Water quality, plume modelling and tracking before and during dredging in Mermaid Sound, Dampier, Western Australia.

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Abstract

In areas with relatively unpolluted bottom sediments, such as at Dampier Harbour, the primary impacts of dredging on water quality will be the elevation of turbidity levels in the water column and the associated transport of sediments onto benthic communities. During the environmental impact assessment process for two recent Dampier dredging projects, considerable emphasis was placed on the likely extent to which turbidity and sedimentation would be elevated at various spatial scales.

A water quality monitoring program established to coincide with the dredging program assessed turbidity, suspended sediments and other parameters every three days. The monitoring program was designed to assess the degree to which water quality at sites over sensitive coral communities was impacted by dredging and to test the predictions of a numerical model of the effects of dredging on sediment suspension and transport.

Monitoring results showed that despite having a significant overall relationship, turbidity and total suspended solids (TSS) measures often showed dissimilar patterns of variation over time at the same site and TSS explained only a small portion of variation in turbidity levels. This was assumed to result from different spectral qualities of sediments in suspension at differing times and at various locations.

Average turbidity levels were clearly elevated at monitoring sites within 1-2km distance of dredging or spoil disposal sites ($\bar{x}$ ~ 4 NTU) when compared to Reference sites outside this radius ($\bar{x}$ ~1 NTU). Although some Reference sites did show occasional episodes of elevated turbidity unrelated to dredging or disposal impacts, these were rarely greater than 50% of the peak episodes of turbidity at impact sites.

Significant elevation of TSS levels was restricted to sites within 1km of dredging locations ($\bar{x}$ ~ 10 mg/L vs $\bar{x}$ ~ 4 mg/L at Reference sites). Consistent with a priori model assumptions, elevated TSS levels seem due primarily to the propeller wash generated from the trailer hopper suction dredge while manoeuvring during uplift of dredge material.

While turbidity was high at many sites, the one site where coral mortality occurred was characterised by high TSS, suggesting that the cause of coral mortality during these two dredging programs was one or more acute episodes of sedimentation. In this case, suspended sediment concentrations from bottom samples which exceeded 60 mg/L in waters within a few hundred metres of coral appeared to be the sole cause of mortality.

Dissolved oxygen and pH varied little between sites and times and there was no evidence that these parameters were influenced by dredging effects.

The sediment suspension and transport model was highly conservative and actual effects were more localised and ephemeral than predicted. The principal cause of this difference appears to be that sediments settle out of the water column much faster than the model had predicted.

Keywords: sediment, turbidity, modelling, dredging

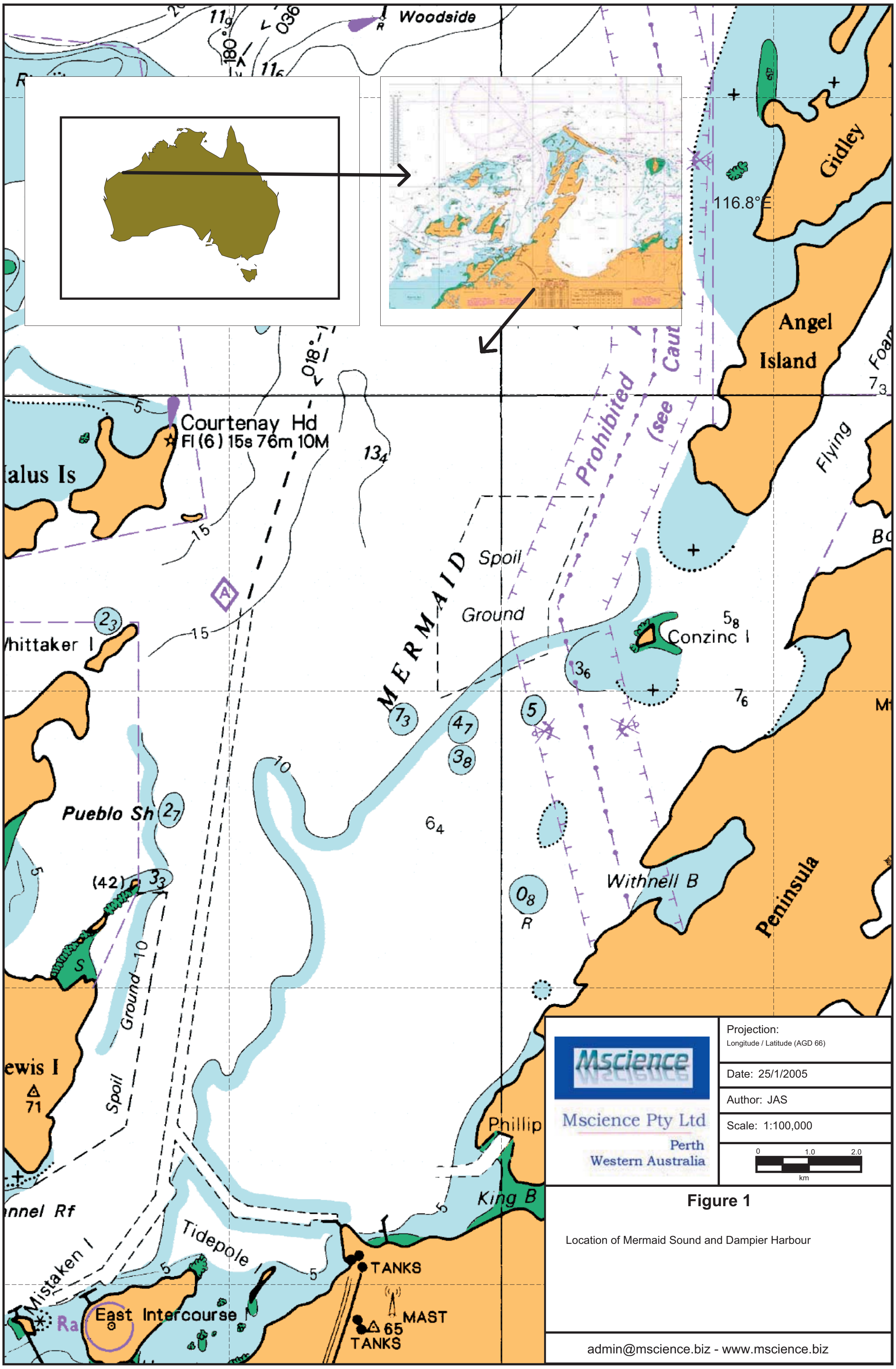
Introduction

Environmental effects during dredging stem from both the removal of habitat in the area being dredged and the effects of suspension of sediments during the uplift and deposition of the dredged material. While the former may be profound and permanent, the latter effect is always spread over a much greater area. An understanding of the distribution and intensity of mobilised sediments is essential to adequately manage the likely extent of impacts of dredging, whether as an input to environmental impact assessment (EIA) or in the design of monitoring programs to measure actual impacts.

Mobilisation of sediments into the water column during dredging will occur from the excavation of sediments at the bed, the loading process, transport and dumping of sediments at spoil grounds, or return water from land disposal, and by disturbance of the bottom by the dredge hull and propellers. The relative importance of each of these sources depends critically on the methods and machinery used for dredging (IADC/CEDA 1998).

Other important considerations in predicting the behaviour of suspended sediments will include the physical composition of sediments in and around the area targeted for dredging, tides, current movements and weather patterns during operations and the bathymetry around uplift and deposition areas. In addition to controlling the fate of sediments mobilised during dredging and deposition, these factors will also control the re-mobilisation of sediments from spoil grounds post dumping and prior to eventual consolidation.

Figure 1. Location of Mermaid Sound in the Pilbara Region of Western Australia.



Environmental impacts of sediments will be derived from physical smothering or abrasion of benthos, or changes to water chemistry such as the addition of nutrients or toxicants, the depletion of oxygen, or the alteration of pH.

This paper describes a study of water quality undertaken in conjunction with two large dredging and disposal programs in the Port of Dampier, Western Australia.

Mermaid Sound

Mermaid Sound is a large northern-facing embayment situated on the coastline of Western Australia's Pilbara Region (Fig. 1). The majority of the Sound represents a drowned coastal environment of plains surrounded by higher ridges which have now become islands or the Burrup Peninsula (Semeniuk et al. 1982). Depths range from 5-20 m with some shallower shoals. Much of the bottom consists of soft sediments (silts and clays), the bulk of which have terrestrial origins, either from before the rise in sea level or from subsequent riverine and surface flows entering the embayment.

Mermaid Sound sits almost entirely within the limits of the Port of Dampier. The Port services export facilities at a number of wharves for iron ore, liquid natural gas, salt and general cargo. It is amongst the largest tonnage ports in Australia with annual movements of cargo well over 80Mt and has a strong and growing industrial usage around much of the southern and south-eastern shoreline. Originally created in the 1960s to support the export of iron ore, the port environment has been subject to a long history of dredging operations and contains a number of active and historic spoil disposal grounds. Most dredging has been of a capital nature and true maintenance dredging to clear sediment influx has been rare.

Within the relatively shallow embayment, significant wave and current action can occur and cause substantial re-suspension of sediments leading to elevated turbidity throughout the water column (Forde 1985). Waves and currents in this area are generated primarily by strong winds (Pearce et al. 2003), the most extreme of which occur during tropical cyclones. Throughout the summer periods, tropical cyclone effects and strong westerly winds frequently cause re-suspension of sediments, as do easterly winds in winter. As weather intensity increases, sediment re-suspension extends to deeper parts of the Sound (Forde 1985) and the direction of winds affects the amount of fetch over various bottom types. The large bulk container and gas transport vessels transiting the port daily also create bottom eddies that lift sediments into the water column. Thus while Mermaid Sound is frequently subject to high turbidity, the location of turbid plumes is complex and varies widely and on short time scales.

Within Mermaid Sound, there exist a number of areas with well developed coral communities (Blakeway & Radford this volume). While previous descriptions of corals in the Dampier area have been focussed on offshore areas of the Dampier Archipelago (Marsh 1978, Simpson 1988, Griffith 2004), it is clear that there are also populations of significance in the nearshore. Susceptibility of corals to adverse impacts of sedimentation has been widely documented (eg Rogers 1990) and environmental assessments of previous dredging programs in the Harbour have nominated coral communities as the local biota most likely to be at risk from dredging impacts on water quality.

The Dredging Program

Dredging undertaken in 2004 in Mermaid Sound included two distinct operations (Fig. 2). The first component comprised dredging to create a new berth pocket and channel for the Dampier Port Authority's Bulk Liquids Berth Project, while the second formed part of Hamersley Iron Pty Limited's Dampier Port Upgrade to extend berth pockets and approaches to their Parker Point facility. These projects are hereafter referred to respectively as the DPA and HI components.

The DPA component:

Technical details of the DPA dredging component can be found in DPA (2004). In summary, the project removed 4.1Mm3 of spoil comprised of 3.8Mm3 of soft marine sediments – mostly silt and clays with some fine sand and over 0.2Mm3 of coarser materials such as gravel and cobble.

Dredges: DPA used two dredges to complete this component.: The *Cornelius Zanen*, a trailer suction hopper dredge, 132m in length with a laden draft of 8.8m for a hopper of 8,000m3 capacity, and the *Storken*, a 37 m long backhoe dredge with a bucket capacity of 3.5-5m3.

Dredging commenced on 8 January 2004 and was completed by 20 May 2004 with all spoil disposed at the Northern Grounds.

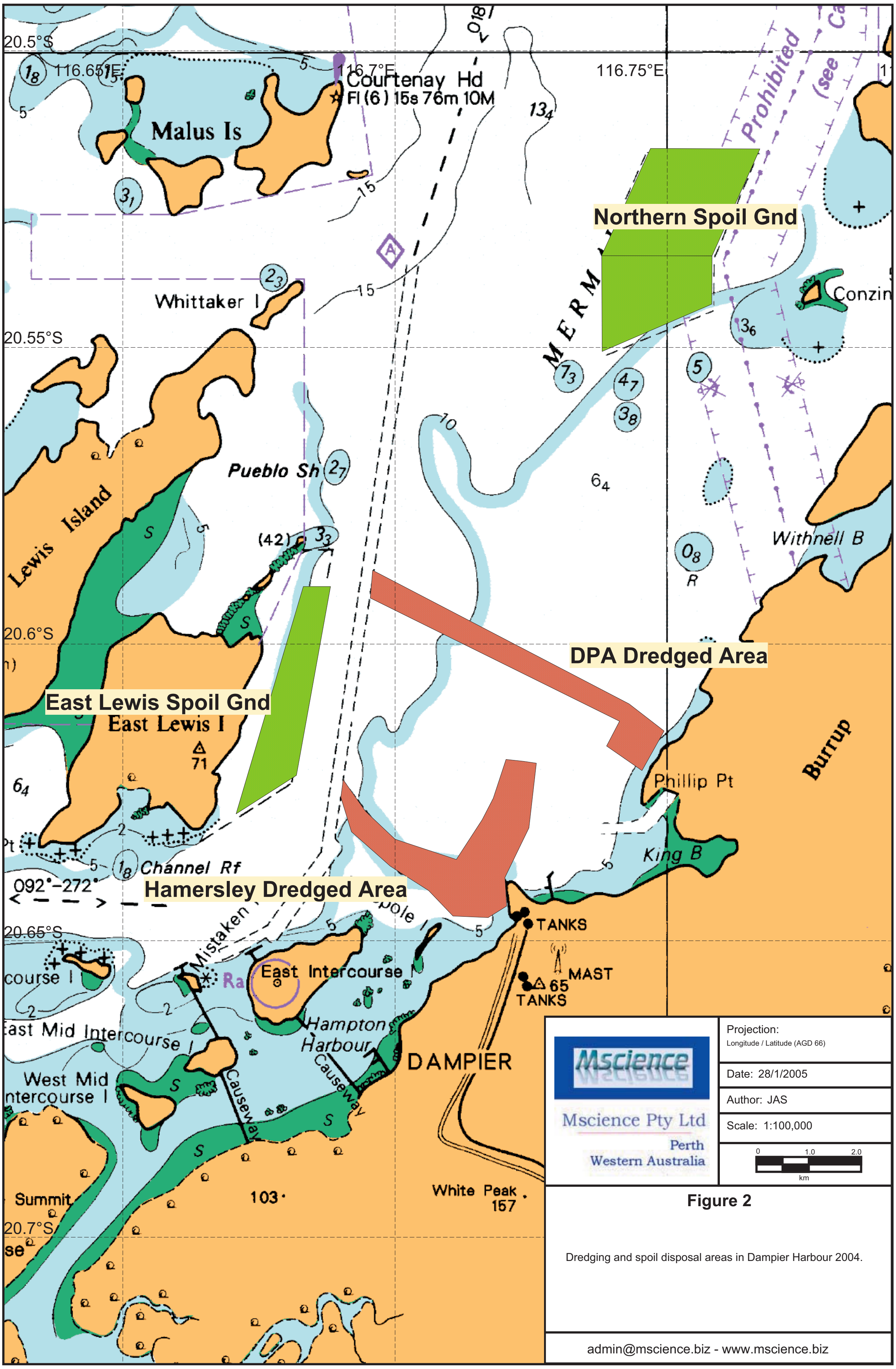
The Hamersley (HI) component

Hamersley dredging operations involved the construction of extended channels, approaches and berth pockets around the Parker Point wharf facility (Fig. 2). Technical details of the program can be found in SKM (2004).

Dredges: Hamersley used 3 dredge types:

- The *Cornelius Zanen*: a trailer suction hopper dredge which operated between the 8th of May and 25th of June 2004. In total the Cornelius Zanen removed approximately 2.1 Mm3 of material. 1.8 Mm3 was disposed of at the East Lewis Island Spoil ground and 0.3Mm3 to the Northern Spoil ground.
- The *HAM218*: a cutter suction dredge, operated from the 2nd of June to the 31st of August and from the 27th of September to the 23rd of October 2004. A total of 1Mm3 was dredged and disposed to landfill in an enclosed area directly east of Parker Point.
- The *Obscured By Clouds*. An excavator dredge, operated prior to the commencement of the main dredging contract and removed chain, buoys and other shipping material from the dredging zone.

Figure 2. Dredging and disposal sites in Dampier Harbour in 2004.



Sediment levels in waters adjacent to the landfill area were elevated from sediment loads in return water and seawall construction activities also occurring at that time. Due to perceived impacts on water quality at the adjacent King Bay monitoring site a management program was commenced in October which deployed sediment curtains around the outflows. Observer records (surface and diver) suggested that these controls were effective and that the major effects on water quality from these operations were confined to 27 Sept – 5 Oct and 18-23 October.

Description of sediments dredged.

Sediment sampling and analysis programs have been undertaken at several locations and on several occasions from the early 1990s to the present. Due to a lack of riverine input and a low level of industrial activity dealing with toxicants around the Harbour shoreline , Dampier sediments are rarely found to be contaminated (MScience 2004). The most commonly occurring contaminant is the antifoulant tributyltin (TBT), which is usually found in berth pockets at concentrations above the National Ocean Disposal Guidelines for Dredged Material (EA 2002). Around the Hamersley wharves and drainage points for surface runoff, Fe levels and some trace metals associated with iron ore are elevated. Previous testing of these sediments (controlling for Fe levels) has shown that toxicity is extremely low at even the highest levels found around these sites (Tsvetnenko & Black 2001). Elsewhere throughout the inner harbour a metals fraction associated with fine clays (as indicated by Al levels) controls abundance of a suite of metals (MScience 2004).

The Models

During the assessment of these dredging projects by the Western Australian Environmental Protection Authority in 2003, there was no clear agreement on the likely spatial extent of sedimentation anticipated on corals (EPA 2003 a&b). To assist in predicting where impacts might occur and monitoring be required, both dredging proponents commissioned modelling exercises to predict the levels and extent of suspended sediments in the water column likely to eventuate from dredging, disposal and subsequent re-suspension from spoil grounds.

The model of sediment transport developed for the DPA program considered that the major sources of sedimentation would be propeller wash at the dredging site and dumping at the disposal site (GEMS 2003). In line with the precautionary principle, where there was uncertainty in model parameters, conservative values were chosen such that the model would tend to overestimate the extent and magnitude of impact. The model predictions were aligned to the dredging schedule current at the time, which was December to March.

Model predictions included the evolution of bottom sediment load through the period and monthly averages of turbidity in the water column throughout the Sound. It predicted a build up of deposited sediments in the immediate vicinity of the dredging area and spoil ground from the settlement of the larger (> 75µm) sediments. Sediment loads were expected to be high at the HOLD and DPAN sites, with SUPB relatively unaffected (Fig. 3) – largely due to a postulated predominantly northerly drift.

Finer sediment fractions were assumed to remain suspended for longer periods and lead to a steady increase in turbidity which would spread widely throughout the Sound. After approximately 3 months of dredging, the model predicted that a widespread plume would have developed over much of the Sound with sites along the Burrup subjected to around 10mg/L TSS or 3-4 times background levels (GEMS 2003, Fig 6.6). Around the dredging site, SUPB was still predicted to be less impacted than DPAN or HOLD, principally due to the northerly flows caused by predominant summer south-westerlies.

The sediment transport model developed for the HI dredging (GEMS 2004) also used propeller wash and sediment dumping as the primary sources of sediment. It modeled dredging over the period May – June.

The model for the HI dredging predicted that the evolution of plumes would not reflect steady accumulation of turbidity across the Sound, but would be more variable in time and more spatially limited.

A one-day study of water column sediment directly around dredging operations (Damara 2004) validated the GEMS model assumption that propeller wash was the major source of resuspension. Levels of resuspension were highly dependent on the under keel clearance and on the particle size distribution of sediments.

The Study

While the models of sediment suspension and transport were based on the best available information, it was recognised that their predictions were subject to considerable uncertainty. To provide a test of the validity of model predictions and a history of water quality around sites established as at risk of impact from sedimentation, a water quality monitoring program was put in place to accompany other environmental monitoring during the dredging operations.

Monitoring included a 3 day cycle of water quality testing and 6 day cycle of aerial photography over the life of dredging. A pre-dredging baseline monitoring program was not conducted due to the exogenous effects of seasonal variation in water quality and potential for significant short term water quality impacts from other sources in this busy harbour.

Although the predictive models presented data on suspended sediments as depth-averaged values, the actual monitoring program was designed to detect any stratification of effects over the depth profile and collected surface and bottom water samples. From an impacts perspective, bottom levels will be most relevant for sedimentation on corals, while surface values will relate better to light attenuation and the visual detection of plumes. Forde (1985) confirms that, in common with most waters, suspended sediments at Dampier are generally more elevated at the bottom than at the surface.

Methods

Site Locations

The water quality monitoring program for the Mermaid Sound dredging projects incorporated 19 monitoring locations throughout the Dampier Archipelago. The two dredging programs used some common sites and some different to cover the range of locations potentially at risk of altered water quality. The names, designation and locations of each of the monitoring sites are given below in Table 1 and shown in Fig. 3.

Table 1. List of monitoring sites used by both programs.

Site	Function	Program
Angel Island (ANGI)	Reference (Near)	DPA/HI
Conzinc Bay North (COBN)	Impact	DPA/HI
Conzinc Island (CONI)	Impact	DPA/HI
Dampier Wharf North (DPAN)	Impact	DPA
East Lewis Island 1 (ELI1)	Impact	HI
East Lewis Island 2 (ELI2)	Impact	HI
East Lewis Island 3 (ELI3)	Impact	HI
Gidley Island (GIDI)	Reference (Near)	DPA/HI
High Point (HGPT)	Reference (Far)	DPA/HI
Holden Point (HOLD)	Impact	DPA
King Bay (KGBY)	Impact	HI
Malus Island (MALI)	Reference (Far)	DPA/HI
North Withnell (NWIT)	Reference (Near)	DPA/HI
South Withnell (SWIT)	Reference (Near)	DPA/HI
Supply Base (SUPB)	Impact	DPA
Tidepole Island (TDPL)	Impact	HI
West Intercourse Island (WINI)	Reference (Far)	DPA/HI
West Lewis Island 1 (WLI1)	Reference (Far)	DPA
West Lewis Island 2 (WLI2)	Reference (Far)	DPA

The monitoring sites were selected to coincide with the location of nominated monitoring sites in the benthic coral monitoring program (see Stoddart et al. this volume). They provide a uniform distribution of monitoring at varying distances and directions from the source of the sediment plume at the dredging and disposal areas. This allows for an assessment of the influence of tidal currents, wind direction and other meteorological variables on the migration of a sediment plume away from the dredging operations.

Reference sites were selected on the basis of similar bathymetry and weather aspect wherever possible and as sites outside the immediate impact of dredging. As the most similar biotic communities were usually located close to each other, there was a concern that the 'Near Reference' sites might be impacted by the same factors influencing the Impact sites. To provide confidence that a data set from unimpacted sites would be available, a second set of Reference sites was selected on the basis of being distant from any impacts. These 'Far Reference' sites were less similar to Impact sites than the 'Near Reference' set.

The DPA monitoring program commenced on 6 January 2004 and concluded on 8 May 2004. The HI program started on 8 May 2004 and concluded on 23 October 2004. These dates coincided with the period during which dredges operated.

Sampling Methods

DPA Program

Water quality sampling at 14 sites was undertaken 32 times over a period of 18 weeks from 6 January 2004 to 24 May 2004. Monitoring was conducted every three days from 6 January 2004 to 24 March 2004. Following approval from the Department of Environment, the frequency was reduced to weekly monitoring for the remainder of the sampling program. On occasions the monitoring frequency varied slightly as a result of sea conditions and safe access to the monitoring locations. Monitoring was undertaken over a full range of tidal and weather conditions.

Hamersley Iron

Monitoring of the 13 sites was undertaken at a frequency not exceeding every third day, as specified in the state environmental approval conditions. Monitoring frequency did vary, however, as a result of sea conditions and safe access to the monitoring locations. Monitoring was undertaken over a full range of tidal and weather conditions.

At each site water quality was measured at near bottom and near surface, actual depths varied depending on swell conditions at the time of sampling. In situ readings were recorded using a multi parameter probe. Parameters recorded at each site using this instrument included:

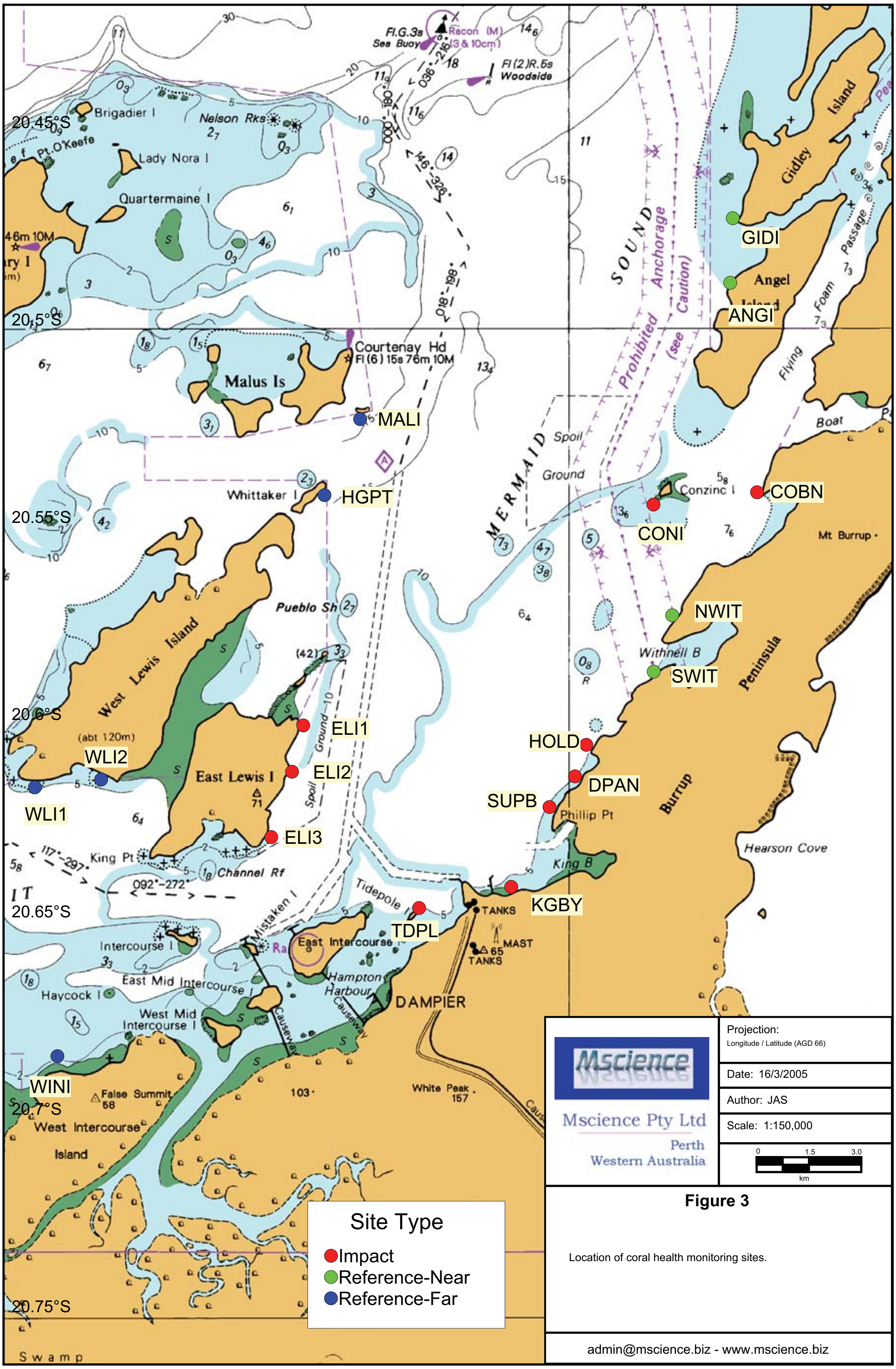
- Depth of Sample (m);
- Dissolved Oxygen (mg/L);
- pH:
- Turbidity (NTU);
- Temperature (°C); and
- Salinity (mg/L).

Throughout the duration of the dredging program three models of multi-parameter probe were used as a result of damage or failure of the instrument. The models used included:

- In situ Troll 9000;
- YSI Sonde 6820; and
- Yeo-Kal YK-611.

Each instrument in use was calibrated for each parameter on a fortnightly basis. Analysis of the data shows no significant fluctuation as a result of the transition between the three instruments.

Figure 3. Location of monitoring sites in Mermaid Sound.



Total Suspended Solids (TSS) at each monitoring site was measured by laboratory analysis of collected water samples. Two litres of water was taken from both the bottom and surface levels at each of the sites, resulting in a laboratory accuracy of +/- 1 mg/L. Samples were taken using a 12 volt pump connected to a 15mm hose weighted with 1.5kg of lead. Duplicate samples were taken during most monitoring trips.

Aerial photography

Throughout the dredging program aerial surveys of the dredging location, monitoring locations and surrounding areas were undertaken on a weekly basis. Surveys were flown on the same day as the water monitoring trip to allow for cross-referencing of visual observations and actual data. Surveys were flown over midday to reduce glare from the water surface and increase visibility of the dredge plume. All surveys were flown at a height of 770m in a Cessna 172 light aircraft.

Photographs were taken of all monitoring sites and some surrounding areas regardless of plume density. Photographs of other areas were also taken where increased turbidity was observed, whether resulting from dredging or natural occurrences. Photographs were taken at 5 or 6 mega pixels using a digital SLR camera with polarizing lens.

Dredge plumes were interpreted visually from the resulting aerial photography and classified as either high, medium or low intensity. Resulting classifications and spatial distribution of the plume were recorded for later analysis.

Results

Turbidity or total suspended solids

Overall, there was a weak but significant relationship between turbidity and TSS (Table 2) with an R-squared of 0.189 ($p<0.01$). No differences were found between relationships based on profile (Surface or Bottom samples) and the general solution for the prediction of turbidity from TSS was

$$\text{Turbidity (NTU)} = 0.4 + 0.27\ \text{TSS (mg/L)}$$

The relationship between turbidity and TSS did not improve when viewed on a site by site basis. However, it was apparent that sites with elevated turbidity produced a closer relationship than at other sites (Tables 2, 4, 6).

Table 2. Relationship between turbidity and TSS by site.

SITE	N	r-sq
ANGI	131	0.014
COBN	62	0.001
CONI	131	0.076
DPAN	66	0.461
ELI1	72	0.243
ELI2	72	0.167
ELI3	72	0.091
GIDI	132	0.003
HGPT	133	0.017
HOLD	66	0.170
KGBY	66	0.049
MALI	133	0.004
NWIT	131	0.015
SUPB	65	0.261
SWIT	124	0.000
TDPL	61	0.535
WINI	130	0.032
WLI1	57	0.006
WLI2	60	0.001

Total Suspended Solids

Concentrations of total suspended solids ranged from virtually 0 to 75 mg/L. Levels in bottom samples were generally similar to surface samples within the normal range of variation, but were more prone to occasional very high levels (Fig. 4). From examination of later graphs and comparisons of duplicate samples, the very high levels in bottom samples originate both from occasional episodes of very high sediment mobilisation from dredging or from wave surge, as well as through sampling errors when the sample inlet was very close to the substrate.

In summary, TSS for both bottom and surface samples was higher at Impact Sites than at either the Near or Far Reference sites in both surface and bottom waters (Table 3, P<0.000, Fig. 5). There was no obvious seasonal signal to TSS levels at any site, and values appeared to respond to immediate conditions (such as heavy swell).

Table 3. TSS statistics at impact and reference sites.

Total Suspended Sediment (mg/L)				N	Mean	Maximum	Std. Deviation
Profile	**Bottom**	**Site type**	**Impact**	445	6.9	75	8.67
			Near Reference	267	4.5	58	5.47
			Far Reference	264	4.5	24	4.01
	Surface	**Site type**	**Impact**	446	5.4	42	5.16
			Near Reference	263	4.0	17	3.28
			Far Reference	262	4.2	20	3.57

Figure 4. Levels of total suspended sediments from surface and bottom samples.

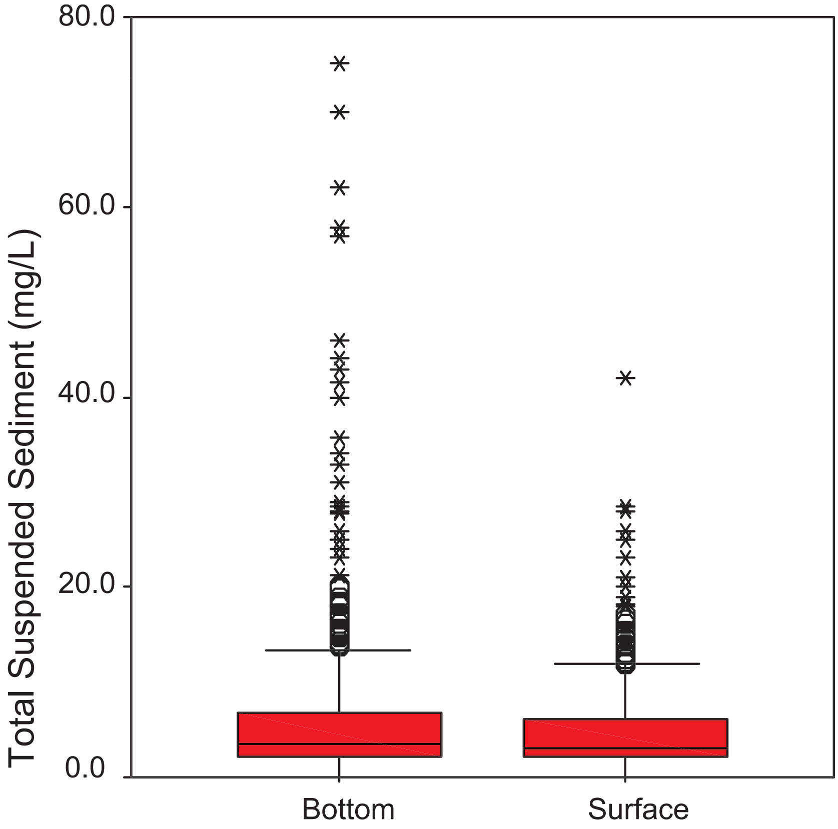


Figure 5. Comparison of TSS at impact and reference sites.

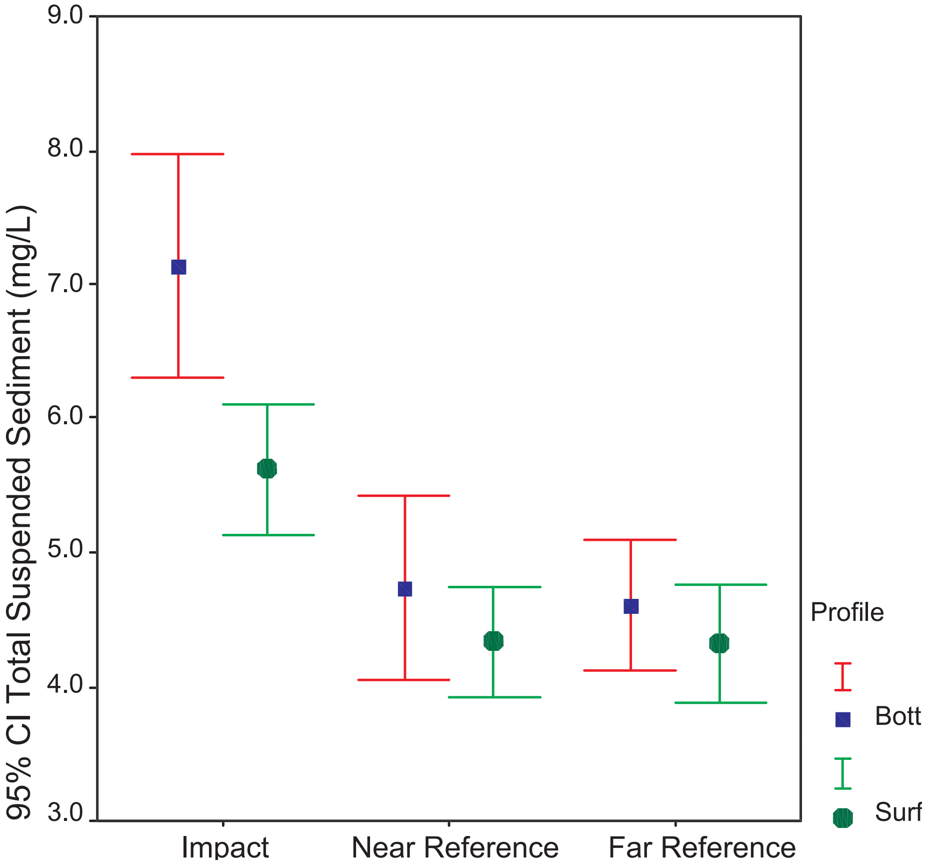


Table 4. TSS levels by site over both programs.

SITE	Surface Samples		Bottom Samples	
	Mean	Maximum	Mean	Maximum
ANGI	3.55	12	4.00	40
COBN	4.20	12	5.41	16
CONI	3.71	25	3.81	12
DPAN	7.16	28	8.65	43
ELI1	4.06	12	3.78	13
ELI2	4.50	19	3.67	12
ELI3	4.44	13	4.50	26
GIDI	4.22	17	5.03	58
HGPT	3.96	17	4.45	21
HOLD	6.34	28	9.07	57
KGBY	4.21	14	6.67	46
MALI	3.98	20	4.08	23
NWIT	4.19	15	3.99	15
SUPB	8.57	42	14.12	75
SWIT	4.06	12	4.83	28
TDPL	4.85	15	4.63	12
WINI	4.29	12	4.71	18
WLI1	4.80	18	5.42	24
WLI2	4.07	12	3.95	12

When individual sites are examined, it was clear that the greatest impact of sediment occurred at site SUPB, which was located within 200m of the DPA additional berth dredged by the trailer suction hopper dredge. Average and maximum values for both surface and bottom samples were around twice those of most other sites (Table 4, Fig. 6). Other sites that stand out as having received high sediment loadings are HOLD, DPAN and KGBY (bottom only). These sites are discussed further under the Turbidity section.

Occasional very high (>50 mg/L) TSS was recorded from the bottom samples at GIDI. This site was the most affected by swell action coming from the open ocean.

Turbidity

As for TSS, turbidity was similar between surface and bottom samples, although in this parameter the greater abundance of high outliers in bottom samples was less pronounced (Fig. 7). Turbidity ranged from close to 0 to almost 50 NTU.

For both surface and bottom samples, Impact Sites were more turbid than either Near or Far Reference sites (Table 5, Fig. 8, P<0.000). While Far Reference site means were above those of the Near Reference sites, this was not a significant difference. Examination of individual sites (Fig.s 9,10) suggests that it arises due to elevated turbidity at WINI – a site frequently noted as affected by terrestrial runoff or freshwater seepage.

Figure 6. Mean and 95% confidence intervals for TSS by site.

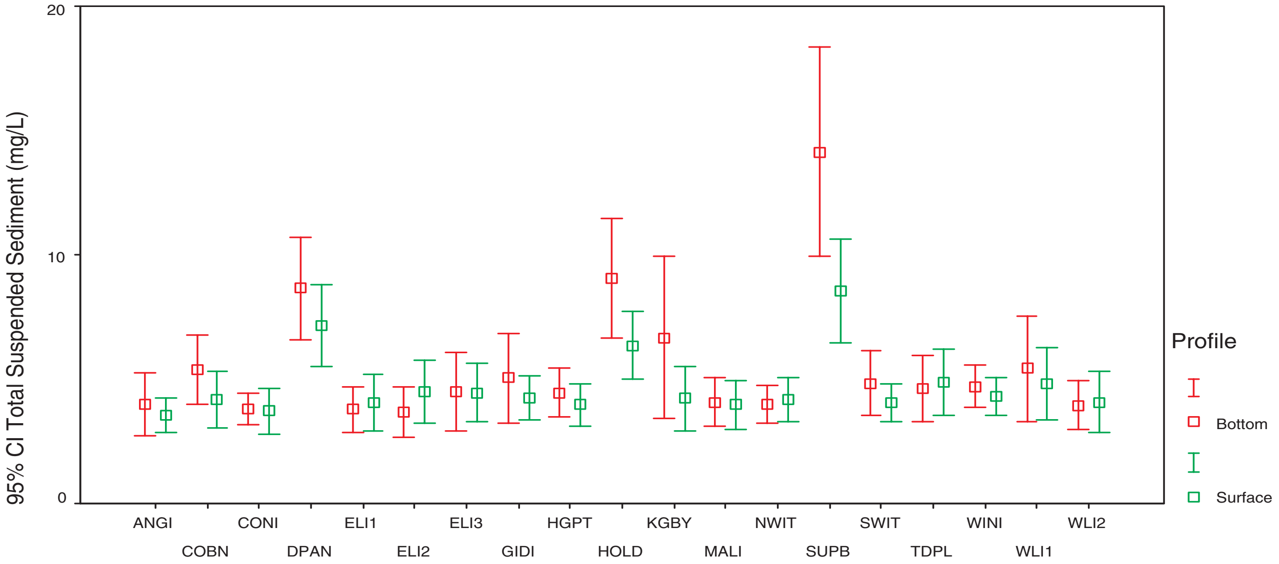


Table 5. Turbidity statistics at impact and reference sites.

Turbidity (NTU)				N	Mean	Maximum	Std. Deviation
Profile	Bottom	Site type	Impact	433	3.75	48	5.873
			Near Reference	304	0.73	7	1.021
			Far Reference	290	1.24	17	1.971
	Surface	Site type	Impact	426	2.83	37	4.042
			Near Reference	300	0.72	8	1.078
			Far Reference	286	1.03	13	1.831

Figure 7. Levels of turbidity from surface and bottom readings.

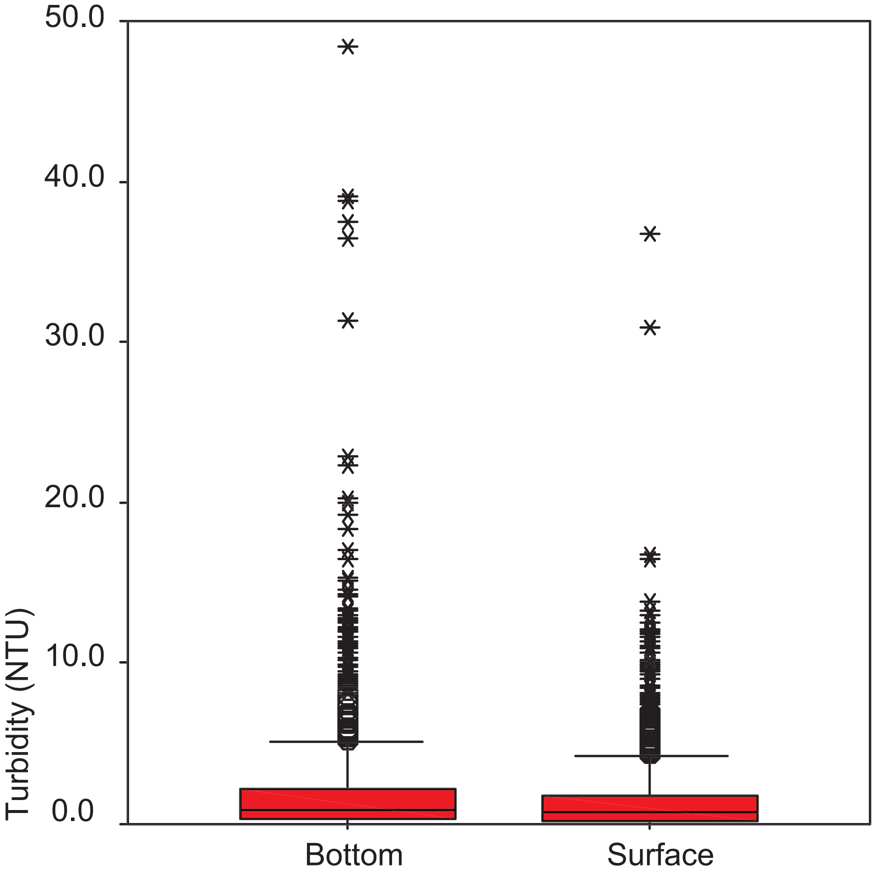
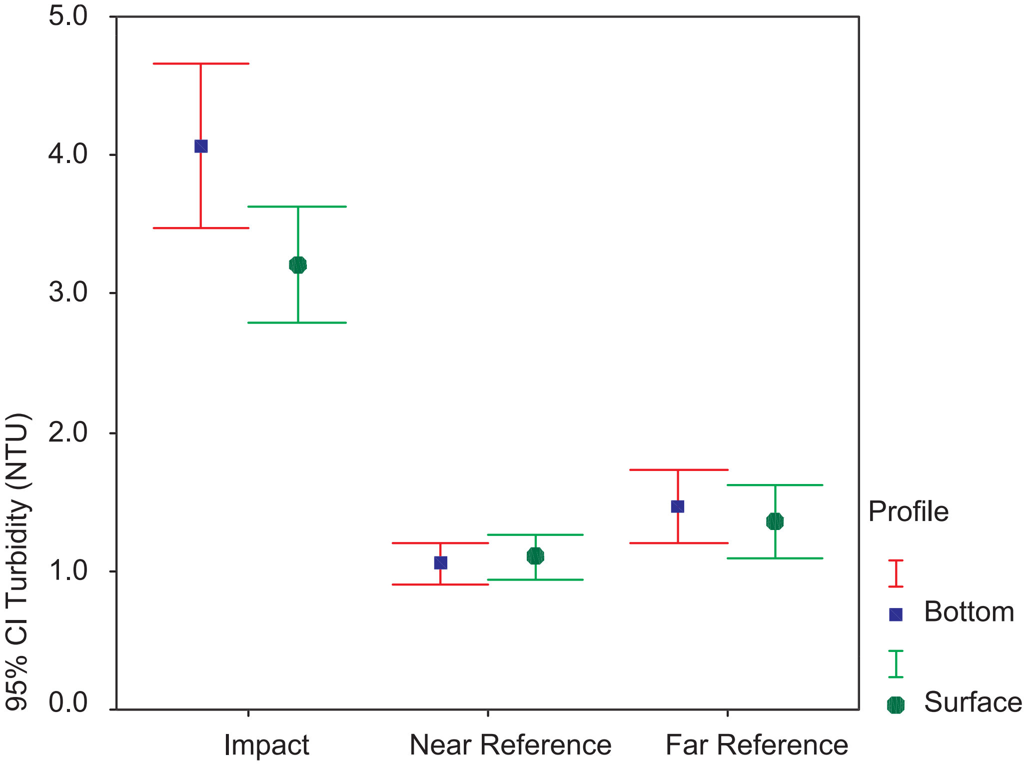


Figure 8. Comparison of turbidity at impact and reference sites.



Unlike the outcome for TSS, the clear difference between impact and Reference sites seen in Fig. 8 is indicative of elevated turbidity levels at the majority of impact sites (Table 6, Fig. 9 & 10). The exception is turbidity levels at CONI and COBN which are similar to those at Reference sites. Amongst the Reference sites, turbidity at WINI was elevated around the cyclone event and for some time after for both surface and bottom samples. This seems to have been associated with freshwater runoff and seepage at that area leading to substantial levels of microalgae in the water column for long periods at that site.

Figure 10 shows that for all sites the onset and recovery from turbidity or suspended sediment events is usually rapid and brief. The exceptionally high levels of suspended sediments at SUPB in February (Fig. 11) seem to have been the principal factor associated with coral mortality at that site.

Temperature, Dissolved Oxygen, pH and salinity

Unlike the turbidity and TSS measures, other water quality parameters showed little apparent effect of the dredging. Dissolved oxygen, pH and salinity showed no correlation with elevated levels of turbidity or TSS.

The water column around sites monitored usually showed little evidence of stratification and surface and bottom samples are similar at most times of the year (Fig. 12, 13). A notable exception is the drop in salinity in surface samples seen immediately after the intense rainfall from tropical cyclone Monty at the beginning of March (Fig. 13).

Dissolved oxygen levels (Fig. 14) were correlated with both temperature and pH (r = 0.38 for T alone and 0.5 for T and pH, both p<0.000). While pH might be expected to remain around 8.2 +/- 0.1 units for most of the year, the mid-year fluctuations seen to around 8.6 (Fig. 15) may be more than instrument error. Monitoring at King Bay 2003 by the Western Australian Water Corporation (unpublished data) shows that pH rose steadily from around 8.1 in January to 8.35 by June suggesting a consistent seasonal pattern.

Table 6. Turbidity levels (NTU) by site over both programs.

SITE	Surface		Bottom	
	Mean	Maximum	Mean	Maximum
ANGI	0.40	4	0.54	7
COBN	0.57	2	1.17	6
CONI	0.59	4	0.83	11
DPAN	3.18	10	4.72	18
ELI1	3.18	17	3.53	23
ELI2	4.68	37	4.72	39
ELI3	3.16	11	3.09	12
GIDI	0.70	6	0.64	5
HGPT	0.92	11	0.88	9
HOLD	2.54	11	5.59	22
KGBY	2.91	10	2.50	7
MALI	0.73	8	0.66	3
NWIT	0.87	8	0.73	6
SUPB	4.96	31	10.91	48
SWIT	0.91	5	1.02	4
TDPL	3.95	14	4.06	13
WINI	2.02	13	2.44	17
WLI1	0.34	2	0.98	4
WLI2	0.34	2	0.90	8

Figure 9. Mean and 95% confidence interval for turbidity at all sites.

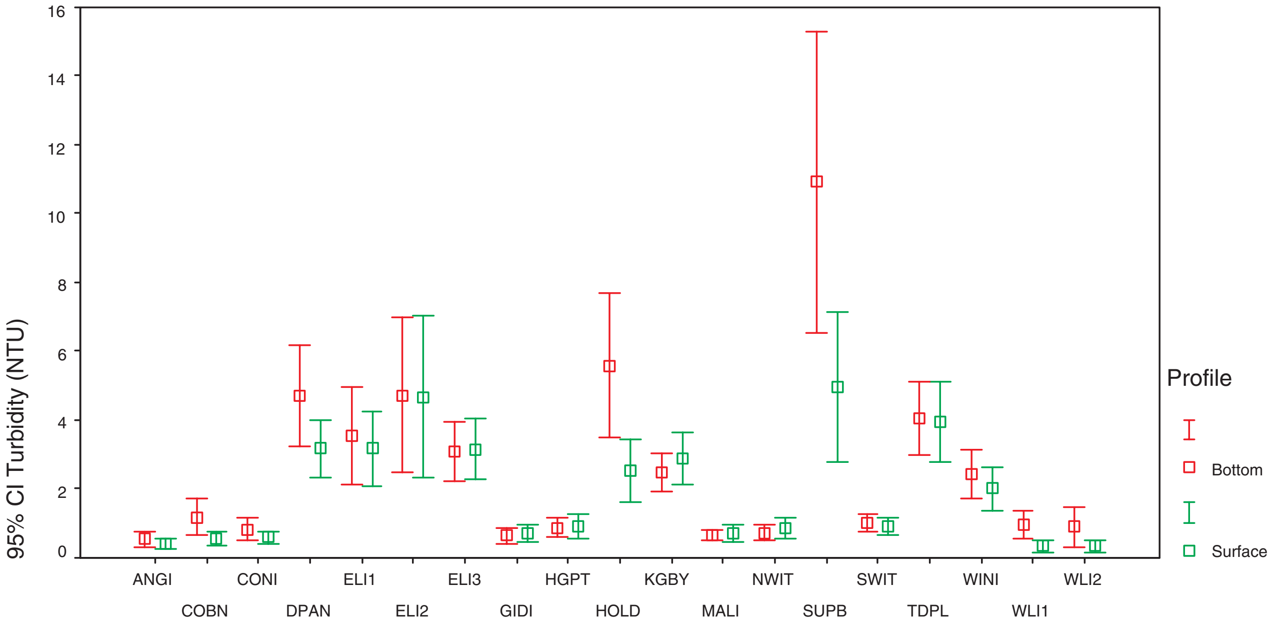
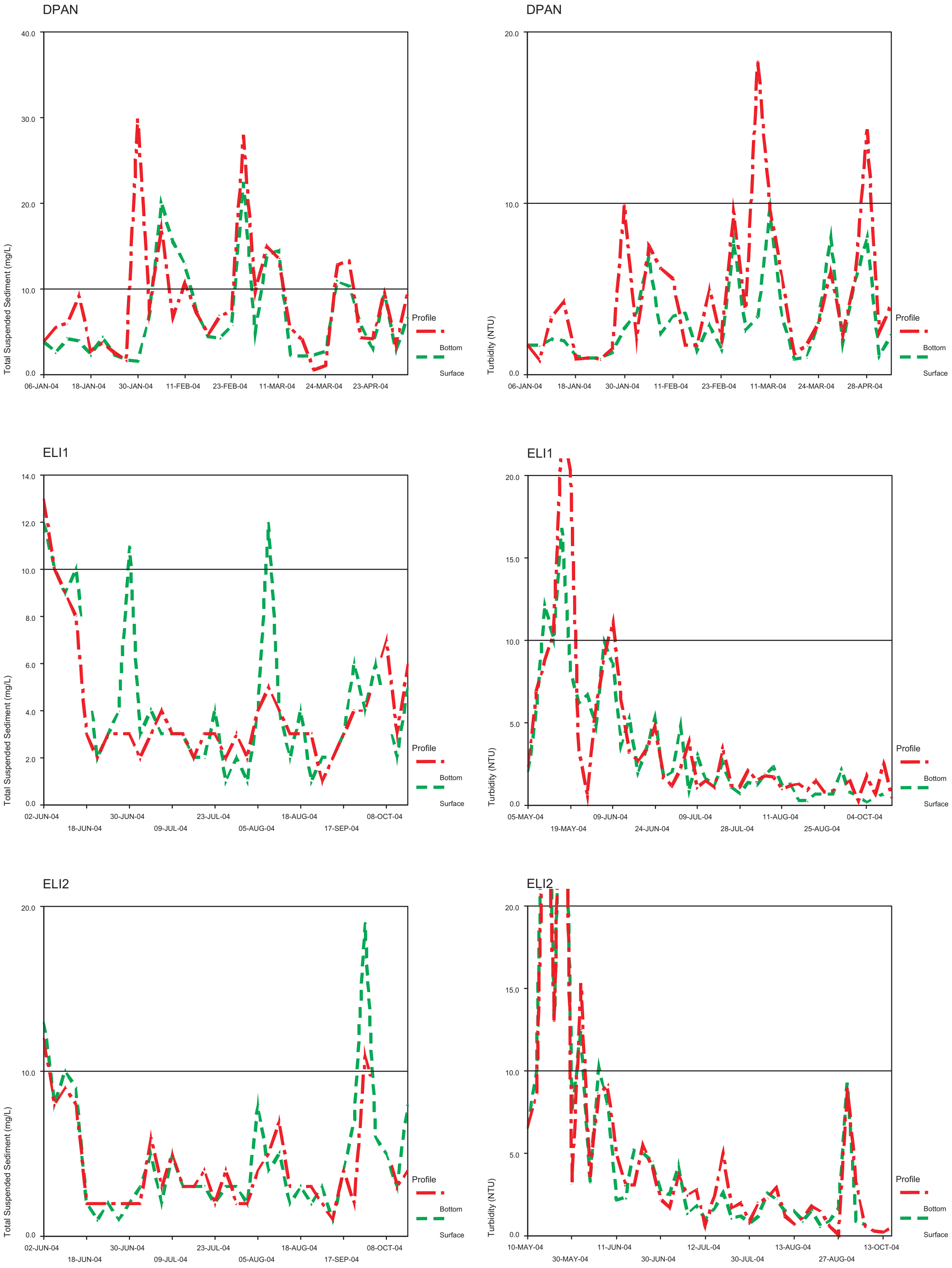
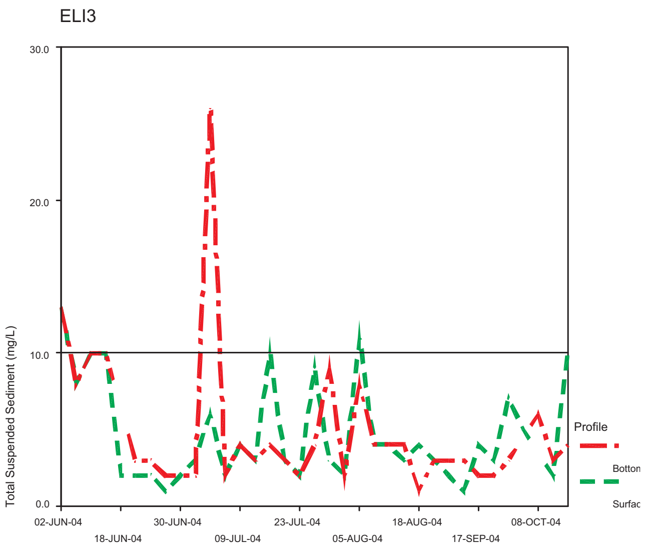
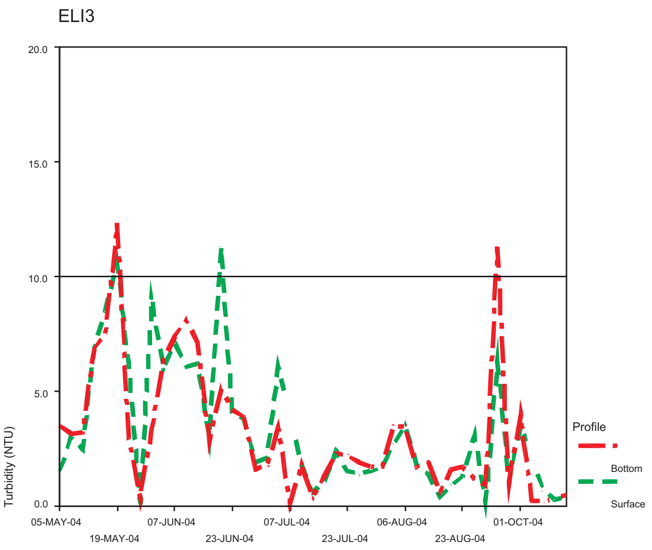
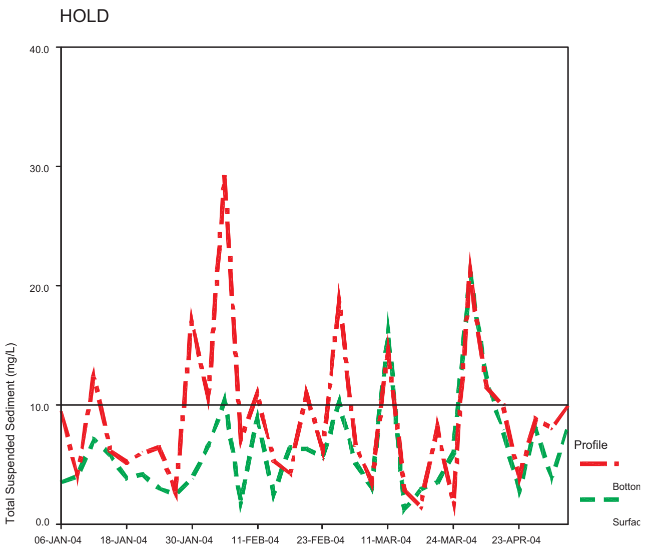


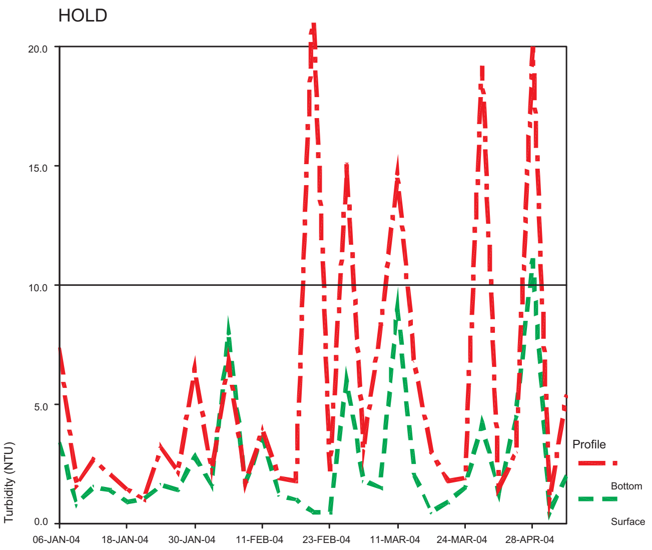
Figure 10. Comparison of TSS and turbidity over time at individual sites.

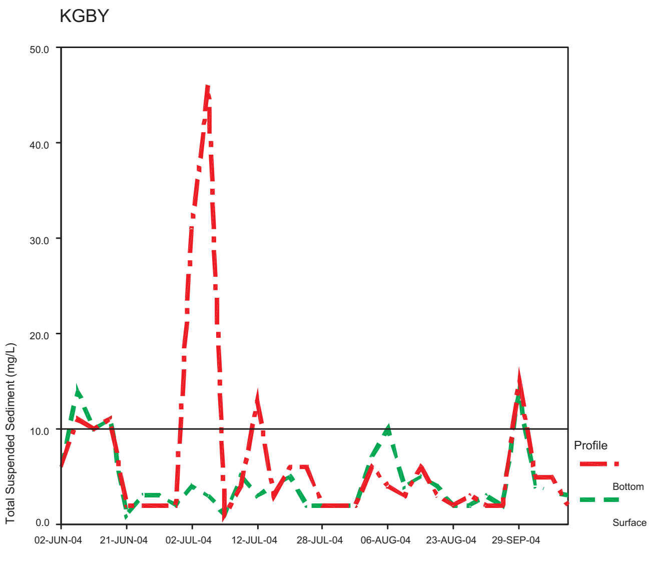


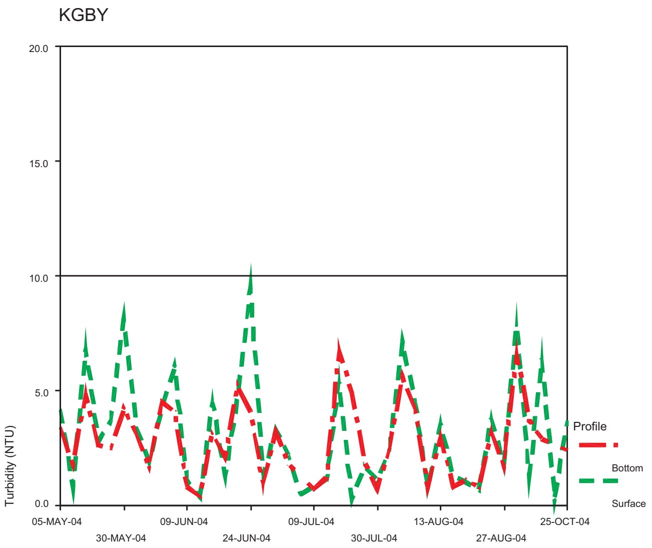

ELI3
Total Suspended Sediment (mg/L)
30.0
20.0
10.0
0.0
02-JUN-04
18-JUN-04
30-JUN-04
09-JUL-04
23-JUL-04
05-AUG-04
18-AUG-04
17-SEP-04
08-OCT-04
Profile
Botton
Surfac

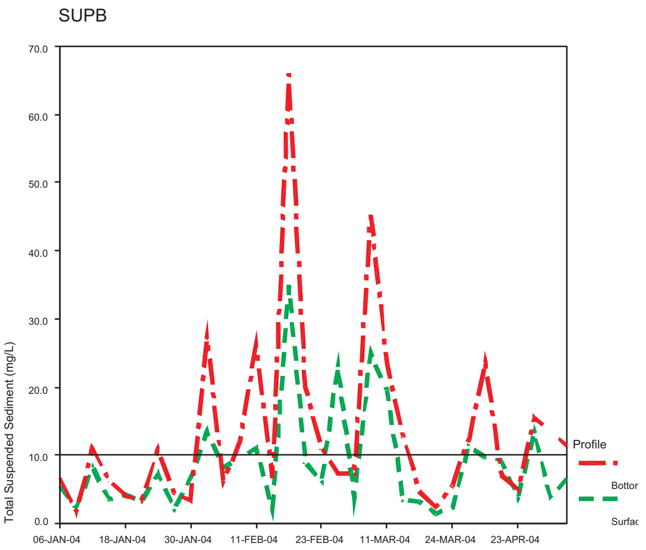

ELI3
Turbidity (NTU)
20.0
15.0
10.0
5.0
0.0
05-MAY-04
19-MAY-04
07-JUN-04
23-JUN-04
07-JUL-04
23-JUL-04
06-AUG-04
23-AUG-04
01-OCT-04
Profile
Bottom
Surface

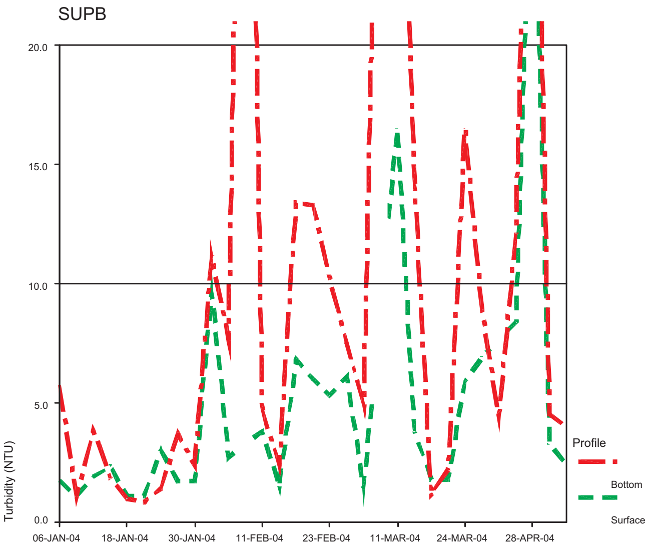

HOLD
Total Suspended Sediment (mg/L)
40.0
30.0
20.0
10.0
0.0
06-JAN-04
18-JAN-04
30-JAN-04
11-FEB-04
23-FEB-04
11-MAR-04
24-MAR-04
23-APR-04
Profile
Botton
Surfac

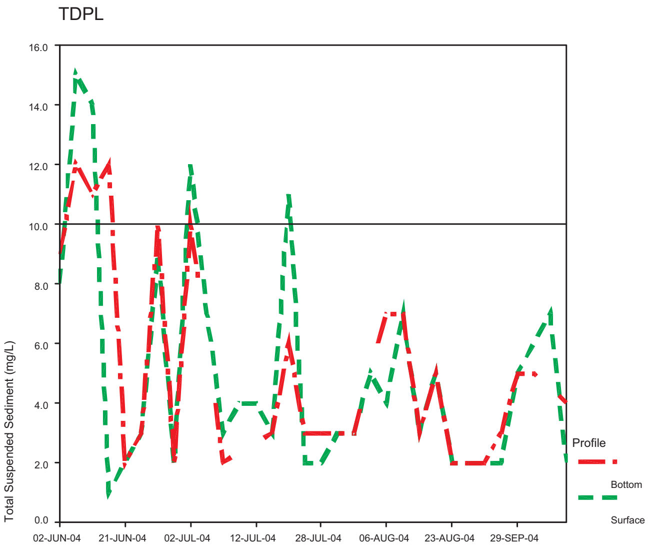

HOLD
Turbidity (NTU)
20.0
15.0
10.0
5.0
0.0
06-JAN-04
18-JAN-04
30-JAN-04
11-FEB-04
23-FEB-04
11-MAR-04
24-MAR-04
28-APR-04
Profile
Bottom
Surface

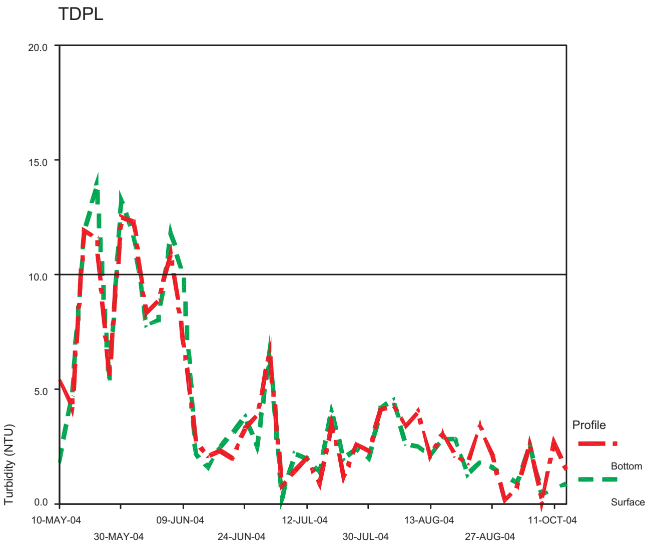

KGBY
Total Suspended Sediment (mg/L)
50.0
40.0
30.0
20.0
10.0
0.0
02-JUN-04
21-JUN-04
02-JUL-04
12-JUL-04
28-JUL-04
06-AUG-04
23-AUG-04
29-SEP-04
Profile
Bottom
Surface

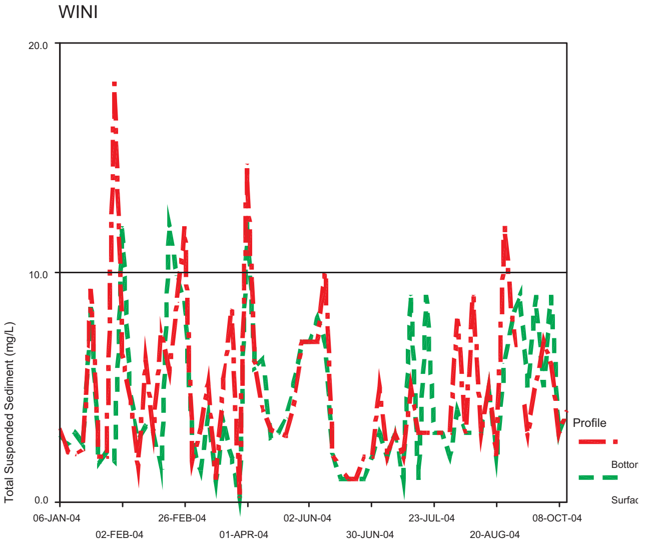

KGBY
Turbidity (NTU)
20.0
15.0
10.0
5.0
0.0
05-MAY-04
30-MAY-04
09-JUN-04
24-JUN-04
09-JUL-04
30-JUL-04
13-AUG-04
27-AUG-04
25-OCT-04
Profile
Bottom
Surface


SUPB
Total Suspended Sediment (mg/L)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
06-JAN-04
18-JAN-04
30-JAN-04
11-FEB-04
23-FEB-04
11-MAR-04
24-MAR-04
23-APR-04
Profile
Bottor
Surfac


SUPB
Turbidity (NTU)
20.0
15.0
10.0
5.0
0.0
06-JAN-04
18-JAN-04
30-JAN-04
11-FEB-04
23-FEB-04
11-MAR-04
24-MAR-04
28-APR-04
Profile
Bottom
Surface


TDPL
Total Suspended Sediment (mg/L)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
02-JUN-04
21-JUN-04
02-JUL-04
12-JUL-04
28-JUL-04
06-AUG-04
23-AUG-04
29-SEP-04
Profile
Bottom
Surface


TDPL
Turbidity (NTU)
20.0
15.0
10.0
5.0
0.0
10-MAY-04
30-MAY-04
09-JUN-04
24-JUN-04
12-JUL-04
30-JUL-04
13-AUG-04
27-AUG-04
11-OCT-04
Profile
Bottom
Surface


WINI
Total Suspended Sediment (mg/L)
20.0
10.0
0.0
06-JAN-04
02-FEB-04
26-FEB-04
01-APR-04
02-JUN-04
30-JUN-04
23-JUL-04
20-AUG-04
08-OCT-04
Profile
Bottor
Surfac

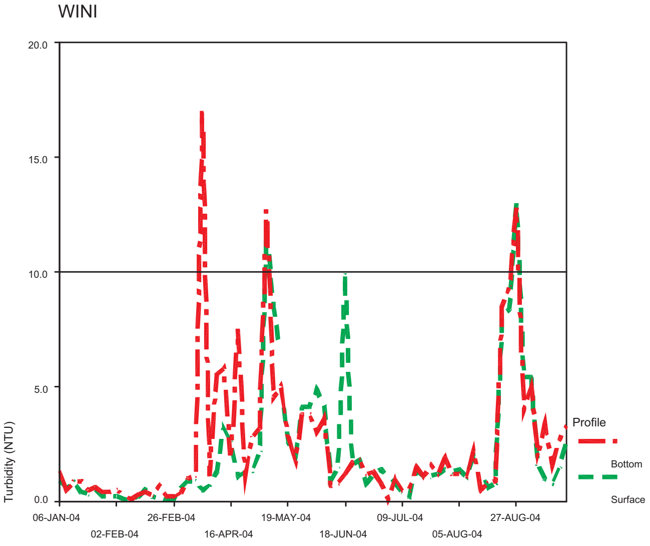

WINI
Turbidity (NTU)
20.0
15.0
10.0
5.0
0.0
06-JAN-04
02-FEB-04
26-FEB-04
16-APR-04
19-MAY-04
18-JUN-04
09-JUL-04
05-AUG-04
27-AUG-04
Profile
Bottom
Surface

Figure 11. Suspended sediment levels at SUPB at the time of postulated coral mortality (maximum values from Bottom samples).

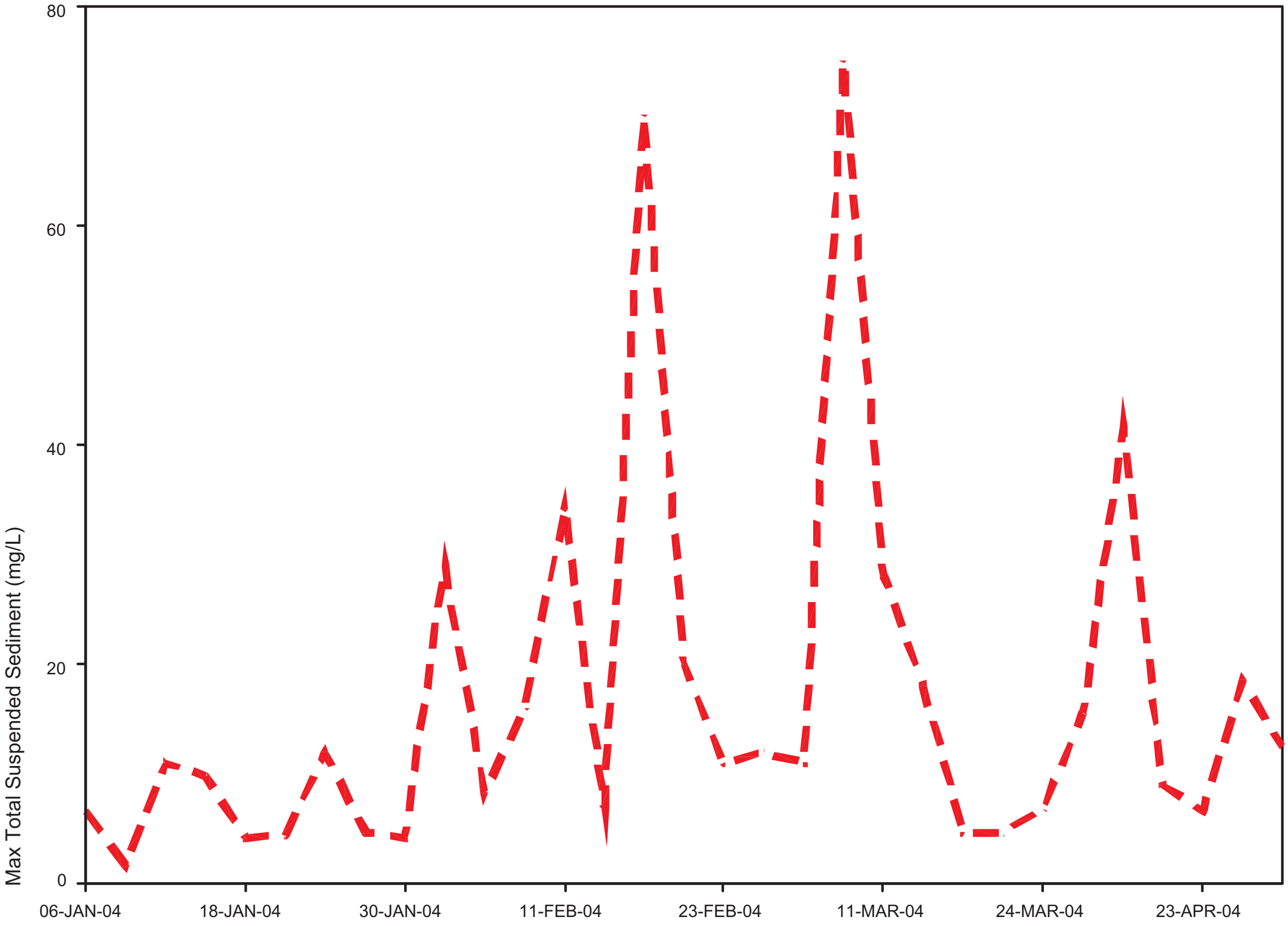


Figure 12. Water temperature over the monitoring period.

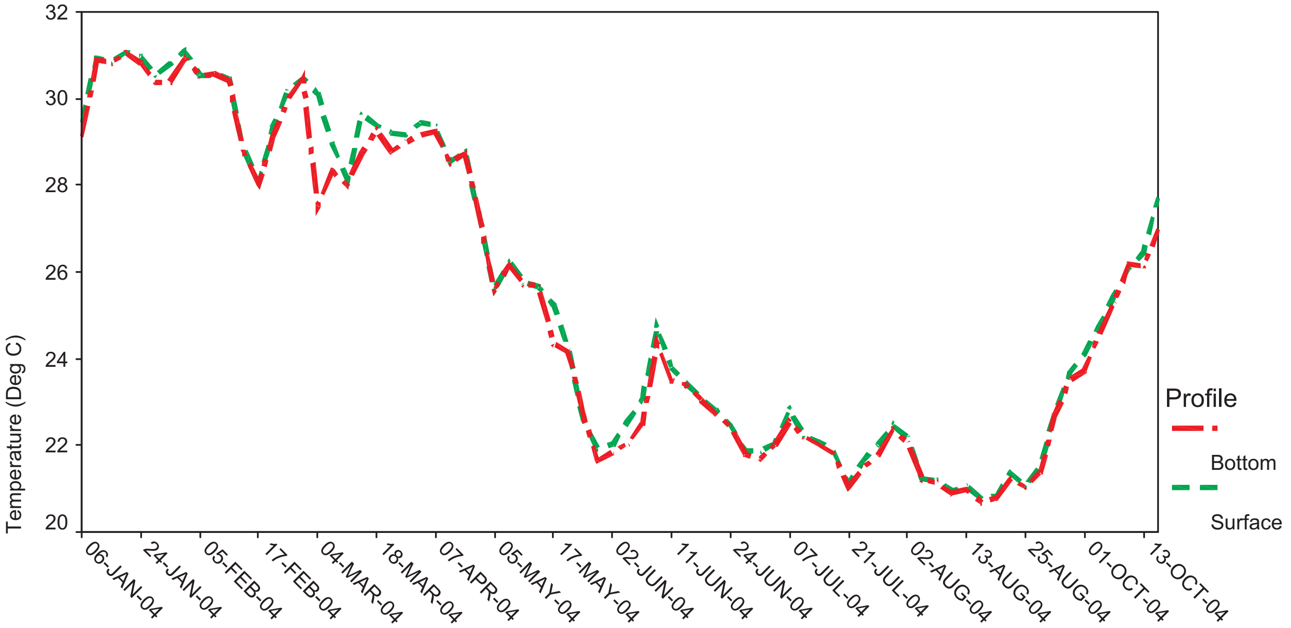


Figure 13. Fluctuation in salinity during the year.

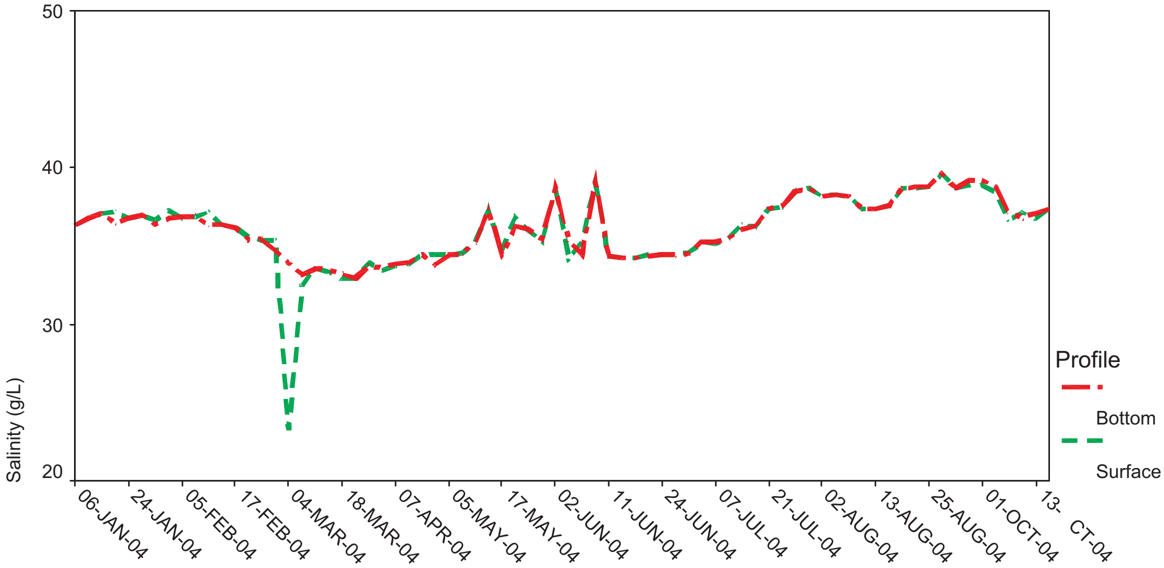


Figure 14. Dissolved oxygen levels over the monitoring period.

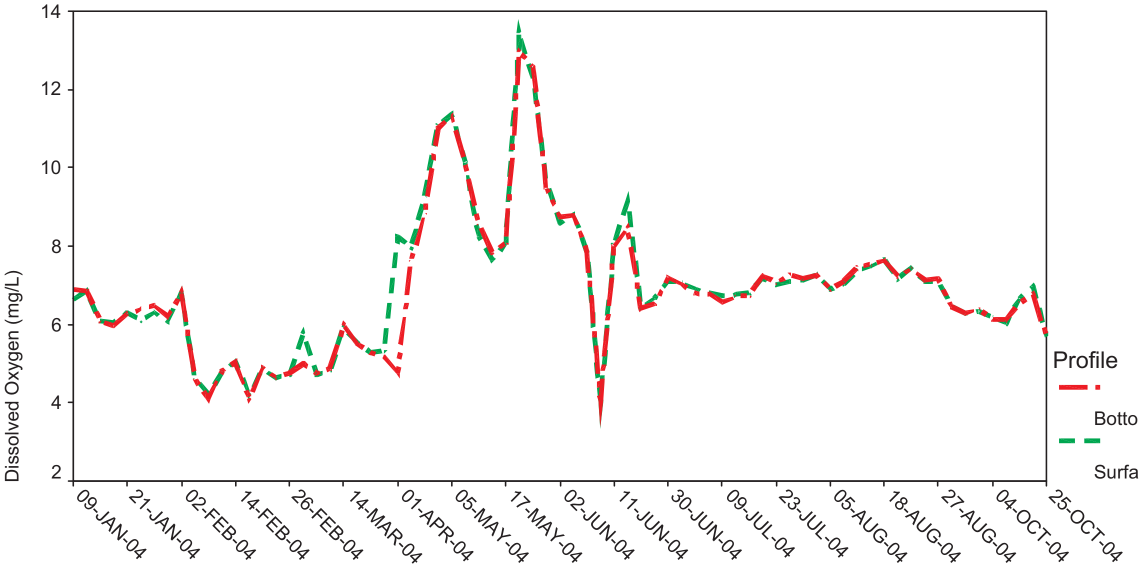
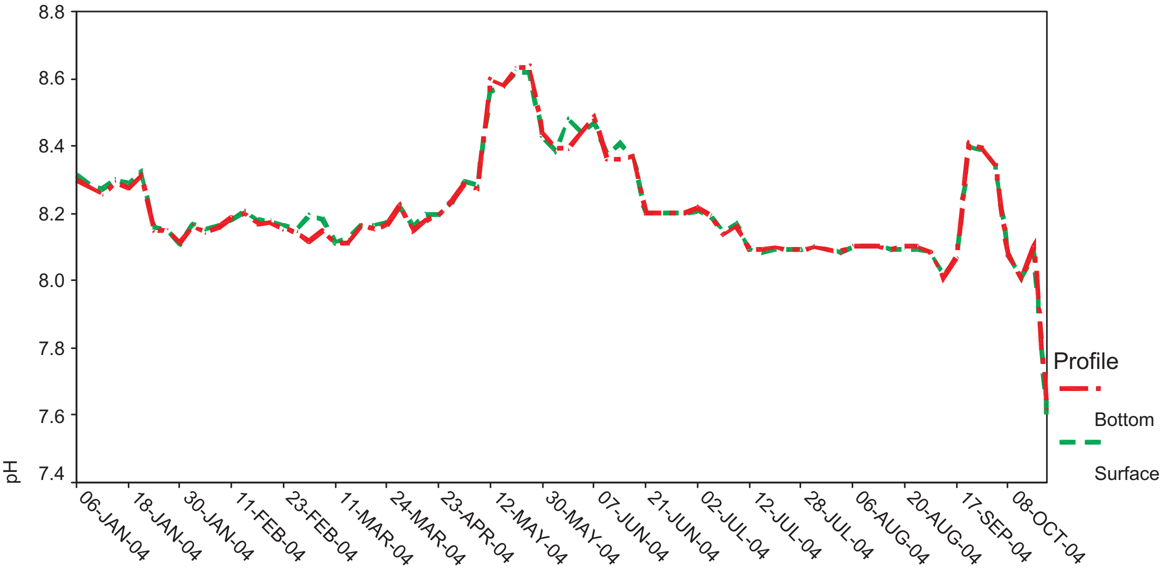


Figure 15. Variation in pH during monitoring



Comparisons with the GEMS Model

Contrasting the GEMS (2003) prediction of levels of suspended sediments at sites around the dredging uplift at Dampier Wharf (Fig. 16) with actual measured levels during dredging (Fig. 17) shows that the prediction of suspended sediment levels (labelled as Turbidity in GEMS Figure 11) rising steadily as dredging proceeds was not met. Rather the actual elevation occurred as a series of short-lived peaks in suspended sediments mostly at SUPB. Levels were well below those predicted.

Discussion

Turbidity vs TSS

Turbidity is a measure of the amount of light scattering through water caused by particles suspended in the water column. It responds to the spectral qualities of suspended particles as well as their density. The higher turbidity, the greater the scattering and thus the more opaque the water appears.

Total suspended solids (TSS) is a measure of the mass of suspended solids per litre of water.

These two parameters are often used interchangeably in discussion of water quality impacts, but in areas such as Dampier, they are not necessarily related and have differing impact pathways. Turbidity as a measure of scattering is also a direct measure of light attenuation as light passes through the water column. Thus it represents the potential for light starvation of corals and other photo-dependent organisms.

TSS is a direct measure of the potential amount of sediment likely to fall onto benthic organisms – after correction for density of the particles.

Assessed from the entire data set collected here, while significantly related, TSS and turbidity would be poor predictors of each other at Dampier when assessed over different sites or at different times. Forde (1985) noted a similar effect with the relationship of suspended sediment load and light attenuation varying substantially between two assessment periods. The Damara study for the DPA project showed a close correlation between turbidity and TSS (Figure 5 of Damara 2004) but only included data from a single day at a single site. The relationship between turbidity and TSS from this study and the Damara work were similar with turbidity (in NTU) about 0.25 to 0.3 of TSS (in mg/L).

In addition to the concentration of suspended sediments, turbidity will be affected by the particles' size distribution, composition and refractive and reflective index (Sadar & Engelhardt undated). It is likely that much of the error variance in the TSS-turbidity relationship seen here arises from temporal and spatial differences in these parameters of sediments over space and time.

Some spatial variance can be avoided by examining relationships on a site by site basis. However, when relationships were examined by site here, correlations were not increased except for samples with higher levels of turbidity.

What is background?

While the water quality at Mermaid Sound is seen as seasonal, at any location this may be more dependent on the local effects of weather conditions over the previous few days. The frequency of strong westerly winds in summer and residual effects of cyclones leads to elevated turbidity across much of the inner half of the Sound. Easterly winds in winter may also raise turbidity across large parts of the Sound. Nevertheless, periods of calm weather in either season lead rapidly to improved visibility.

Local variation in exposure to wind and wave conditions may cause some sites to react differently from adjacent sites within a kilometre or so. Forde (1985) notes that sediment traps near Gidley Island contained the largest loads of sediment post-cyclone and this was of a calcareous nature. This is consistent with diver observations of coarse sediments on corals at that site after Cyclone Monty and the occasional peak of TSS in bottom samples from GIDI. There was also a clear effect of non-dredging plumes noted at the adjacent Angel Island and Conzinc Island sites. During falling tides, a fine light-coloured plume was noted coming down Flying Foam Passage. This plume frequently affected visibility adversely at these sites before turning northwards and passing offshore of Gidley Island.

Thus the 'background' level of turbidity or TSS is highly site-dependent. As a result, the status of local benthic communities can vary naturally in response to isolated effects - such as the decline in some corals seen at GIDI following impact from coarse sediments resuspended by wave action (Stoddart et al. this volume).

Comparisons with model

Overall:

The GEMS model substantially over-predicted the impacts of the DPA dredging and disposal operations. The model was designed to be conservative in allowing for an overly large resuspension of sediments from the dredging activities. However it also predicted that suspended sediments would spend much more time in the water column than actually occurred and would thus travel farther and impact over greater areas than occurred (Fig. 18). TSS effects were in fact extremely localised in time and space: in most cases, the effect of sediment suspension episodes seen in one monitoring period were rarely detectable in the next monitoring period (3d later).

Predictions of widespread effects at increments of 1-5mg/L contained in the DPA model were unable to be verified by visual plume tracking or measured water quality. This may be because a) they didn't occur, or b) changes at that scale are within observed daily variation in this area.

The agreement between the predictions of the location and duration of plumes and the visual assessments done from aerial photographs was much closer for the HI dredging model than the DPA model. The primary difference between the model predictions was that the sensitivity of modelling in the HI model was decreased to a 5mg/L step – which equates better to a visual ability to detect plumes above natural background in this area.

Figure 16. GEMS prediction of the evolution of sediment around the Dampier dredging operations (GEMS Fig 6.9 showing depth-averaged sediment levels).

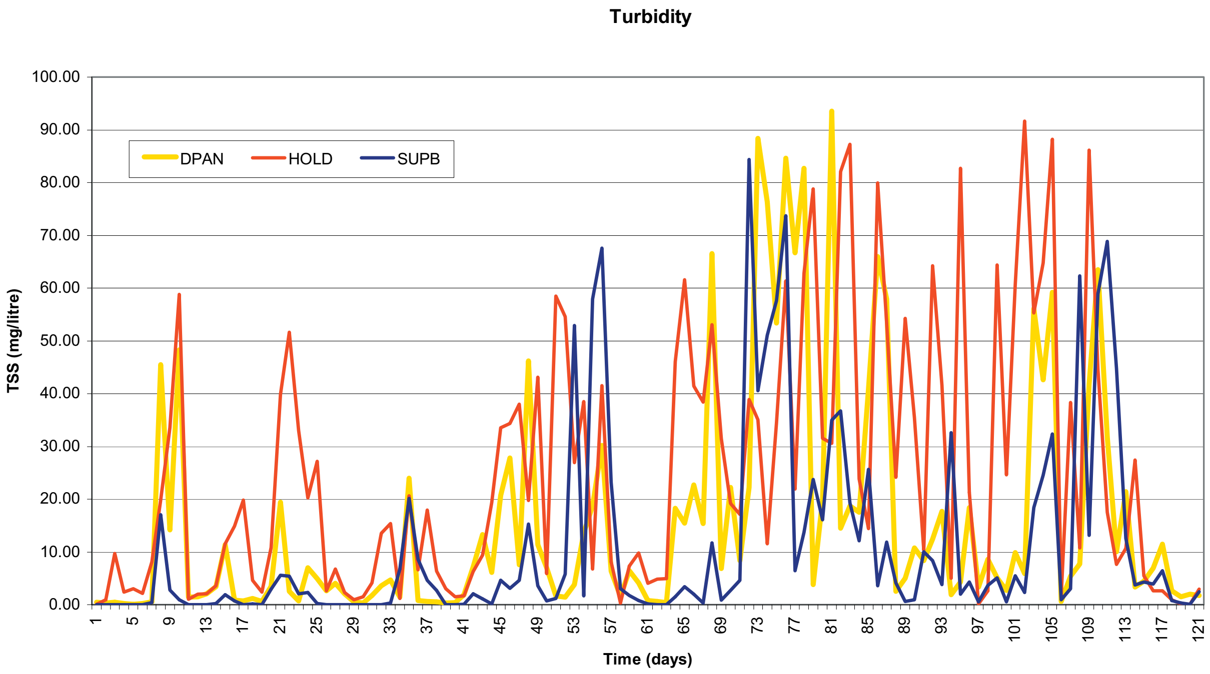
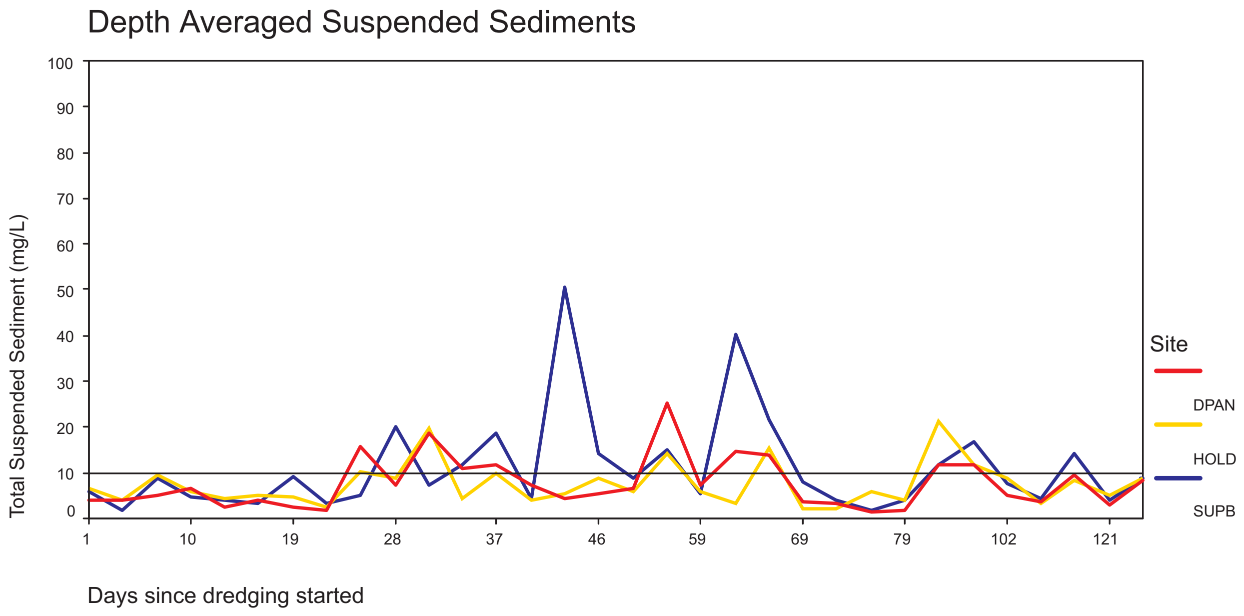


Figure 17. Actual levels of TSS at sites near DPA dredging.



Around the dredging site:

In the model of localised impacts around the DPA dredging site, the GEMS model predicted the steady evolution of very high levels of suspended sediments as dredging progressed. The model assumed that sediment would accumulate locally during dredging and be continually resuspended by subsequent dredging activity. Actual levels seen were much lower than predicted and tended to be short-lived peaks, consistent with rapid settlement of suspended sediment and minimal resuspension of sediment settling locally.

The model also predicted that dredging around the site of the new berth would result in impacts on water quality predominantly on sites to the northeast of the area to be dredged. Due to predominant westerly winds and the shape of the coast, GEMS predicted that turbidity at sites HOLD and DPAN would be greater than at SUPB as a result of northerly drift. In fact, SUPB was by far the most effected site for both TSS and turbidity. The localisation of effects seems to result from:

- the dredge spending much more time in the very immediate area of SUPB than originally assumed;
- sediment build up from prop wash being extremely localised;
- local boundary effects limiting flow – observations of turbidity on many occasions suggested that there was a boundary layer of water around 50m wide along the shoreline which remained roughly in place except under very heavy wind or wave conditions.

What is too much sediment?

As an indicator of light attenuation, turbidity needs to be elevated for considerable periods to produce impacts by depriving corals of photosynthetic energy from zooxanthellae. Similarly, chronic elevation of sediment levels might stress corals by diverting energy towards sediment removal processes (such as mucus production). Acute sedimentation on the other hand is likely to cause mortality by overwhelming corals with a layer of sedimentation (Nugues & Roberts 2002).

Divers observing corals every two weeks during dredging did occasionally observe sediment covering live coral, but did not report unusually high levels of mucus production – except for *Millepora* which appeared to be a response to water temperature rather than to sediment cover. At sites where turbidity/sedimentation episodes occurred immediately prior to diver visits, visibility was too limited to allow safe diving and thus very short term sediment cover or mucus production was unable to be assessed.

The only dredging related mortality observed by the coral health monitoring program (Stoddart et al. this volume) was at the Supply Base site (SUPB) during the DPA program. Following the commencement of dredging adjacent to this site, turbidity was sufficiently high or weather sufficiently rough, so as to prevent observation of corals over an extended period and when corals were finally observed on 11 April, approximately 80% mortality had occurred – almost entirely by direct smothering.

The Supply Base site shows the highest levels of mean and maximum turbidity and TSS. On 42% of monitoring days, TSS in bottom samples from SUPB was above 10mg/L and 22% for turbidity. However, it is more likely that the important figure is the TSS in excess of 60mg/L in mid February. Once the capacity of coral to clear sediments is overwhelmed, further sediment will add to the depth of the layer.

Elsewhere corals have been shown to tolerate a variety of acute sediment loads – Larcombe et al (2001) show coral reefs at Magnetic Island often experience suspended sediment concentrations above 20mg/L for over 24hrs, but rarely over 40mg/L for that period.

At the HOLD and DPAN sites adjacent to the SUPB mortality turbidity was frequently high for extended periods and prevented observations many weeks. However, once visibility improved at these sites, there was no observable mortality or other visible effects of that high turbidity.

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