CHAPTER 26

HYDRODYNAMICS OF DARWIN HARBOUR

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1. INTRODUCTION

Historically, mining, agricultural and urban developments in Australia have proceeded without fully understanding their environmental impact on estuaries and coastal waters. The management focus was on measuring environmental degradation and assessing the need for remedial measures. These remedial measures were often economically and socially expensive, and not the optimum way to achieve sustainable resource development. Science-based solutions need to be developed for assisting resource development and urban expansion without compromising the sustainability of living resources and the quality of urban and traditional life. Northern Australia provides this opportunity because while large-scale developments are planned it currently has a low urban population density, it is resource rich and still has a relatively pristine marine environment.

Darwin (12° 35' South and 131° 31' East; see Figure 1) is the capital of the Northern Territory, Australia, and is located around the eastern shores of Darwin Harbour. Annual average rainfall is 1500 mm and this rain falls mainly between the months of December to April. The remainder of the year is dry. From May to October the dry, south easterly trade winds prevail, and in the wet season the wind blows moisture-laden air from the northwest. The Northern Territory waters may experience several tropical cyclones per year. Occasionally, a cyclone hits Darwin; in 1974 tropical cyclone Tracy caused devastation in Darwin when most of the cities housing and infrastructure was destroyed or badly damaged.

To date little has been done to understand the link between hydrodynamics, sediment and nutrient dynamics of the harbour in order to assist with the management of infrastructure developments. Some modeling of dredge disposal has been done to track the fate of dredge spoil dumping plumes. Salinity may play an important role in resuspending sediment due to dispersion when freshwater runs over the top of salinised muds.

After extensive community consultation the NT Government has declared beneficial uses for Darwin Harbour as a basis for the protection of its aquatic habitat and its cultural, aesthetic and recreational values. The NT Government has also stated that the Harbour will be managed to ensure that the majority of the mangrove

E. Wolanski (ed.), The Environment in Asia Pacific Harbours, 461–476.

communities will be conserved. The aim is therefore to achieve environmental sustainability whilst allowing responsible economic development. However, the scientific data are missing to facilitate the system of review and regulation to maintain beneficial uses and the ecological services provided by the harbour (eg fishing and a healthy estuary). This chapter provides the first peer-reviewed publication on key physical processes controlling the hydrodynamics, the flushing rate, and the sedimentation of Darwin Harbour, and, as demonstrated in the previous chapter by McKinnon et al. in this book, these physical processes play a major role in controlling the health of Darwin Harbour waters.

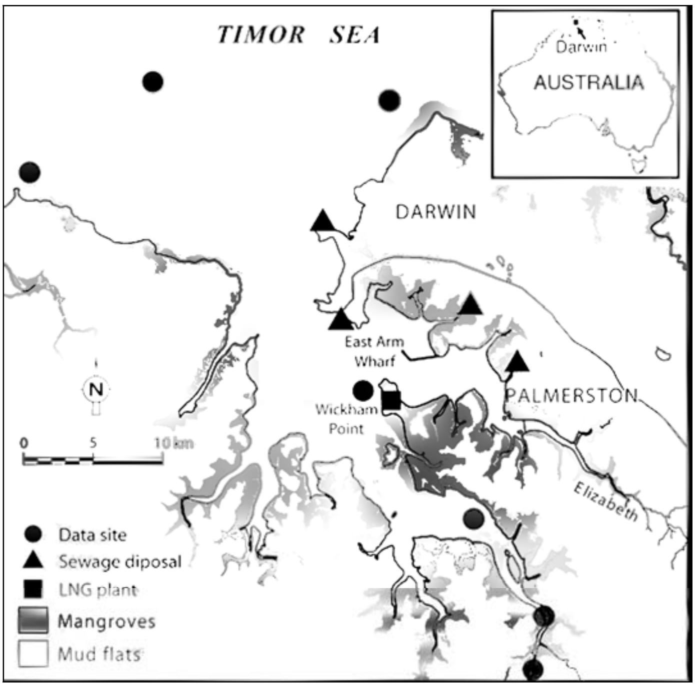


Figure 1. *General location map and a map of Darwin Harbour showing the mangroves, intertidal mud flats, oceanographic data sites, sewage discharge outfalls, and major harbour infrastructures. East Arm is the estuary of the Elizabeth River. Middle Arm is the southernmost estuary (marked by two data sites in this figure) that drains the Blackmore Estuary. West Arm is the estuary to the west.*

2. INFRASTRUCTURE

Darwin Harbour has always been a trading port albeit one of low traffic. The infrastructure has grown steadily especially since the mid 1990's (see Table 1).

In 1942 Darwin Harbour was bombed by the Japanese Imperial Forces and many shipwrecks still lie on the bottom of the harbour. Until the mid 1990's, the main shipping traffic was limited to live cattle exports and the export of manganese and some other minerals. Since then the major wharf facility has been moved to the new East Arm Wharf (construction began in 1994). East Arm Wharf is currently being expanded to provide increased berthing facilities and storage for bulk oil supplies. Previously the harbour had one marina facility. Another commercial marina was constructed in 1985. Four marinas have been constructed in recent years for recreational vessels and a further one is under planning and construction will begin in mid 2005. In 2004 the Darwin to Alice Springs railway was completed and the East Arm Port expanded giving emphasis for Darwin Harbour to continue as a main trading port in the Australasia region. Construction also began on a Liquid Natural Gas processing plant and pipeline for gas delivered from the Timor Sea.

Table 1. *Infrastructure developments.*

Fort Hill – Stokes Hill Wharves	1880
Sadgrove Creek barge facilities	1970
Naval Base Marina	1977
Sadgroves Creek Basin	1985
Cullen Bay Marina	1992
East Arm Wharf	1994
Bayview Marina	1997
Tipperary Waters	1999
Alice Spring – Darwin Railway	2004
Wickham Point LNG Facility	2004
Waterfront development	2005

In addition to the infrastructure developments Darwin Harbour has several sewage treatment plants servicing about 100,000 people and discharging into the main harbour at a number of points shown in Figure 1. Most of the population lives around the coastal zone. Therefore the majority of runoff from the residential and industrial areas will enter the harbour waters. Planned expansion of residential areas is to occur in the upper parts of the harbour.

There have been several aquaculture projects initiated in Darwin Harbour. The first was a pearl oyster farm near Wickham Point (see Figure 1) and since then several prawn farms have been established in the middle arm (i.e. the Blackmore Estuary; for a detailed location map see Figure 1 of the previous chapter by McKinnon et al. in this book). It should be noted that the majority of the recent infrastructure developments, aquaculture and sewage disposal have been sited in the upper arms of the harbour which may the least flushed, hence the most susceptible to environmental degradation from human, land-based activities.

3. HARBOUR OCEANOGRAPHY

The harbour has 3 main zones, namely the outer harbour, the inner harbour and the 3 arms. East Arm has mainly mud beds with a large calcareous sand deposit upstream of the East Arm Wharf. Middle Arm has mainly mud beds but with some significant shoals of siliceous sands that fine seaward indicating a terrestrial origin. West Arm is mainly mud.

The harbour is 50 km in length measured from the outer boundary to the uppermost estuarine limit in Middle Arm. Infrastructure developments are significantly modifying the shape of the harbour domain through construction of wharves, marinas, jetties and the associated dredging. For example the width of the East Arm at high tide prior to the construction of the East Arm Wharf was 3.5 km, it is now 2.2 km.

Darwin Harbour has semidiurnal macro-tides, with a strong diurnal inequality; the highest astronomical tide is 8 m (Table 2). There is a major spring-neap fluctuation, the smallest neap tide is 0.3 m.

The tides propagate into the harbour as a progressive wave, with a 1.5 hr lag between the mouth and the upper reaches (Figure 2). The tides also become asymmetric as they propagate into the upper reaches where the ebb tide lasts about 1 hr longer than the flood tide. This is reflected in peak tidal currents being about 25% larger at flood tide than at ebb tides.

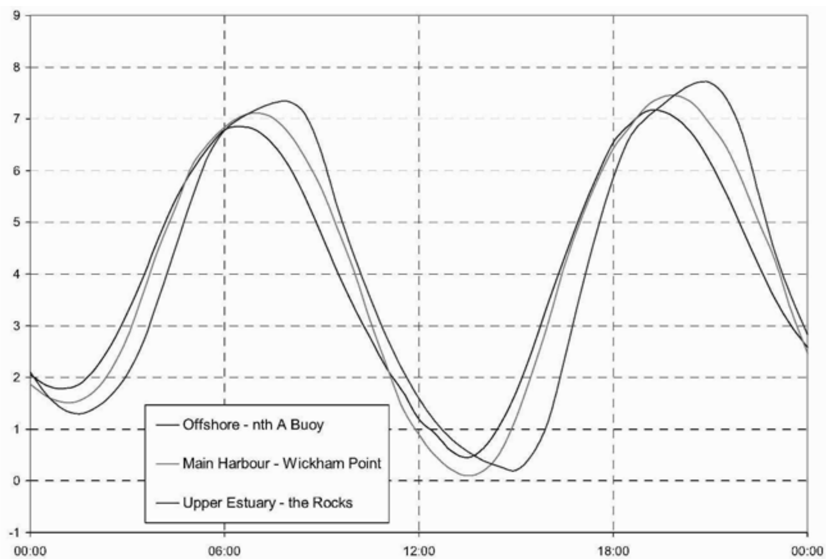


Figure 2. *Time series plot of the tides at three locations in Darwin Harbour during spring tides and in the dry season when runoff is negligible. Nth buoy=offshore, Darwin=Darwin city, Rocks= upper Blackmore Estuary. Note the increasing range and asymmetry of the tide as it propagates up-estuary.*

At spring tides, the peak tidal flux through the heads of the harbour is ~1.2 x 10^5 $m^3\ s^{-1}$. Runoff occurs mainly in the wet season through the three rivers draining into each of the arms (Figure 1). The largest measured cumulative runoff during an exceptional flood, was 10^3 $m^3\ s^{-1}$ or about 1% of the peak tidal discharge at the mouth.

A program of occasional current monitoring has been carried out since 1998, and in 2004 an extensive data set was collected on currents and sediment transport. The

Table 2. *Tidal planes (in metres above local gauge values) for Darwin Harbour.*

Highest Astronomical Tide (HAT)	8.0
Mean High Water Springs	6.9
Mean High Water	5.9
Mean High Water Neaps	4.9
Mean Sea Level (MSL)	4.0
Mean Low Water Neaps	3.1
Mean Low Water	2.2
Mean Low water Springs	1.2
Lowest Astronomical Tide (LAT)	0.0

location of the oceanographic mooring sites is shown in Figure 1. These data are used to calibrate a numerical model of the water circulation. The present numerical hydrodynamic model covers a 620 km^2 domain ending at the shoals offshore from the heads of Darwin Harbour. The models used are RMA2, a finite element depth averaged model, and RMA11, a cohesive sediment transport model (King, 2004). The models use tidal elevations at the sea as a boundary condition. In the upper arms, the models assume no freshwater inflow during the dry season and they use the flows recorded at gauging stations in the rivers draining into the arms during the wet season.

The model output, verified against field data (Figure 3), shows a complex circulation near headlands and embayments, which includes jets, eddies, separation points, and stagnation zones (Figure 4). These currents are different at flood and ebb tides. It results that dispersion of water-born particles is asymmetric and that trapping occurs near headlands and in embayments (Signell and Geyer, 1990; Wolanski, 1994). The importance of the tidal asymmetry on the fate of fine sediment is described later.

4. SALINITY

The salinity varies both spatially (horizontally and vertically) and temporally (both at tidal frequency and at seasonal frequencies). Oceanic salinity at the mouth of the harbour remains almost constant (variation less than 1) throughout the year.This implies that the freshwater runoff is strongly diluted by the time it reaches the mouth of the harbour. There is no marked river plume exiting Darwin Harbour so most of the mixing between freshwater runoff and the ocean occurs within the harbour and this is attributed to the large tides (eg Wolanski and Spagnol, 2003).

Most of the freshwater runoff occurs in the period January to March in the form of a few discrete flood events. Each event lasts from a few days to a few weeks, reflecting the small watershed and the patchy rainfall. During these events the horizontal salinity gradient is at a maximum (Figure 5) and a sharp front visibly separates water in each arm from that in the main body of the harbour and the water is stratified on both sides of the front (Figure 6). Mixing is inhibited between the arms and the harbour. As a result of the strong tidal currents, the vertical stratification persists for up to two weeks in the arms, and for less than one week in the main body of the harbour. In the wet season the harbour is a stratified estuary.

In the dry season the system is vertically well-mixed in salinity. Due to evapotranspiration an along-channel salinity gradient is created. This salinity gradient reaches a maximum value late in the dry season. For instance, on October 10, 2004, the salinity was 35.9 at the mouth of the West Arm and 38.9 in the upper

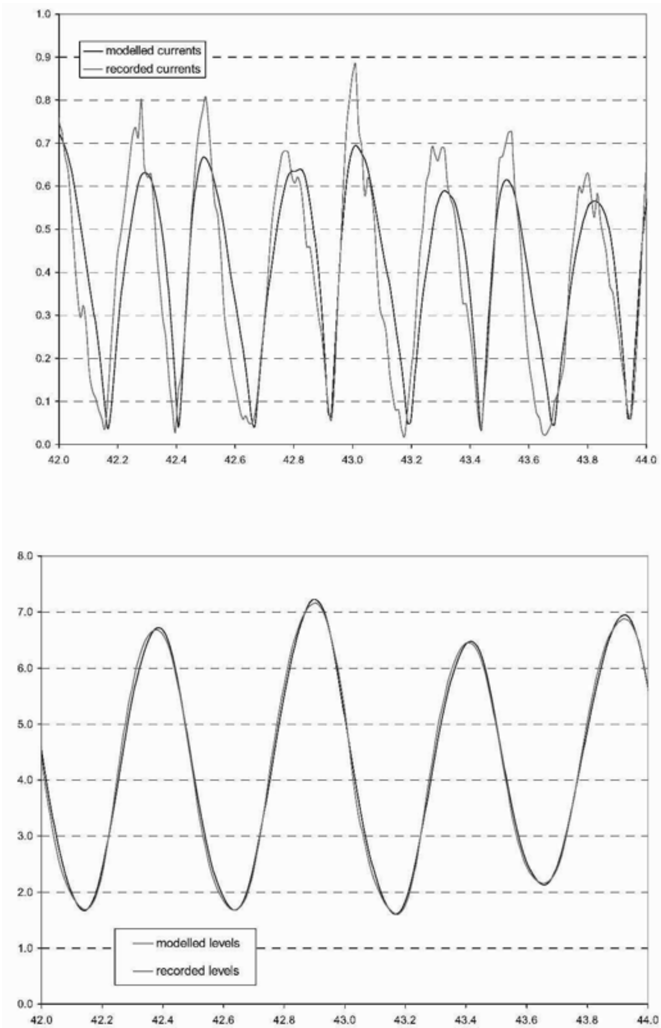


Figure 3. *Comparison of depth-averaged, predicted versus recorded tidal currents (m s^{-1}) and water levels (m) near Wickham Point.*

reaches (not shown). The vertical stratification was less than 0.1 across the depth. In the dry Season the West Arm is an inverse estuary. The loss of water by evaporation is compensated by an inflow of oceanic water. The water is then trapped in the upper reaches of the arm. A similar process was found in the East Arm. In the Middle Arm, a small freshwater spring inflow persists in the upper reaches. This results in the formation of a salinity maximum zone located in the mid-region of the arm (Wolanski, 1986), and the water is still trapped upstream of the salinity maximum zone.

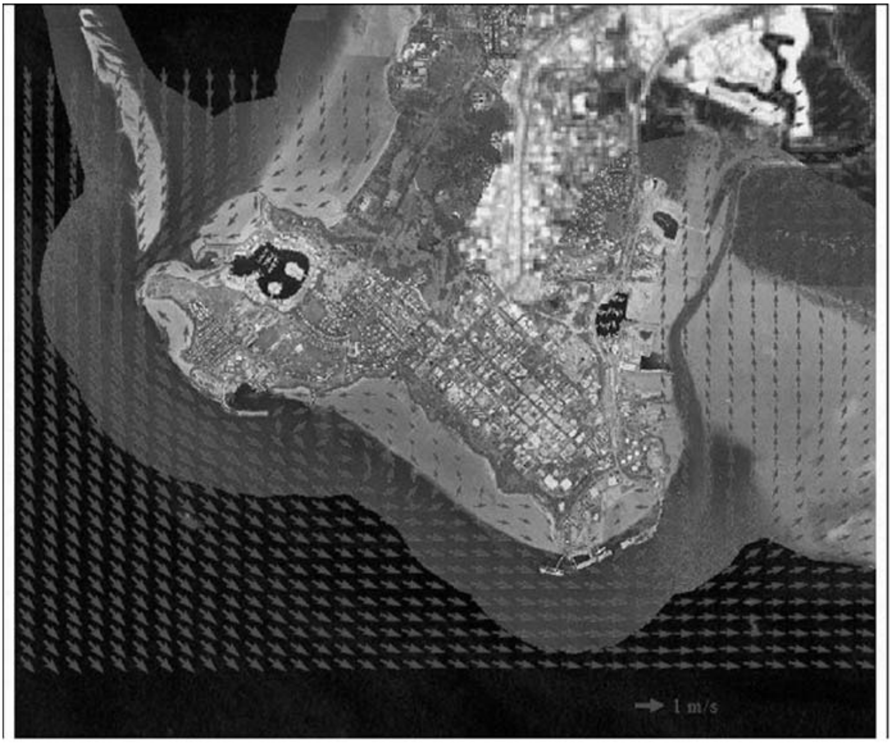


Figure 4. *A snapshot of the predicted distribution of the horizontal currents at flood tide near Darwin City during a spring tide. The blue shading indicates the intertidal area.*

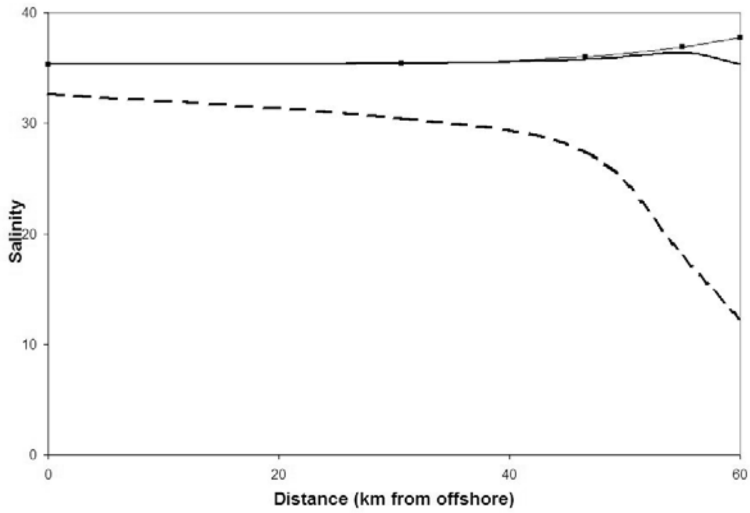


Figure 5. *Horizontal profiles of salinity to the tidal limit of Darwin Harbour in the wet (---) and dry (line) seasons of Darwin Harbour for the Middle Arm (circles) and the West Arm (squares).*

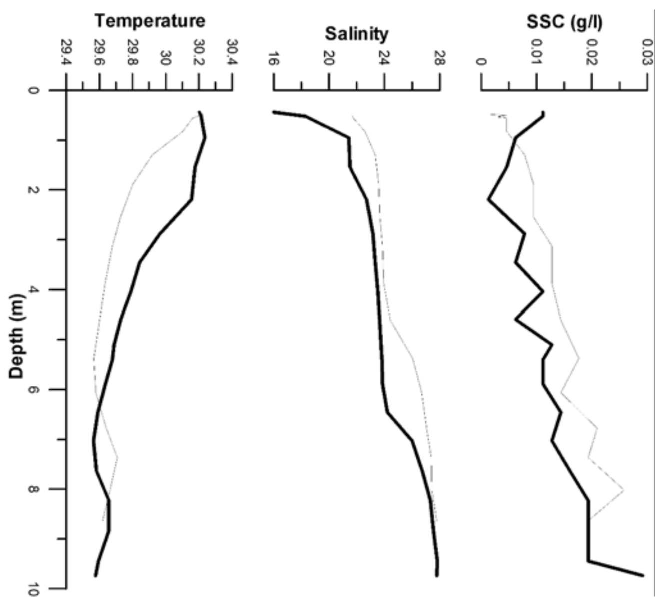


Figure 6. *Vertical profiles of salinity, temperature, and suspended sediment concentration (SSC) in the harbor (thin line) and in the West Arm (thick line) on either side of a front spanning the width of the arm near high tide at 1310 h on March 22, 2004.*

5. RESIDENCE TIME

In the dry season Darwin Harbour is an inverse estuary, similar to many other Australian tropical estuaries (Wolanski, 1986). A salinity maximum zone is observed in the upper reaches. The loss of water from evaporation and evapotranspiration is compensated by an inflow of oceanic water. Excess salt is exported by tidal dispersion. A steady state a salt balance is established, so that the tidally-averaged outflow of salt is equal to the inflow of seawater. This balance implies that (Wolanski, 1986):

$$E_t\, S\, A_h \sim E\, A\, dS/dx \qquad (1)$$

where S is the salinity, E_t is the evaporation/evapotranspiration rate, x is the distance along channel, E is the along-channel eddy diffusion coefficient, A is the cross-sectional area, and A_h is the surface area of the harbour including the intertidal (both vegetated and unvegetated) area. In each arm, $E \sim 0.007$ m d^{-1}, $A_h \sim 10$ km^2, $A \sim 400$ m^2, thus $E \sim 100$ m^2 s^{-1}.

Therefore in the dry season the flushing time T_f of water from the arms of Darwin Harbour is

$$T_f \sim L^2/E \sim 20 \text{ days} \qquad (2)$$

where L is the length of the estuary.

This long residence time is also supported by the output from the numerical model (see Animation 1 discussed later).

6. COARSE SEDIMENT

The predicted, tidally-averaged, residual circulation (Figure 7) shows a number of eddies centered near sand shoals, suggesting that the location of these shoals is determined by the tidal circulation (Bastos et al., 2004).

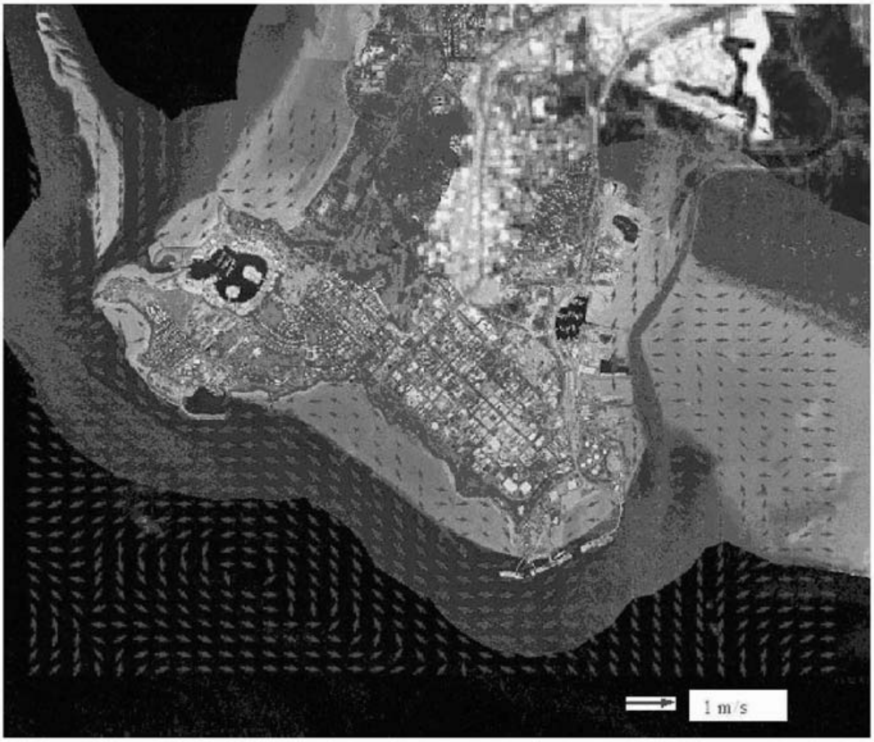


Figure 7. *Synoptic distribution of the predicted, residual, tidally-averaged circulation near Darwin City, superimposed on an aerial photo taken at low tide.*

7. SUSPENDED SEDIMENT

The waters are moderately turbid; with a small vertical stratification is suspended sediment concentration (SSC; see Figure 6). SSC values are usually less than 50 mg l^{-1}. A turbidity maximum zone exists inside the mouth of each arm in both the dry and wet seasons. In that turbidity maximum SSC values can reach 250 mg l^{-1} (see Figure 8). This figure also demonstrates that the SSC values fluctuate markedly at tidal frequency and also with the spring-neap tide cycle. This behaviour is similar to other tropical, shallow, macro-tidal estuaries such as the Fly Estuary, the Ord Estuary and King Sound where, like in Darwin Harbour, these processes lead to the formation of turbidity maximum zone and trapping of fine sediment (Wolanski and Spagnol, 2003; Wolanski et al., 1995 and 2004).

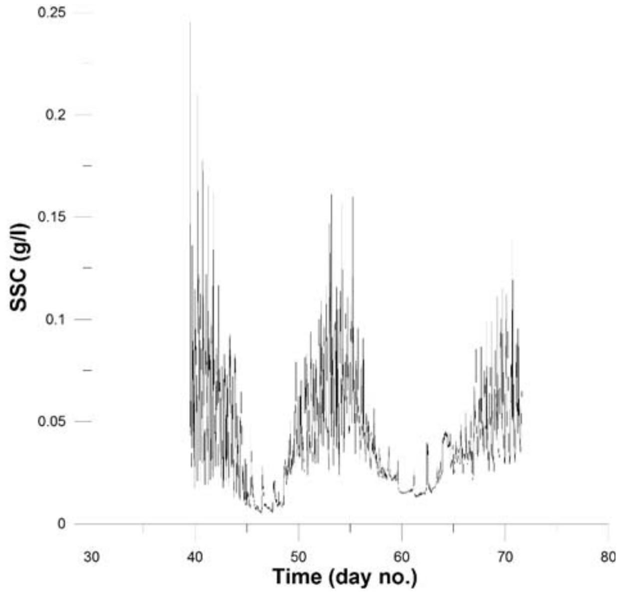
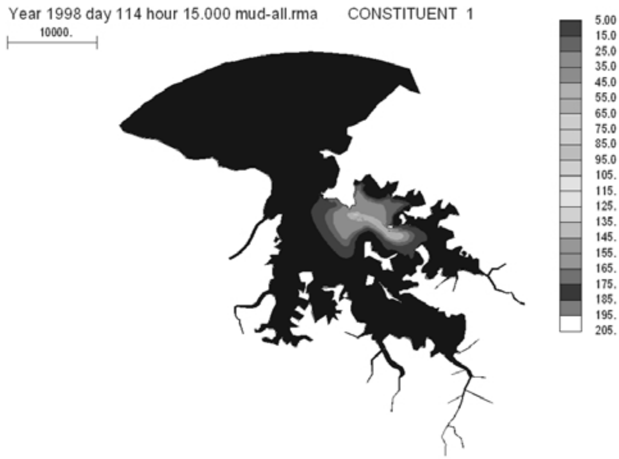


Figure 8. *Time series plot of the suspended sediment concentration (SSC) in the main body of the harbor near Wickham Point. Time starts on January 1, 2004.*

A small amount of fine sediment is delivered to the upper arms by runoff; the majority of the fine sediment in the upper arms is dispersed from the channel banks and mangrove zones by the freshwater runoff. Most of this sediment then drops out of suspension from the surface plumes because the SSC is smaller in the plume than near the bottom (Figure 6). This fine sediment is then eroded and deposited at tidal frequencies, especially at spring tides. The combination of the complex circulation near headlands and embayments, and of the asymmetry of the tidal currents controls the fate of fine sediment (Animation 1). This animation shows the predicted spread of mud discharged continuously near Darwin City within the harbour. The mud is rapidly dispersed and preferentially transported up-estuary towards mud banks and mangroves where it settles. The remaining small fraction is exported to the ocean.

The net fluxes of sediment over one month were also calculated from the field data on currents and suspended sediment concentration collected at 15 min intervals, over one month, in both the dry and wet seasons of 2004, at four sites in the inner harbour, using the method of Wolanski et al. (2004). These net fluxes, shown in Figure 9, are directed up-estuary, also indicating trapping of fine sediment.



Animation 1. *The predicted movement of a muddy plume arising from a continuous mud discharge from a dredging operation.*

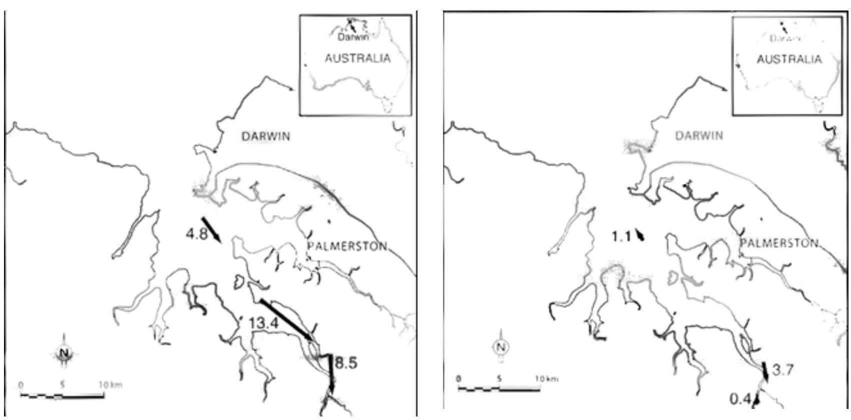


Figure 9. *Net suspended sediment fluxes (tons $m^{-1}d^{-1}$) at the oceanographic mooring sites in (left) February-March 2004 (wet season) and (right) October-November 2004 (dry season).*

Futher evidence of tidal trapping in the upper arms of the harbour was collected during the 2004 – 2005 wet season when an outbreak of a noxious aquatic weed was discovered in Darwin River which then flows into Berry Creek (see a location map in Figure 10), a small tributary of the Blackmore Estuary. The river was blocked and the weed was treated with the herbicide 2,4D (Padovan, unpublished data). 2,4D can be used as a conservative tracer as it has a half life of ~ 30 days and in acidic form does not adsorb to sediments. Monitoring of 2,4D concentrations in the Blackmore Estuary showed that the concentrations increased in an upstream direction showing that the chemicals were trapped and not able to advect or diffuse downstream (Figure 10).

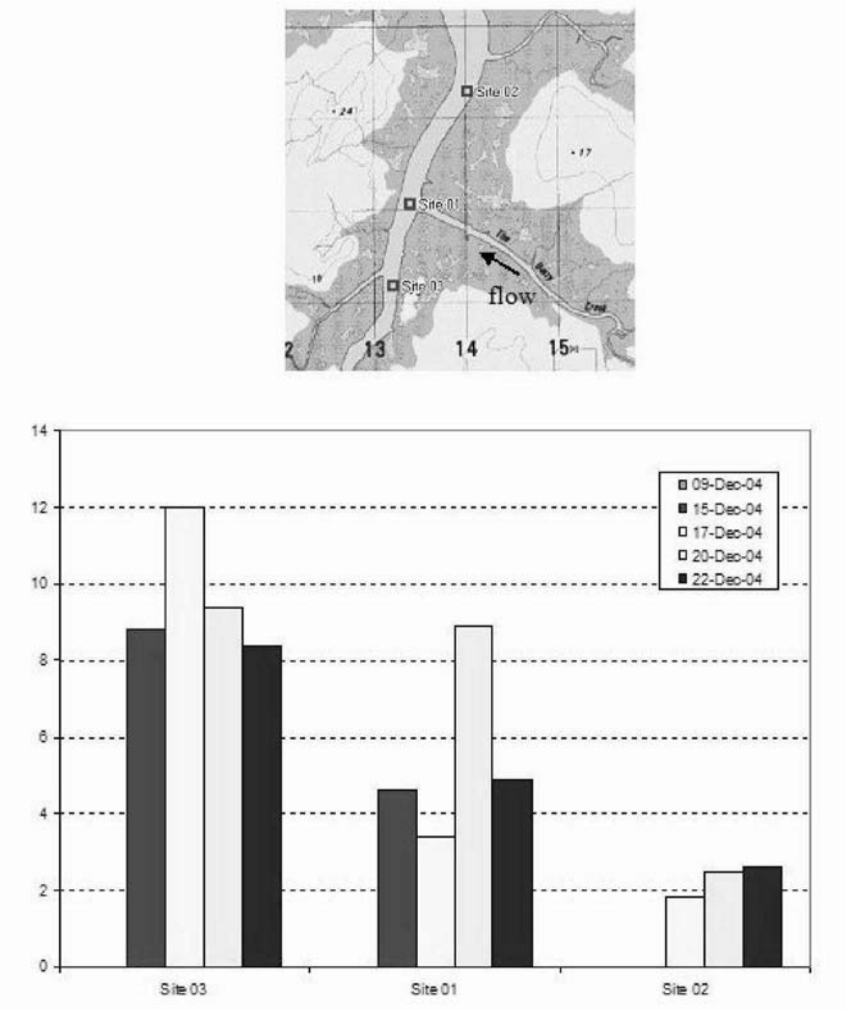


Figure 10. *2,4D monitoring sites on the Blackmore Estuary showing how the 2,4D concentrations increased upstream of the river confluence, indicating that particles are trapped and their advection and diffusion downstream is limited.*

Microscope pictures of the suspended sediment in suspension show the fine sediment is flocculated, with floc size typically 50-200 μm. Near the mouth of each arm, in waters with SSC values less than 40 mg l^{-1}, there exists a marine snow zone where the floc size is in the range 200-1000 μm (Figure 11). In that zone, the influence of plankton and bacteria on the flocculation of suspended mud is dominant, similarly to that experienced in other macro-tidal tropical estuaries (Wolanski and Gibbs, 1995; Ayukai and Wolanski, 1997; Wolanski and Spagnol, 2003). This occurs because muddy marine snow offshore is formed as a result of the small mud flocs adhering to sticky transparent exopolymeric particles (TEP; see Passow and Alldredge, 1994; Alldredge and Gotschalk, 1988). The flocs are teeming with very small plankton that we could just detect with our microscope (<5 μm) and these attracted plankton, presumably to feed on, while other plankton seem to be smeared and stressed by the sticky flocs (see animations 2 and 3), appearing to try to remove the coating of mud, behaving in a similar way that benthic coral organisms behave at the bottom (Fabricius and Wolanski, 2000).

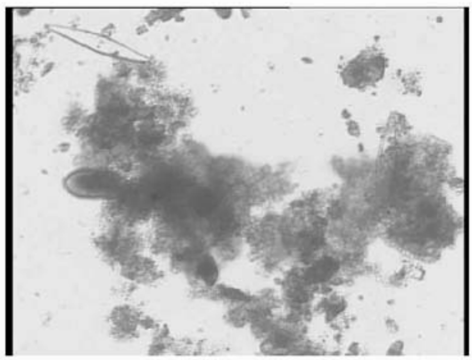
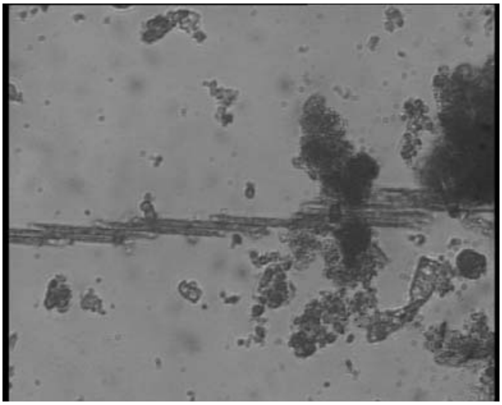
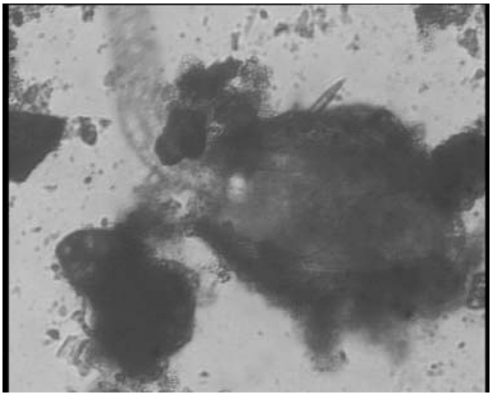


Figure 11. *Microphotograph spanning 500 μm of a marine snow floc at the mouth of the Middle Arm.*



Animation 2. *Micro-movie spanning 500 μm of a muddy marine snow floc in Darwin in Darwin Harbour, showing Asteronella diatoms moving and feeding on the mud.*



Animation 3. *Micro-movie spanning 500 μm of an animal caught in sticky, muddy marine snow and apparently trying to shed the muddy coating.*

The muddy marine snow layer in each arm of Darwin Harbour is important to the fate of fine sediment because it enhances the trapping of fine sediment (Ayukai and Wolanski, 1994).

8. CONCLUSION

Although macrotidal, Darwin Harbour is poorly flushed, especially in the dry season when the residence time in the upper reaches is of the order of 20 days. Much of the riverine fine sediment remains trapped in mud flats and mangroves with little escaping to the sea. The complex bathymetry of headlands and embayments generate complex currents comprising jets, eddies, and stagnation zones that can trap pollutants inshore. The tidally averaged circulation may control the location of the sand banks, indicating a feedback between the bathymetry and the water circulation. The environment in Darwin Harbour has the potential to degrade and the water circulation in the harbour must be considered when planning developments.

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