8

Figure 24 illustrates redistribution of sediment thickness after one-year modelling with baseline flow, showing sediment accumulation in the lower estuary, in tidal creeks, and along the west coast of the Keppel Bay. Sediments delivered to the estuary and Keppel Bay during the flood are partly buried into deep sediments and partly washed out into the ocean.

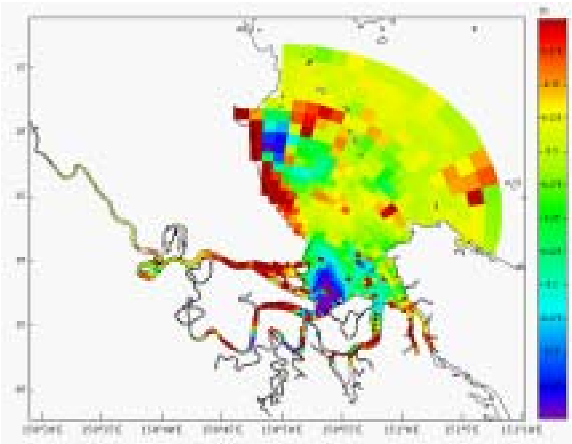


Figure 24. Simulated sediment thickness after one-year modelling (scenario with baseline flow)

Discussion

The calibration study and subsequent validation of the 3-D sediment transport model have revealed large uncertainties in the model predictions. The validation tests against diurnal measurements at various locations in Keppel Bay indicated that an error by a factor of around 3 is likely to be associated with the predicted concentrations. This error is likely to increase during long-term simulations when the modelled system drifts away from the initial quasi-equilibrium state imposed by initial settings. Errors associated with the open boundary conditions and uncertainties in the initial mass of the sedimentary pool, may have little impact on the model predictions over a few tidal cycles, but could accumulate during the long-term simulations. Numerical experiments with a varying initial thickness of sediments showed that doubling the initial mass of sediment deposits scales sediment fluxes to the estuary and Casuarina and Connor creeks by factors of 1.2, 1.6 and 1.2 respectively.

While the model does not reproduce every individual measurement, it is capable of predicting general trends of sediment distribution in the Fitzroy Estuary and Keppel Bay, as well as a typical range of sediment concentrations. Combined with the data analysis, the modelling results enabled plausible hypothesis pertaining to fine sediment dynamics in the study area to be formulated.

The model suggests that during a year with a high-flow event, only half the annual load to ocean is delivered during the flood period. The remaining 50% is associated with a gradual discharge to ocean of the sediment deposits accumulated in the lower estuary and Keppel Bay during the flood. According to simulations it may take a few years until fine sediment delivered to the system during a moderate flood is washed out, and this time could exceed decade for a high-flood event.

To provide a broader context to the one-year simulations and assess the potential role of high-flood events in sediment fluxes, 15-year flow data were converted into sediment loads using the same linear regression between flow and sediment concentrations as used during the modelling. Figure 25 shows sediment loads into estuary integrated with time. According to this data up to 85% of the total sediment loads over the past 15 years may have been delivered to the estuary during the 1991 high-flood event. It is worth mentioning here that the linear relationship between flow and sediment concentration used to build these loads is likely to overestimate sediment concentrations during high flow events; however, even with a conservative estimates, tenths of MT of sediments are still likely to have been delivered to the estuary and Keppel Bay in 1991.

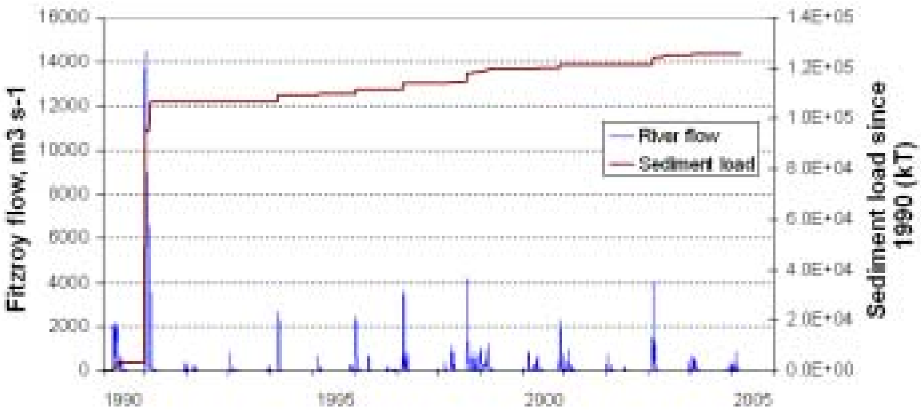


Figure 25. Sediment loads through the Fitzroy barrage, integrated with time

One may speculate about the subsequent fate of these sediments using an analogy with 1998 conditions. Simulations for 1998 (up to 4000 m^3/s flow) have indicated that up to half the sediments delivered to the estuary from catchments during the flood event remained trapped within the modelling domain after one year. If the same ratio between sediment loads to ocean and deposition in the study area applies to the 1991 flood, then this single flood could have delivered enough sediment into the estuary to maintain elevated discharge rates to the ocean over the ensuing decade. However, due to the highly nonlinear nature of sediment transport, the analogy between 1991 and 1998 may not be valid. If during the 1991 flood the net discharge of fine particles to ocean exceeded their delivery from catchments, then most of the sediments were delivered to the ocean during the flood event and there was little or no accumulation of sediments in the study area. In either case, tenths of MT of fine sediments are still likely to have been delivered to the ocean due to the 1991 flood event.

The analysis undertaken in this study has the following implications for catchment management practices. Following a year with an elevated flood event, sediments accumulating in the Fitzroy Estuary and Keppel Bay develop a sedimentary pool that might be sufficient for maintaining elevated discharge rates of fine sediments to the ocean over many years, depending on the intensity of the flood event. If the years following that high flood event have only low and moderate flows, then any alterations in land-use practices will have a minor impact on the sediment delivery to the ocean, as the loads would be maintained by the background fluxes associated with the past deposits, and episodic discharge during the flood event would have little impact on the annual loads. Significant changes in sediment delivery to the ocean are expected to occur during high flood events, when fresh sediments delivered from catchments dominate net annual loads to ocean.

References

Ambrose, R.B., Wool, T.A. & Martin, J.L. (1993) *The water quality analysis simulation program, WASP5. Part A: Model documentation*. Environmental Research Laboratory, Athens, Georgia 30613.

Ariathurai, R. & Krone, R. B. (1976) Finite element model for cohesive sediment transport. *Journal of the Hydraulics Division, ASCE*, 104, HY2, 323–328.

Connell, D.W., Bycroft, B.M., Miller, G.J. & and Lather, P. (1981) Effects of a barrage on flushing and water quality in the Fitzroy River estuary, Queensland. *Australian Journal of Marine and Freshwater Research*, 32, 57–63.

Delo, E.A. (1988) *Estuarine muds manual*. Technical Report SR164, Hydraulic Research Ltd, Wallingford, England.

Dyer, K.R. (1989) Sediment processes in estuaries: future research requirements. *Journal of Geophysical Research,* 94(C10), 14327–14339.

Herzfeld, M, Waring, J., Parslow, J., Margvelashvili, N., Sakov, P. & Andrewartha, J. (2002) *MECO: Model for estuaries and coastal oceans, scientific manual.* CSIRO Marine Research, Hobart.

Herzfeld, M., Webster, I. & Andrewartha J. (2005) *Hydrodynamic modelling of the Fitzroy Estuary and Keppel Bay*. Technical Report 38, Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Brisbane.

Larcombe, P. & Woolfe, K. (1999) Increased sediment supply to the Great Barrier Reef will not increase sediment accumulation at most coral reefs. *Coral Reefs*, 18, 163–169.

Margvelashvili, N., Robson, B., Sakov, P., Webster, I., Parslow, J., Herzfeld, M. & Andrewartha J. (2003) *Numerical modelling of hydrodynamics, sediment transport and biogeochemistry in the Fitzroy Estuary*. Technical Report 9, Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Brisbane.

Neil, D., Orpin, A., Ridd ,P. & Yu, B. (2002) Sediment yield and impacts from river catchments to Great Barrier Reef lagoon. *Marine Freshwater Research*, 53, 733–752.

Onishi, Y., Serne, J., Arnold, E., Cowan, C. & Thompson, F. (1981) *Critical review: Radionuclide transport, sediment transport, water quality, mathematical modelling and radionuclide adsorption/desorption mechanism.* NUREG/CR-1322, Pacific Northwest Laboratory, Richland, 512 pp.

Radke, L., Ford, P, Webster, I., Atkinson, I. & Oubelkheir, K. (2005a) *Keppel Bay: Physical processes and biogeochemical functioning.* Technical Report 34, Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Brisbane.

Radke, L., Ford, P., Webster, I., Douglas, G., Oubelkheir, K., Atkinson, I., Robson, B., Verwey, P., MacKenzie, K. & Klementson, L. (2005b) *Results of two dry-season surveys of Keppel Bay and Casuarina Creek: Biogeochemical properties of the water column and underlying sediments*. Geoscience Australia, Record 2005/18, Canberra.121 pp.

Rochford, D.J. (1951) Studies in Australian estuarine hydrology. I. Introductory and comparative features. *Australian Journal of Marine Freshwater Research*, 2, 1–116.

Smith, J.D. & McLean, S.R. (1977) Spatially averaged flow over a wavy bed. *Journal of Geophysical Research*, 82, 1735–1746.

Taylor, B. & Jones, M. (2000) *National Land and Water Resources Audit: Fitzroy audit summary report 2000,* Department of Natural Resources, Central Queensland University and CSIRO, Brisbane.

Turner, A. & Millward, G. (2002) Suspended particles: Their role in estuarine biogeochemical cycles. *Estuarine, Coastal, and Shelf Science*, 55, 857–853.

Uncles, R.J. & Stephens, J.A. (1989) Distribution of suspended sediment at high water in a macrotidal estuary. *Journal of Geophysical Research*, 94(C10), 14395–14405.

USACE (1999) *Coastal engineering manual, Part III*. U.S. Army Corps of Engineers, Washington, DC 20314-1000.

van Leussen, W. (1999) The variability of settling velocities of suspended fine-grained sediment in Ems Estuary. *Journal of Sea Research*, 41, 109–118.

Walker, S.J. & Sherwood, C.R. (1997) *A transport model of Port Phillip Bay*. Technical Report 39, CSIRO, Division of Oceanography.

Webster, I., Ford, P., Robson, B., Margvelashvili N. & Parslow J. (2003) *Conceptual models of the hydrodynamics, fine sediment dynamics, biogeochemistry and primary production in the Fitzroy estuary*. Technical Report 8, Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Brisbane.

Wolanski, E. & De'ath, G. (2005) Predicting the impact of present and future human land use on the Great Barrier Reef. *Estuarine, Coastal and Shelf Science*, 64, 504–508.

Wolanski, E., Fabricius, K., Spagnol, S. & Brinkman R. (2005) Fine sediment budget on an inner-shelf coral-fringed island, Great Barrier Reef of Australia. *Estuarine, Coastal and Shelf Science*, 65, 153–158.