Technical Appendix S9

Ichthys Gas Field Development Project: summary of the long-term water-quality program for Darwin Harbour

Report

Ichthys Gas Field Development Project

Summary of the Long-Term Water-Quality Program for Darwin Harbour

28 MARCH 2011

Prepared for

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42907349 : R1589

INPEX Document No. C036-AH-REP-0118 Rev 0

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Date:	**28 March 2011**
Reference:	42907349 : R1589 / M&C3461 /0
Status:	Final

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Abbreviations

Abbreviation	Description
BOM	Bureau of Meteorology
CI	Channel Island
Cwlth	Commonwealth
DO	Dissolved Oxygen
DSDMP	Dredging and Dredge Spoil Disposal Management Plan
EAF	East Arm Sediment Sample Site
EIS	Environmental Impact Statement
INPEX	INPEX Browse Ltd
LAT	Lowest Astronomical Tide
LNG	Liquefied Natural Gas
MAF	Middle Arm Sediment Sample Site
Max	Maximum Values
Min	Minimum Values
n	Number of data-points
NATA	National Association of Testing Authorities
NEW	North East Wickham Point
NT	Northern Territory
NTU	Nephelometric Turbidity Units
SD	Standard Deviation of a range of values
SSC	Suspended Sediment Concentration
SSI	South Shell Island
URS	URS Australia Pty, Ltd
WR	Weed Reef

Introduction

1.1 Background

INPEX Browse, Ltd (INPEX) is presently seeking environmental approval to construct and operate a Liquefied Natural Gas (LNG) plant at Blaydin Point within Darwin Harbour, Northern Territory. Dredging activities will be required to create a shipping channel and turning basin, berthing pockets at the product loading jetty, and an approach apron and berthing pocket at the module offloading facility in East Arm. Trenching will be required along the pipeline route through Darwin Harbour and at the pipeline shore crossing on Middle Arm Peninsula. A dredge spoil disposal ground is proposed to be at a site offshore from Darwin Harbour.

A Draft Environmental Impact Statement (EIS) was prepared for the Northern Territory Government under the *Environmental Assessment Act 1994* (NT) and for the Commonwealth Government under the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth). Within this document a provisional Dredging and Dredge Spoil Disposal Management Plan (DSDMP) outlines the coral monitoring activities that will be undertaken throughout the Project construction phase. A proposed reactive coral monitoring program requires the collection of baseline data for water quality parameters at the coral communities of Channel Island and Weed Reef for 12 months prior to the commencement of dredging activities. INPEX has retained URS Australia (URS) to provide environmental consulting services in relation to the above mentioned collection of baseline water quality data.

1.2 Darwin Harbour: Physical and Biological Characteristics

Darwin Harbour is one of Australia's largest deep water ports, located at latitude 12° 28' S and longitude 130°50'E. The Harbour is an estuarine system where the water from the Timor Sea mixes with runoff from the northern Australian land surfaces (Wilson et al. 2004). Darwin Harbour experiences a monsoonal climate with a distinct Wet Season when river flows reach their maximum volumes, compared with little to no rainfall in the Dry Season. The Harbour is macrotidal with a maximum tidal range of 7.8 m (5.5 m mean spring range and 1.9 m mean neap range). Despite strong currents of up to 2 m per second, the Harbour, in parts, remains poorly flushed (Byrne 1988). The waters are naturally turbid and standing stocks of nutrients are low (Padovan 1997).

Darwin Harbour is composed of three main arms: the larger East and Middle Arms (that extend for 20 km inland), and the smaller West Arm. Several rivers flow into the Harbour, with the largest being the Blackmore into Middle Arm, and the Elizabeth River into East Arm. Collectively these rivers drain half of the catchment area of the Harbour (Williams & Wolanski 2003). Water depth in the main channel at the mouth of the Harbour ranges from 20 – 30 m, with this decreasing to 5 – 10 m in the arms of the Harbour.

The prominent feature of the coastal and marine habitats of Darwin Harbour is the expansive mudflats backed by mangroves which contain considerable biodiversity (Hanley 1988). It is estimated that hard substrates cover less than 20% of the intertidal and subtidal area of Darwin Harbour. These hard substrates display a distinct zonation of flora and fauna composition, caused by the combined effect of physical, biological and environmental parameters (McKinnon et al. 2005). On the lower intertidal/subtidal interface, rock substrate can be covered with hard and soft corals, sponges, crustaceans, anemones and many species of macroalgae.

1.3 Objective

The primary objective of the long-term water-quality program was to determine baseline turbidity levels at four coral communities within Darwin Harbour. Additional baseline water quality parameters (temperature, conductivity, pH and dissolved oxygen [DO]) were also measured during the long-term water quality program; these can influence coral health but are unlikely to change significantly as a result of dredging. Monitoring baseline turbidity levels will enable the development of trigger levels to guide management decisions and mitigation responses to reduce the risk of impacts upon coral communities during the dredging program. This report provides a summary of the baseline water quality results.

Methods

2.1 Monitoring Sites

Water quality monitoring sites were located at known coral communities within close proximity to the Blaydin Point onshore development area in East Arm (South Shell Island and North East Wickham Point), and the pipeline shore crossing location in Middle Arm (Channel Island). Weed Reef was selected to provide a reference site for Channel Island during construction phase monitoring, as described in the DSDMP. At each site, the logger was placed as near as practicable to the coral community (without having the potential to physically impact upon it), and at a depth close to that at which the highest coral cover occurred (typically around 2-5 m below Lowest Astronomical Tide [LAT]). A geographic reference is provided for the monitoring locations in Table 2-1 and site positions within Darwin Harbour are displayed in Figure 2-1.

Table 2-1 Monitoring sites for long-term water quality program

Location	Site Identification	Latitude Deg. Min	Longitude Deg. Min
Channel Island	CI	12º 32.920' S	130 º 52.432' E
Weed Reef	WR	12º 29.260' S	130 º 48.046' E
North East Wickham Point	NEW	12º 30.090' S	130 º 52.456' E
South Shell Island	SSI	12º 29.851' S	130 º 53.160' E

- Note: Coordinate system WGS 84, grid zone 52

2.2 Field Techniques

2.2.1 Water Quality Monitoring

Sites were typically visited every two weeks during neap tides between 30 January 2010 and 29 January 2011 for a total of 25 surveys. For each survey all four loggers were retrieved and maintained which included:

- Removal of fouling
- Replacing sensors as required
- Replacing wiper brushes
- Battery replacement if required
- Replacing antifouling bronze tape.

During each survey, data were uploaded, the sensors calibrated and logging restarted using the YSI data analysis software "Ecowatch" (for series 6 sondes) before deployment. Calibration was conducted in accordance with the YSI 6 series Environmental Monitoring Systems Operations Manual using National Association of Testing Authorities (NATA) approved reagents and standards. Loggers were swapped out with backup units as required.

At all four sites, near-bottom water quality records of temperature, conductivity, depth, pH, DO and turbidity were obtained at 15 minute intervals using YSI 6600EDS multiparameter loggers (refer to Appendix A for logger specifications). These water quality loggers were attached in a vertical orientation to weighted frames, which positioned the sensors approximately 60 cm above the seabed (Figure 2-2).

Figure 2-1 Locations of water quality monitoring sites

2 Methods

Figure 2-2 Frames used to secure the water quality loggers (with logger in place)

In the initial seven surveys (up to 30 April 2010), acoustic release and rope canister systems were used to retrieve frames and loggers, although difficulties arose using this method due to the considerable tidal range and water currents experienced in Darwin Harbour. From Survey 8 (30 April 2010) onwards, divers were employed to recover the water quality loggers. Weights, anchors and 10 m cardinal lines were attached to all four frames. Two of the four lines had small floats attached at each end (around 100 mm off the seabed) to assist in locating the frames. The other two of the four cardinal lines consisted of 10 m x 12 mm anchor chain with anchors securing the two ends. These anchors and chains assisted the diver to locate the frame and also, when laid in the direction of the prevailing currents, stopped the frame being moved by tidal currents.

2.2.2 Turbidity / Suspended Sediment Concentration Correlation

Sediment dispersion modelling, undertaken to support dredging activity impact assessment, typically produces outputs in Suspended Sediment Concentration (SSC). To convert Nepholmetric Turbidity Unit (NTU) data into SSCs, site specific relationships are required. Investigations of the correlations between SSC and NTU were therefore undertaken using two approaches:

- Filtered water samples collected from sites during the long-term water-quality program fortnightly surveys between January 2010 and January 2011. SSC within each sample was determined, using gravimetric analysis, by the Marine and Freshwater Research Laboratories at Murdoch University in Perth.
- Surface sediment samples collected between 29-30 November 2010 from locations in East Arm and Middle Arm. These were sent to the Microanalysis Australia laboratory in Perth for determination of NTU and SSC values. The <75 µm material was extracted from the sediment

samples using decantation techniques and reconstituted into specific volumes of water. Through serial dilutions, sequences of SSC and NTU values were developed.

2.3 Analysis

Water quality parameters in Darwin Harbour are influenced by Wet Season rains and Middle and East Arm water quality parameters, in particular, are influenced by the flow of fresh water from the Elizabeth and Blackmore Rivers (Padovan 1997, Padovan 2002, Munksgaard & Parry 2003, Padovan 2003, Duggan 2006, McKinnon et al. 2006). Rainfall data for the survey period, as presented on the Bureau of Meteorology (BOM) web site (Darwin Airport weather station), is included in this report to support the interpretation of the water quality results (see Section 3-1).

For each site and survey, temperature (°C), conductivity (mS/cm), depth (m), pH, DO (%) and turbidity (NTU) were recorded by sensors which were calibrated on both deployment and retrieval using the YSI data analysis Software "Ecowatch" (for series 6 sondes). If there were changes in calibration values over the deployment period, the differences were used to adjust the raw data prior to analysis. Instrument malfunction, excessive biofouling and operator error occurred on several occasions over the sampling program, resulting in either missing, erroneous or anomalous data. Data were carefully reviewed and only reliable data were included in the working dataset. If a negative value remained for turbidity following calibration and no anomalies were detected in the data, the lowest reading for the period was set to zero and the data were adjusted to suit. The difference between each 15 min sampling interval was then calculated and graphed to identify and remove outliers. Finally, data were smoothed using a two-hour simple moving average.

Differences in some water quality parameters (including turbidity) between neap and spring tides have been extensively reported in previous monitoring programs (including Padovan 1997, Padovan 2002, Munksgaard & Parry 2003, Padovan 2003, Duggan 2006 and McKinnon et al. 2006). To allow for assessment of water quality variation with tidal cycle, the data were grouped into distinct spring and neap tide periods, using the median daily tidal range for the survey period (5 m) as the demarcation depth:

- Neap Tide: if the tidal range was ≤ 5 m
- Spring Tide: if the tidal range was >5 m

Using this approach, 180 days were classified as spring tides compared to 185 days for neap tides. Spring and neap tide phases were between six and nine days in duration, with an average of seven days. The division of data into spring and neap tides revealed significant differences in turbidity ranges and regimes; these differences were attributed to significant variation in tidal current speeds and associated resuspension of sediment.

Based on historical rainfall data from the past 70 years (BOM 2011), water quality data were also divided into Wet Season data and Dry Season data. For the purposes of this analysis, these seasons were defined as:

- Wet Season: November to April inclusive.
- Dry Season: May to October inclusive.

Using this approach, each season represents six months of the year and the Wet Season covers the time of year when most of the average annual precipitation typically falls in the region.

Results and Discussion

3.1 Rainfall During the Survey Period

The yearly total of rainfall from February 2010 to January 2011 was 2,232 mm (Table 3-1), which was above the long-term annual rainfall data (70 year) average of 1714 mm (BOM 2011). Eighty-eight percent of rainfall fell within the Wet Season, with 64% falling between the months of December and February. The highest rainfall typically occurs between January and March (64%), with 97% falling between October and April and negligible amounts between May and September (BOM 2011).

In the 2010 Dry Season, little rainfall was recorded between June and August (inclusive), though rainfall from the preceding Wet Season persisted into May and the 2010/11 Wet Season rains arrived earlier than usual (in September). This resulted in the second highest Dry Season rainfall total (264 mm) on record for Darwin (BOM 2011).

Table 3-1 Monthly rainfall data (Darwin Airport weather station) during survey period (February 2010 to January 2011)

Month	Season	Rainfall (mm)
February 2010	Wet	428.8
March	Wet	198.4
April	Wet	136.6
May	Dry	66.2
June	Dry	0
July	Dry	0.2
August	Dry	0
September	Dry	40.4
October	Dry	157.8
November	Wet	208.2
December	Wet	390.4
January 2011	Wet	605.6
Annual Total		**2232.6**

Source: BOM (2011)

3.2 Water Quality Monitoring Parameters

Summary statistics for each of the parameters monitored during the water-quality program are presented in Table 3-2. These comprise the means, minima (Min), maxima (Max), standard deviations (SD) and numbers of data points (n). They are presented by parameter, by site and by season.

A high percentage of data capture was achieved throughout the monitoring program and the turbidity dataset is considered adequately comprehensive for use as a baseline to develop monitoring criteria. Potential limitations in the quality of the logged data were mitigated through examination of the datasets and subsequent removal of data points that were considered to potentially be erroneous, typically due to instrument sensor drift, wiper failure or excessive biofouling.

In addition, occasional operator error and instrument malfunction caused some data loss over extended periods, resulting in incomplete datasets for certain parameters at some sites:

- June neap tide temperature and turbidity data, and spring tide conductivity data, from Channel Island

3 Results and Discussion

- All April data from Weed Reef
- February depth data (all), March neap tide turbidity data, and June neap tide temperature, depth and turbidity data from South Shell Island.

Table 3-2 Summary statistics for parameters monitored during water-quality program in Darwin Harbour

		Wet					Dry				
	Site	Mean	Min	Max	SD	n	Mean	Min	Max	SD	n
Temperature (°C)	CI	30.5	28.3	32	0.8	16962	28.1	25	31.5	1.9	12699
	WR	30.4	28.2	31.9	0.9	11836	28.2	25.3	31.3	1.7	15128
	NEW	30.5	28.1	32.2	0.8	17178	28	25.1	31.5	1.8	17410
	SSI	30.4	28.1	32	0.9	13261	28.1	25.3	32.1	2	9686
Conductivity (mS/cm)	CI	44.7	36.3	51	3.2	17251	48.6	43.1	52.8	1.9	12699
	WR	49.1	41.7	56.1	3.5	11836	47.2	35.6	55.5	3.1	15128
	NEW	46.9	37.5	52.8	2.8	17178	47.3	32.5	52.3	3.3	16074
	SSI	46.2	36.7	49.8	2.3	14593	48.7	40.2	52.9	2.6	12667
Depth (m)	CI	8	3.5	11.6	1.6	15532	8	4.2	11.5	1.5	12565
	WR	9.1	4.9	13.2	1.6	11836	8.8	5.1	12.4	1.5	15128
	NEW	7	3	10.7	1.6	17162	6.6	2.9	10.2	1.5	17410
	SSI	6.7	2.5	11.3	1.6	11521	6.3	2.4	11	1.6	12771
pH	CI	8	7.6	8.2	0.1	17067	8	7.9	8.1	0	12699
	WR	7.9	7.6	8	0.1	11835	7.9	7.8	8.1	0.1	13788
	NEW	8	7.8	8.2	0.1	15835	8	7.8	8.1	0.1	17410
	SSI	8	7.6	8.2	0.1	14592	8	7.7	8.5	0.1	12692
DO (%)	CI	88.7	72.3	104.1	3.9	17068	91.7	79.1	105.2	3.9	12699
	WR	94.5	79	115.2	7.4	11648	94.7	86.3	105.5	2.7	13788
	NEW	91.1	62.3	108.2	4.6	17178	93.9	82.6	104.6	3.1	17410
	SSI	88.5	67.3	106.4	5.1	14593	93.5	73.4	121.1	4.5	11653
Turbidity (NTU)	CI	10.2	0.2	113	14.6	16384	5.8	0.1	50.2	6.8	12686
	WR	15.6	0.1	145.2	21.4	11835	4.1	0.1	28.9	4.1	14040
	NEW	9.8	0.1	89.5	12.4	17177	3.9	0	31	4.1	17410
	SSI	8.3	0.2	68	9.7	11569	4.4	0.1	46.4	4.7	11995

(Refer to Table 2-1 for site codes; refer to text for statistics abbreviations)

3 Results and Discussion

3.2.1 Temperature

Temperature data (monthly medians and 95th percentiles) for the Channel Island and Weed Reef sites are presented in Figure 3-1, and for North East Wickham Point and South Shell Island in Figure 3-2. Temperatures recorded across all sites in Darwin Harbour during the survey period ranged between 25℃ and 32℃. Differences in monthly median temperatures between sites, and between neap and spring tides at each site, were typically <1℃ (Figure 3-1 and Figure 3-2). However, values did vary seasonally, with Dry Season mean temperatures (~28℃) slightly less than those in the Wet (~30.5℃) (Table 3-2). Consistent with findings in this survey, Padovan (2003) found lowest water temperatures occurred in Darwin Harbour during June-July, though previous data suggest water temperatures can drop further (to ~23℃). The 2010 Dry Season in Darwin had the second warmest ambient mean air temperatures on record from June to August, which may have contributed to the above-average water temperatures.

In a typical year, highest water temperatures of ~33℃ are generally recorded in October-November (Padovan 2003). In 2010, maximum water temperatures remained below 33℃ (with a median of ~31℃) in October-November, probably as a result of atypically high rainfall and associated cloud cover in these months. Relatively warm ocean temperatures around Northern Australia, warm ambient mean air temperatures and a rapidly developing La Nina during the 2009/10 Wet Season (BOM 2011) may have contributed to the persistence of elevated water temperatures through the remainder of the Wet Season; a period within which water temperatures typically decline due to cloud cover and monsoonal activities (Padovan 2003). In 2010, temperatures did not decline until June, when the monthly median temperatures at all sites dropped rapidly by ~3-4℃ (Figure 3-1 and Figure 3-2). Warm ocean waters that persisted throughout 2010 cooled in early 2011 (BOM 2011) and survey data from December 2010 to January 2011 (Figure 3-1 and Figure 3-2) indicate a return to typical water temperature trends.

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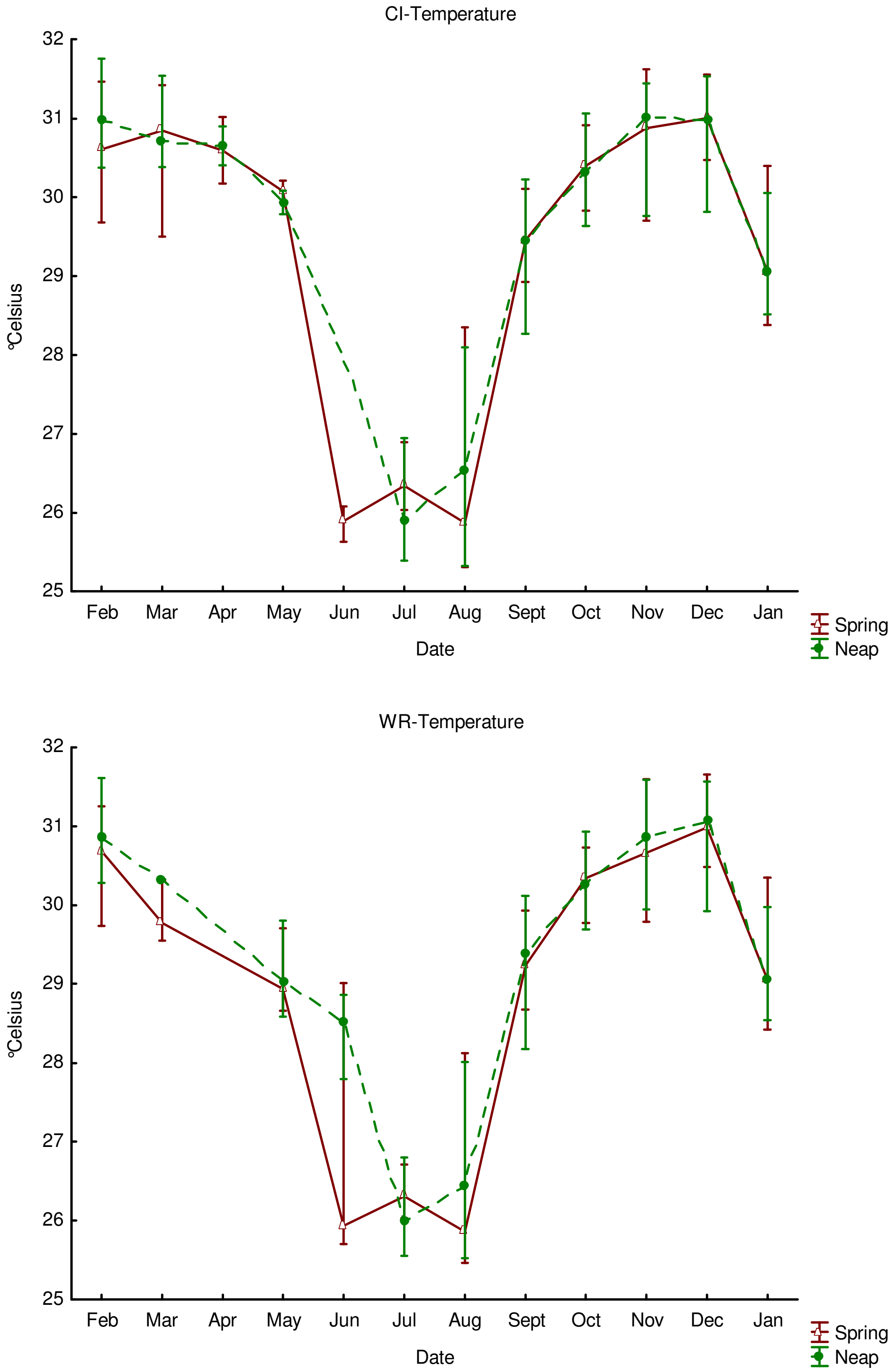

Figure 3-1 Monthly spring and neap tide temperatures from February 2010 to January 2011 at Channel Island (CI) and Weed Reef (WR) (median with 5th and 95th percentile error bars)

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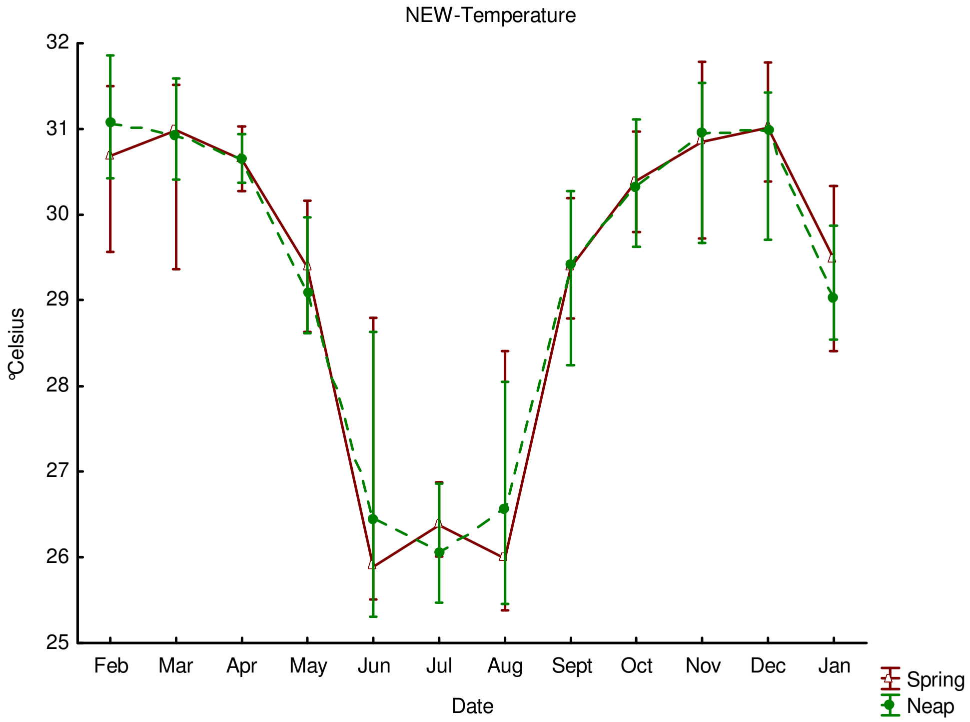

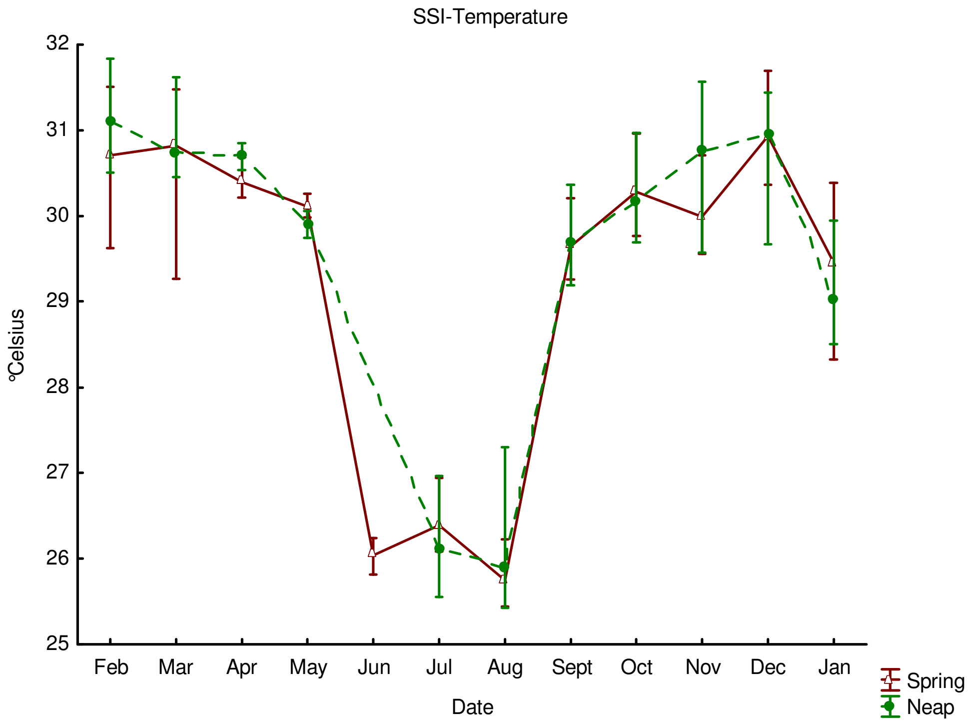

Figure 3-2 Monthly spring and neap tide temperatures from February 2010 to January 2011 at North East Wickham Point (NEW) and South Shell Island (SSI) (median with 5th and 95th percentile error bars)

3.2.2 Conductivity

Conductivity values across all sites ranged from 32.5 mS/cm to 56.1 mS/cm (Table 3-2). Seasonal mean conductivity values for the Wet Season varied from 44.7 mS/cm to 49.1 mS/cm (Table 3-2). Dry Season values were less variable, with monthly mean values between 47.2 mS/cm and 48.7 mS/cm (Table 3-2). Greater variability in conductivity levels, and greater differences between seasons, were recorded in a Darwin Harbour study in 2001/02, when mean levels varied from 44 mS/cm in the Wet Season to 55 mS/cm in the Dry Season (Padovan 2002).

Conductivity varies according to the extent of rainfall and riverflow within the Harbour (McKinnon et al. 2006). The transformation of the Harbour from a relatively homogenous embayment of oceanic water during the Dry Season into an estuary during the Wet Season (as described by McKinnon et al. 2006) is reflected in the Channel Island data (Figure 3-3). Highest conductivity values at Channel Island were recorded during September/October, when values were typically between 48-50 mS/cm. The lowest conductivity was measured in the period January/March (42-44 mS/cm), coinciding with rainfall and freshwater run-off into the Harbour. Darwin also experienced its second wettest Dry Season on record in 2010 (Section 3.1), resulting in generally lower conductivity values than recorded during the Dry Season in previous studies (e.g. Padovan 2002). It should be noted that data were recorded near the seafloor in the present study, hence the typically fresher surface waters were not measured and conductivity and salinity levels would likely have been even lower during the Wet season if mean values through the whole depth profile had been determined (as they were by Padovan [2002]).

Within the tidal cycle, few differences in the ranges of conductivity values were recorded between spring tides and neap tides across all sites (Figure 3-3 and Figure 3-4). From September 2010, at the beginning of the Wet Season rainfall events, the changes in conductivity with tidal phase became more variable, likely due to tidal mixing of oceanic water with freshwater. The influence of increasing rainfall and freshwater in the following months mixed the brackish water and resulted in generally lower and less variable conductivity values between tides, across all sites, by January 2011. However, conductivity values were identified to drift throughout deployment periods, probably due to sensor degradation or excessive biofouling. Evaluating differences identified between tides may have been confounded by the failure to identify and remove erroneous data.

At Weed Reef, which is located further into the main body of the Harbour, conductivity values tended to be slightly higher and more uniform than at other sites (Figure 3-3). Channel Island, North East Wickham Point and South Shell Island are located closer to the rivers that flow into Darwin Harbour, such as the Blackmore and Elizabeth Rivers that flow into the Middle and East Arms respectively. These results concur with previous findings that the degree to which conductivity is reduced, from rainfall and freshwater run-off during the Wet Season, is a function of location within the Harbour (Padovan 2003; Duggan 2006; McKinnon et al. 2006).

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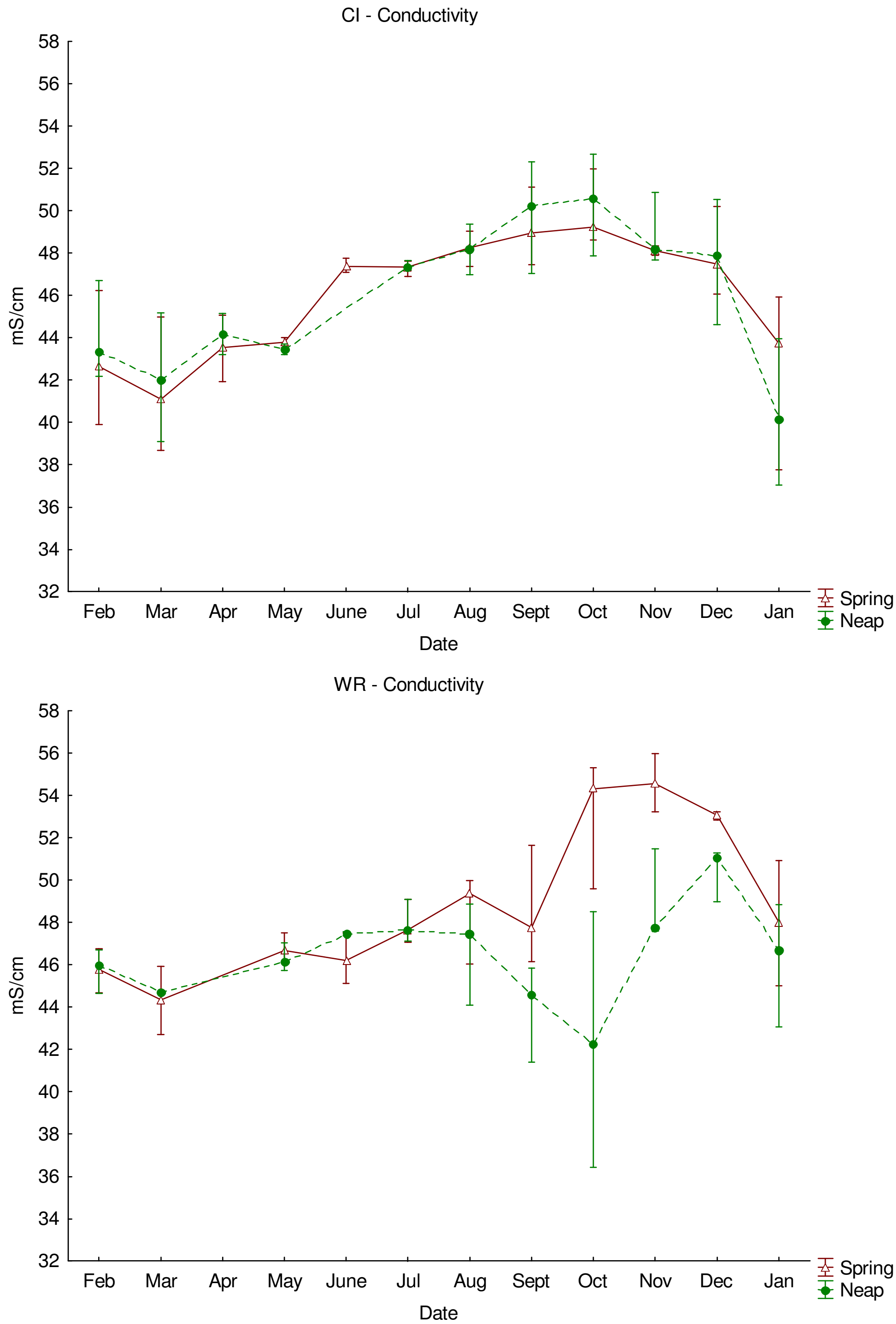

Figure 3-3 Monthly spring and neap tide conductivity from February 2010 to January 2011 at Channel Island (CI) and Weed Reef (WR) (median with 5th and 95th percentile error bars)

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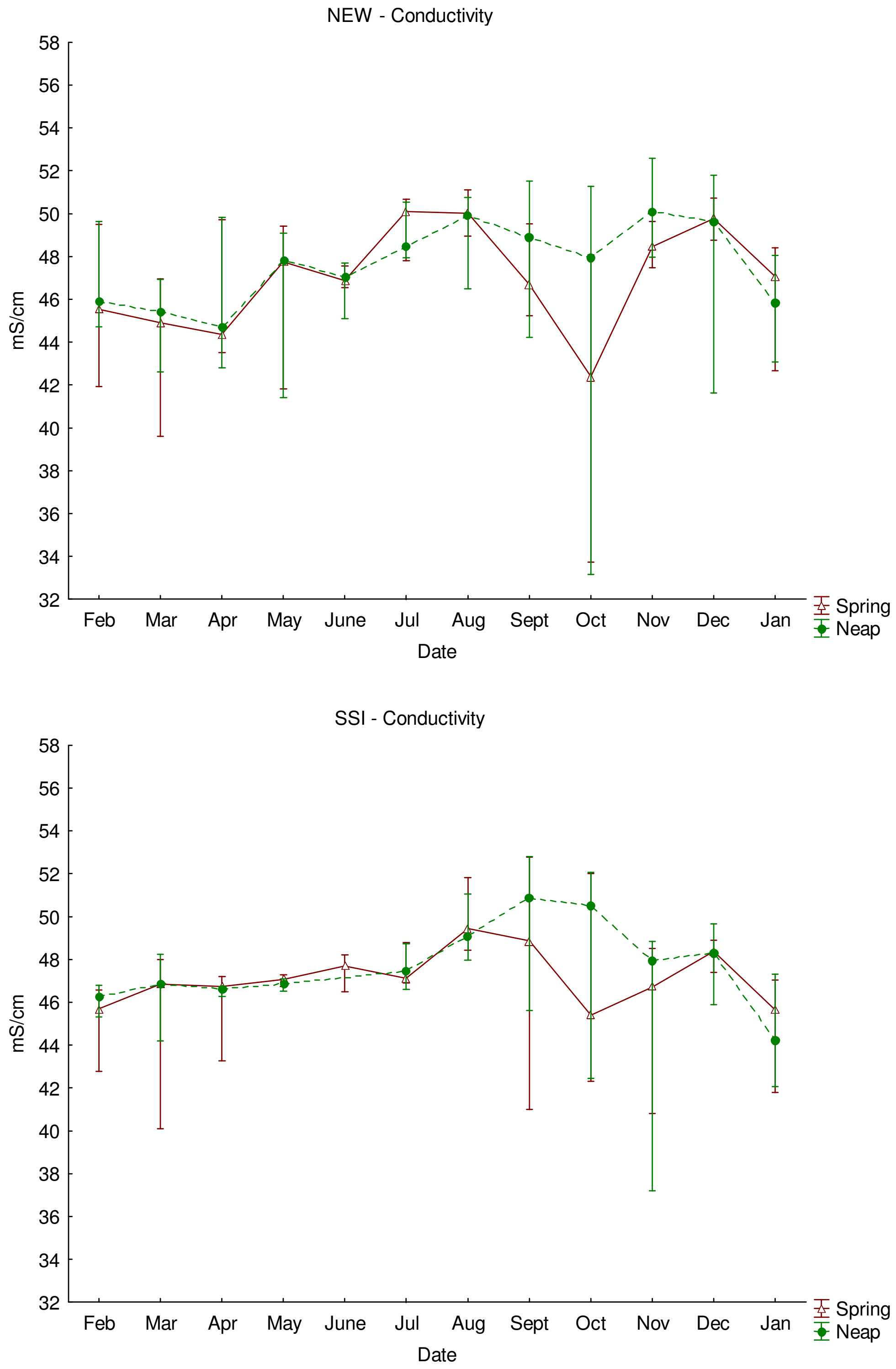

Figure 3-4 Monthly spring and neap tide conductivity from February 2010 to January 2011 at North East Wickham Point (NEW) and South Shell Island (SSI) (median with 5th and 95th percentile error bars)

3 Results and Discussion

3.2.3 Depth

The mean water depth (as measured by logger, not corrected to LAT) was marginally greater at the Weed Reef site (8.9 m) than at the Channel Island site (8.0 m). The North East Wickham Point and South Shell Island sites were shallower (mean depths of 6.8 m and 6.5 m respectively, Table 3-2).

The maximum tidal range of 7.6 m predicted for the survey period (using Seafarer software) was slightly less than the 7.8 m maximum published tidal range (Smit 2003). Using the median daily tidal range for the survey period (5 m) to discern spring tides from neap tides (as described in Section 2-3) resulted in mean tidal ranges of 6.1 m for spring tides and 3.6 m for neap tides. Comparably, Smit (2003) calculated means of 5.5 m during spring tides and 1.9 m during neap tides.

The differences in depth recorded by the loggers varied between sites from 7.2 m (Weed Reef) to 8.8 m (South Shell Island) in spring tides and 5.2 m (Weed Reef) to 6.5 m (South Shell Island) during neap tides (Figure 3-5 and Figure 3-6). Depth ranges were generally higher during the Wet than the Dry Season. However, differences in depth ranges are likely to have been influenced by the changes in deployment methods over the survey period, possible movement of the frames on which the loggers were moored due to tidal currents, or from the analysis of the monthly tidal phase with missing data. Between February and May, the frames were recovered using acoustic buoys on each maintenance occasion. As the frames were not redeployed in exactly the same position, recorded depths at some sites before May were more variable than post-May, when the frames were secured to the seafloor and the loggers were retrieved by divers (Figure 3-5 and Figure 3-6). If either erroneous data were deleted or operator error resulted in missing data, the analysis of monthly depth data were not taken from an equal number of data points, and therefore some bias may exist in the results. This was observed in data presented for June spring tides at South Shell Island, where maximum depths were less than those in following months (Figure 3-6).

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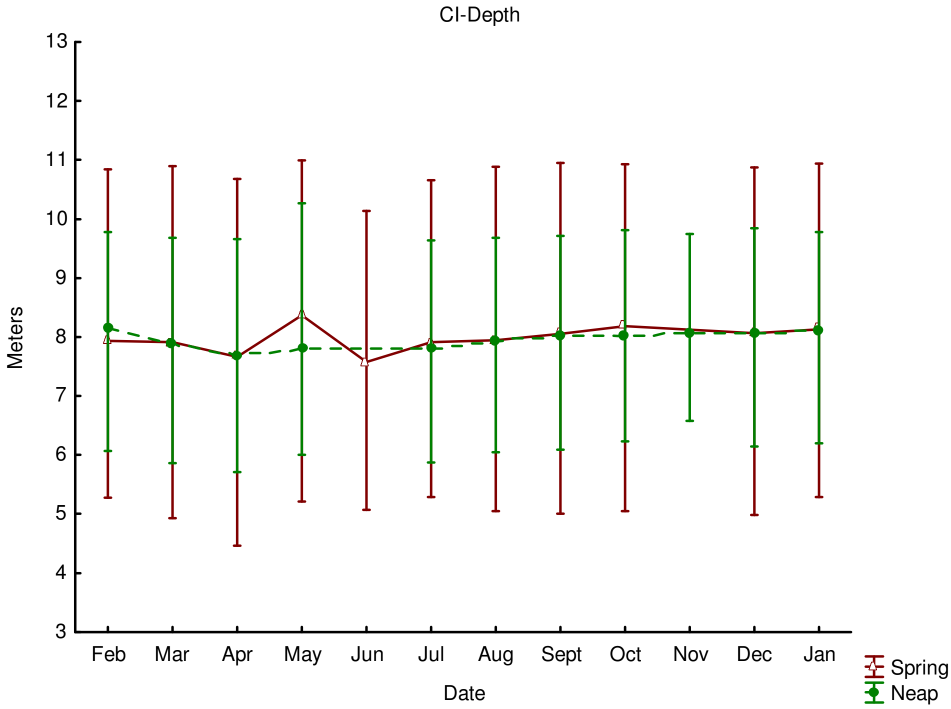


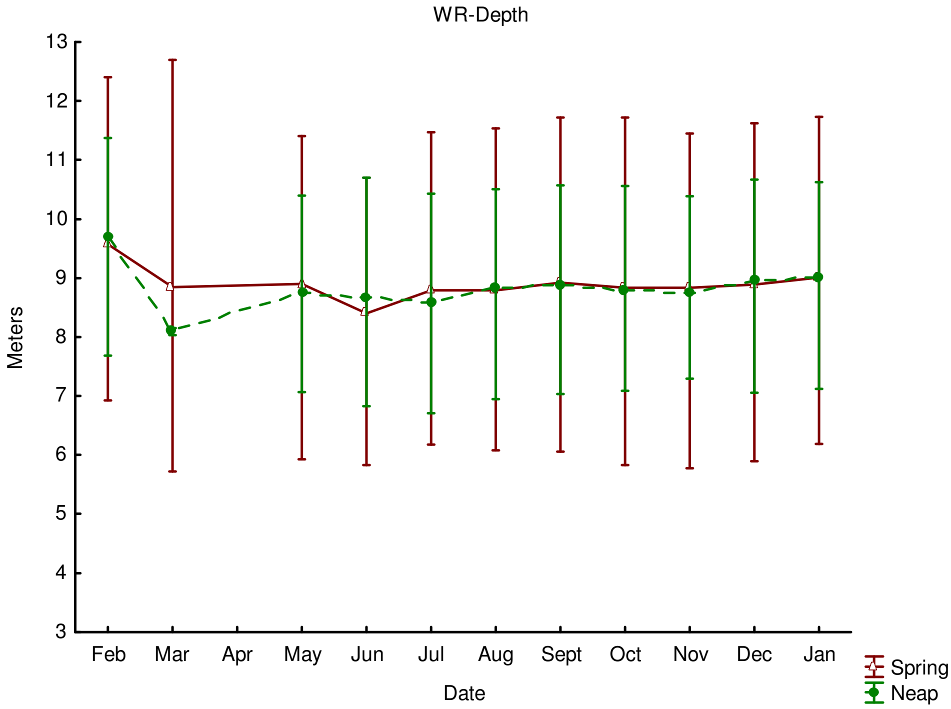
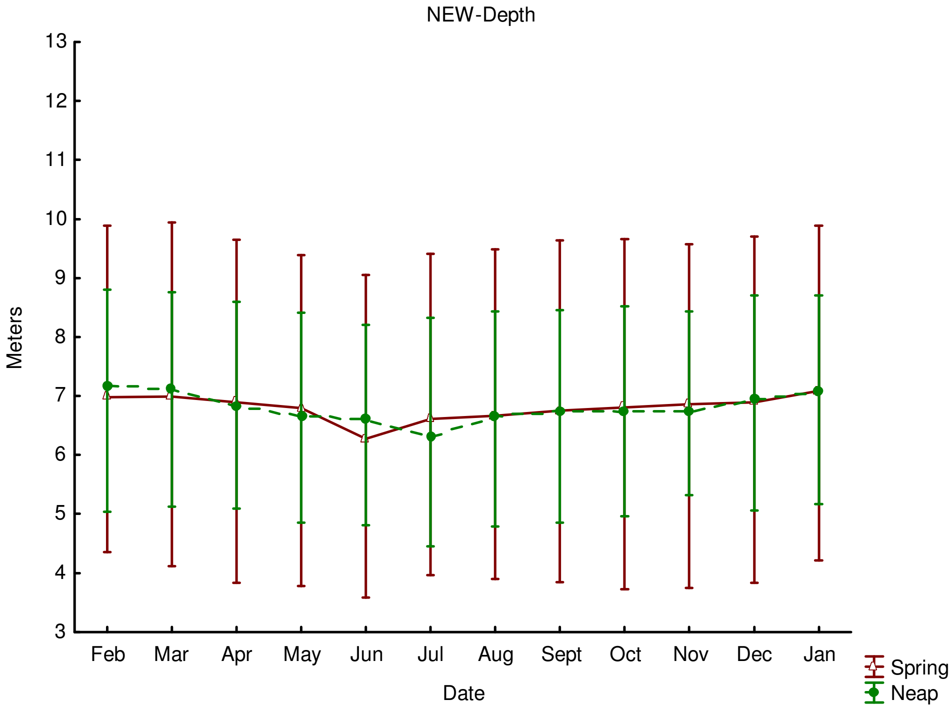


Figure 3-5 Monthly spring and neap tide depths from February 2010 to January 2011 at Channel Island (CI) and Weed Reef (WR) (median with 5th and 95th percentile error bars)

3 Results and Discussion



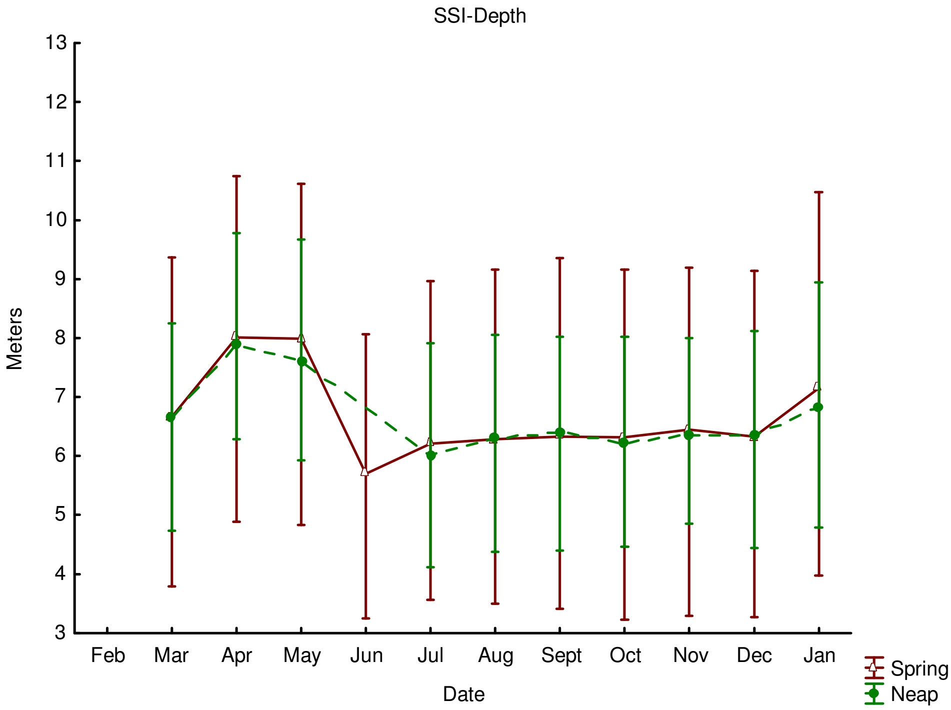


Figure 3-6 Monthly spring and neap depths February 2010 to January 2011 at North East Wickham Point (NEW) and South Shell Island (SSI) (median with 5th and 95th percentile error bars)

3.2.4 pH

The mean pH levels in this monitoring program (7.9 at Weed Reef, 8.0 at the other three sites) are lower by 0.5 units than means recorded by Padovan (1997), although other studies (e.g. Padovan 2002, Wilson et al 2004, Butler & Padovan 2005) have shown that waters in the upper reaches of the Harbour are slightly more acidic, with lower pH values that are closer to the means calculated in this program. Differences in pH levels between monitoring programs may be attributable to freshwater input from rivers (there was atypically high rainfall in the 2010 Dry Season and at the beginning of the 2010/2011 Wet Season, see Section 3-1), natural inter-annual variability, differences in instrumentation or the depth at which the readings were recorded (i.e. near bottom versus depth averaged through the water column).

Over the course of this monitoring program, there was little seasonal or tidal variation in pH levels at any of the sites, and only small differences in pH levels between the four sites (Figure 3-7 and Figure 3-8). The absence of seasonal, tidal and spatial variations in pH is consistent with previous surveys in Darwin Harbour (e.g. Padovan 2003, McKinnon et al. 2006). Slightly lower pH values observed in November 2010 followed rainfall events in September and October; a contributing factor to the decrease in pH may have been the inflow of water from mangrove habitats, within which are processes that can lead to slight acidification of waters passing through them (Padovan 2003).

Differences in calibration standards over time may have contributed to some of the variability in pH values. Given the narrow range of pH values throughout the program, small differences in pH levels due to calibration variability can be very apparent when presented graphically (as in Figure 3-7 and Figure 3-8). Also, excessive biofouling or instrument malfunction may have contributed to difficulty in the interpretation of data captured over certain periods. For example, nine days of data were deleted from spring tides and six days of data were deleted from neap tides at North East Wickham Point in January due to an obvious ‘drift’ in pH values, probably due to excessive biofouling. Therefore, bias may exist in the limited remaining dataset for North East Wickham Point in January 2011. However, it should be recognised that many of the variations are likely to be within the range of precision of the sensors, and also that such small differences in pH are highly unlikely to have any influence on the Harbour ecosystem.

3 Results and Discussion

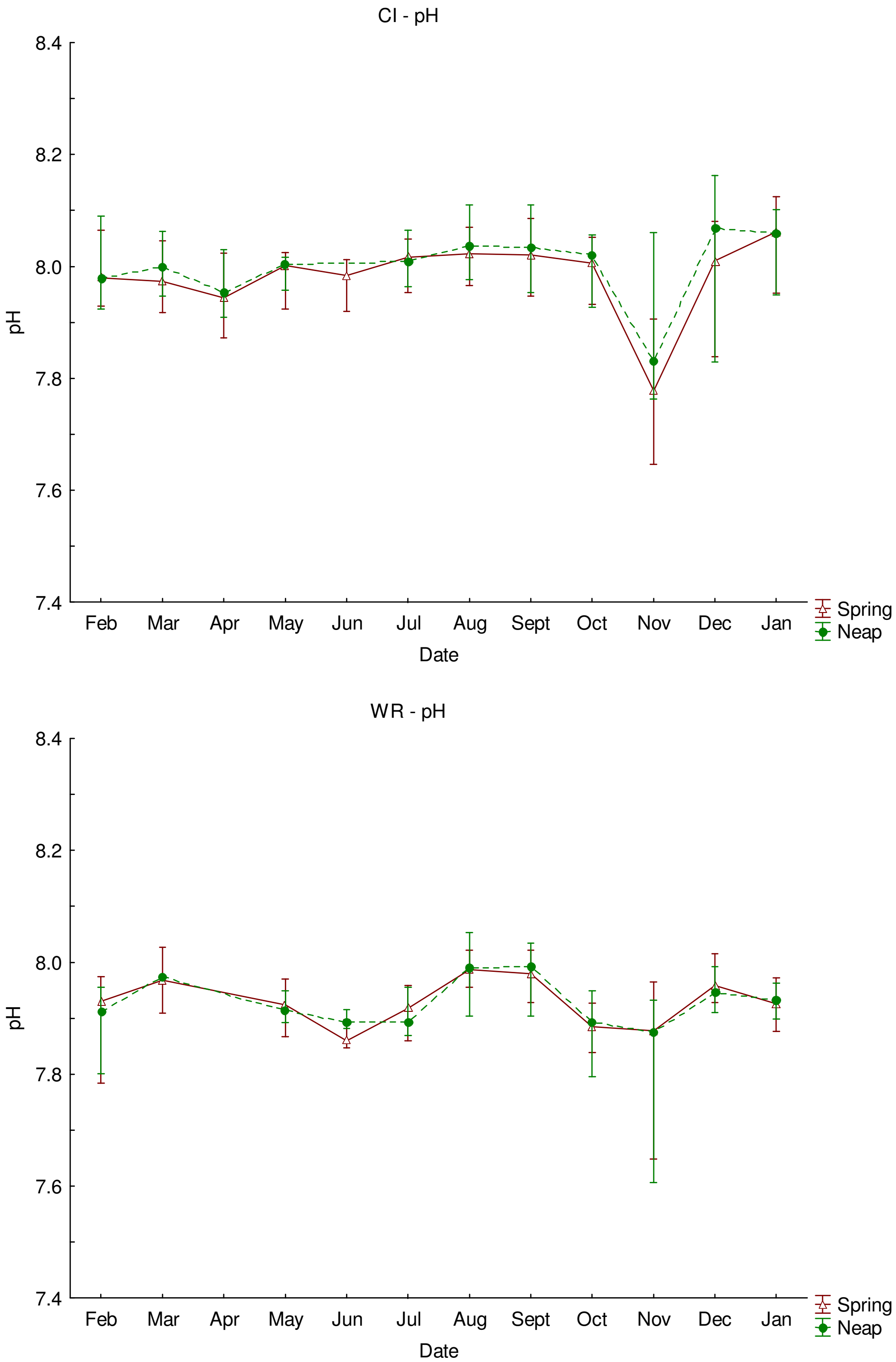


Figure 3-7 Monthly spring and neap tide pH levels from February 2010 to January 2011 at Channel Island and Weed Reef (median with 5th and 95th percentile error bars)

3 Results and Discussion

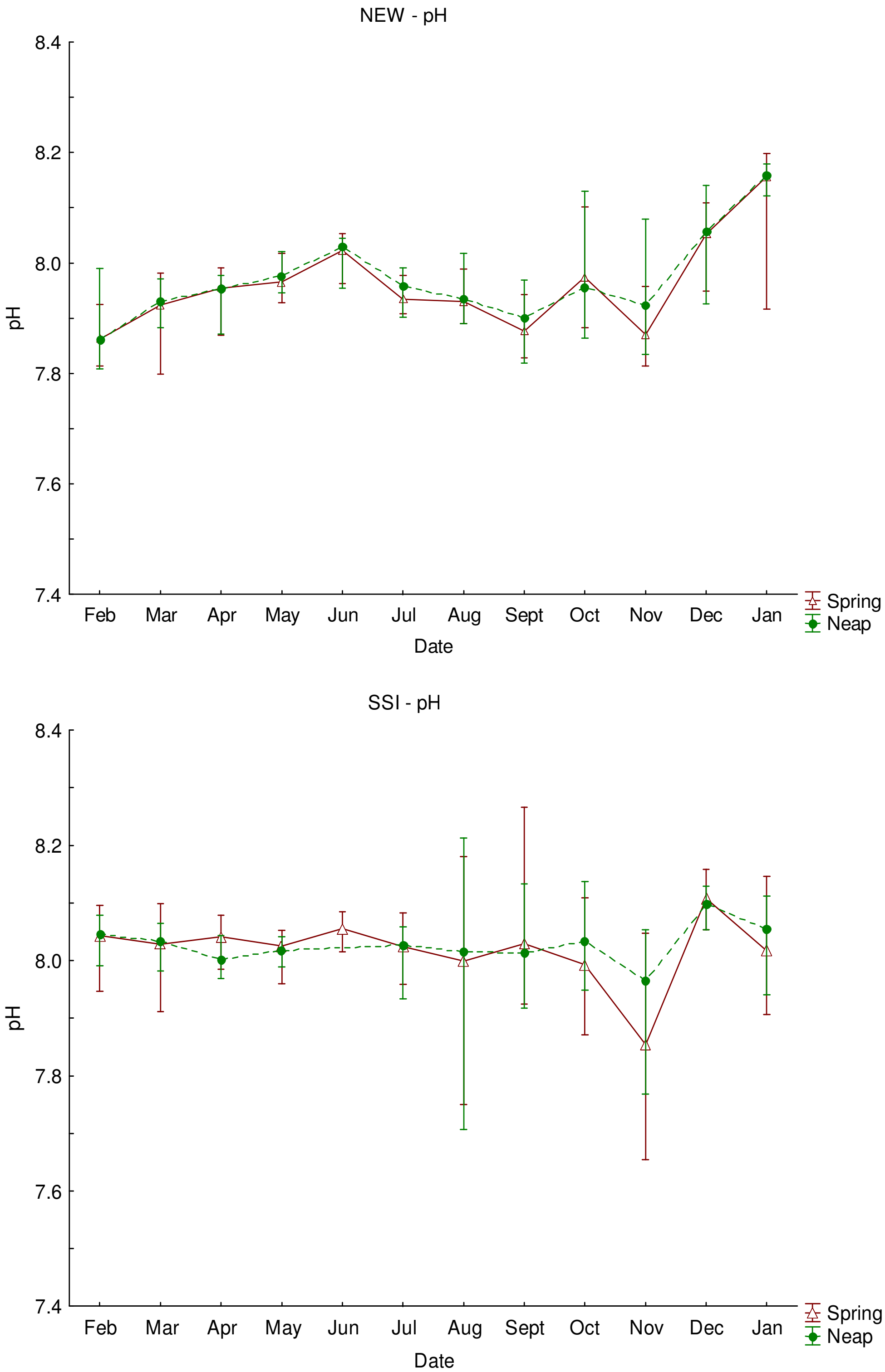


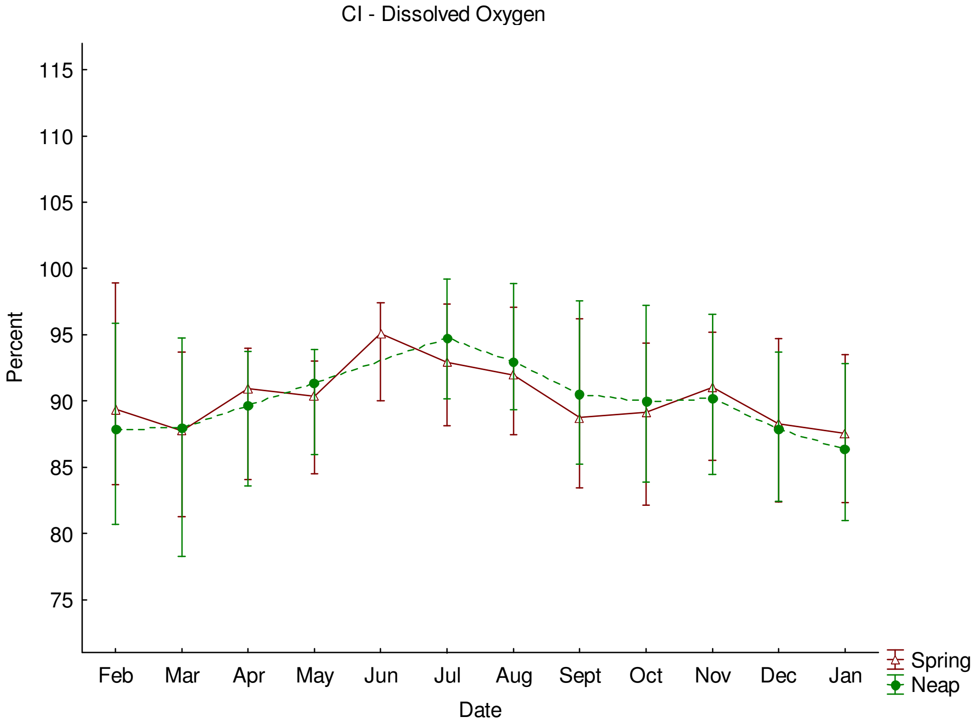
Figure 3-8 Monthly spring and neap tide pH levels from February 2010 to January 2011 at North East Wickham Point and South Shell Island (median with 5th and 95th percentile error bars)

3.2.5 Dissolved Oxygen

Mean DO saturation levels in this monitoring program ranged from 88.5% (South Shell Island) to 94.7% (Weed Reef) (Table 3-2) corresponding with findings from previous studies, in which Darwin Harbour is described as well oxygenated, with typically above 85% saturation (Padovan 2003). Of the four sites, DO saturation was typically highest at Weed Reef (Table 3-2, Figure 3-9 and Figure 3-10).

Minor differences in DO level were detected at all sites between seasons, with slightly higher means recorded during the Dry Season (Table 3-2), corresponding with findings from McKinnon et al. (2006). However, no distinct seasonal patterns in DO are apparent (Figure 3-9 and Figure 3-10). Similarly there are no consistent differences between spring and neap tides. The percentage of DO at each site is influenced by numerous other factors such as wind and rates of photosynthesis and respiration, all of which are variable between sites specific and are dynamic over time.

3 Results and Discussion



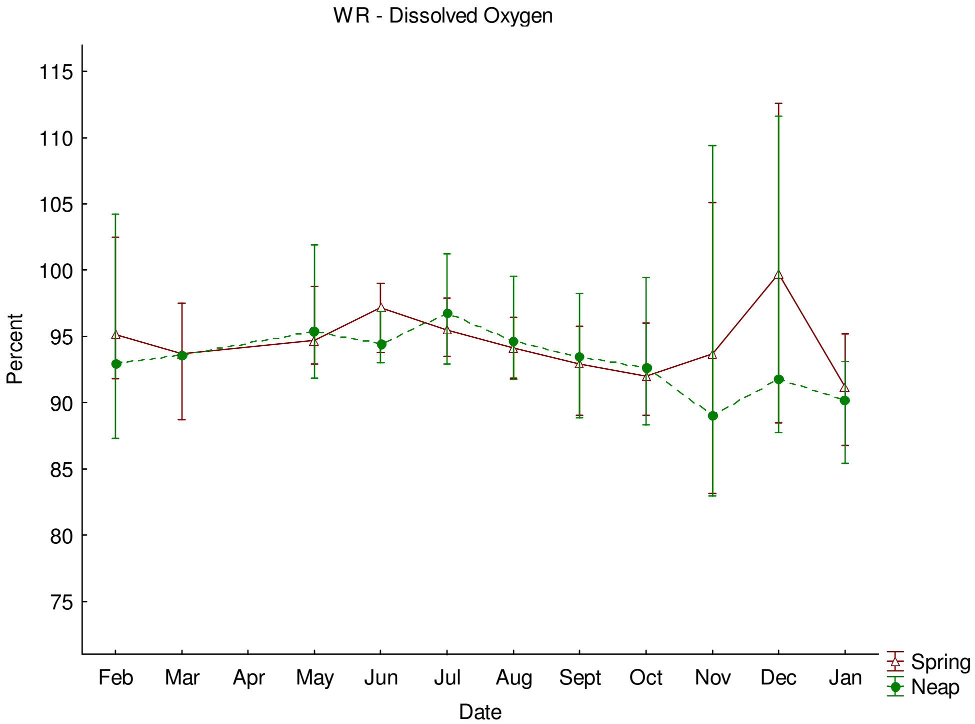
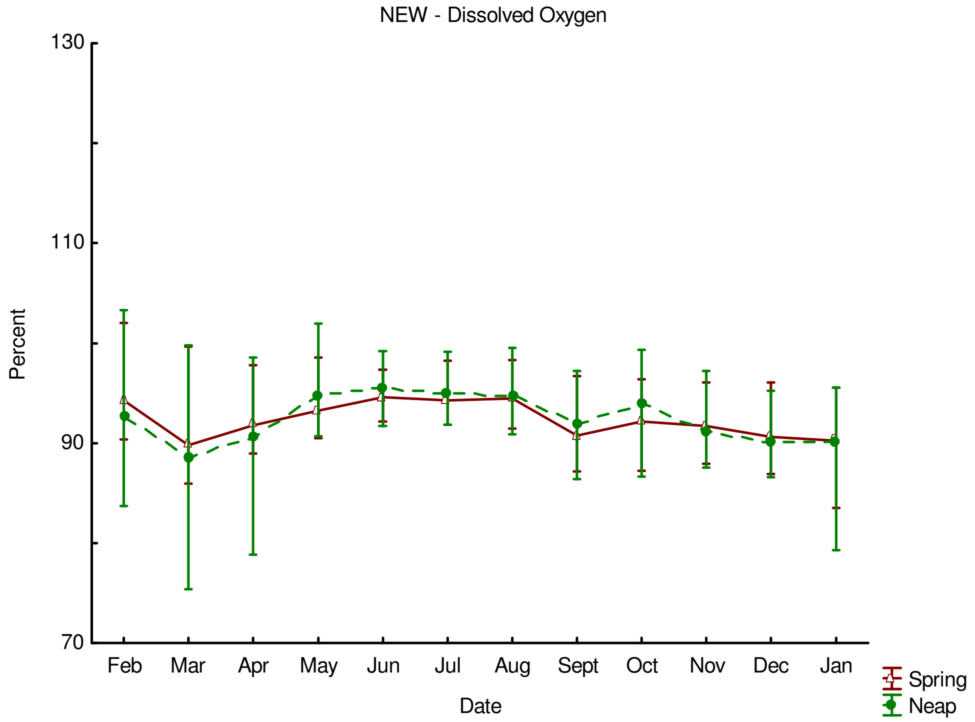


Figure 3-9 Monthly spring and neap tide dissolved oxygen levels from February 2010 to January 2011 at Channel Island and Weed Reef (median with 5th and 95th percentile error bars)

3 Results and Discussion



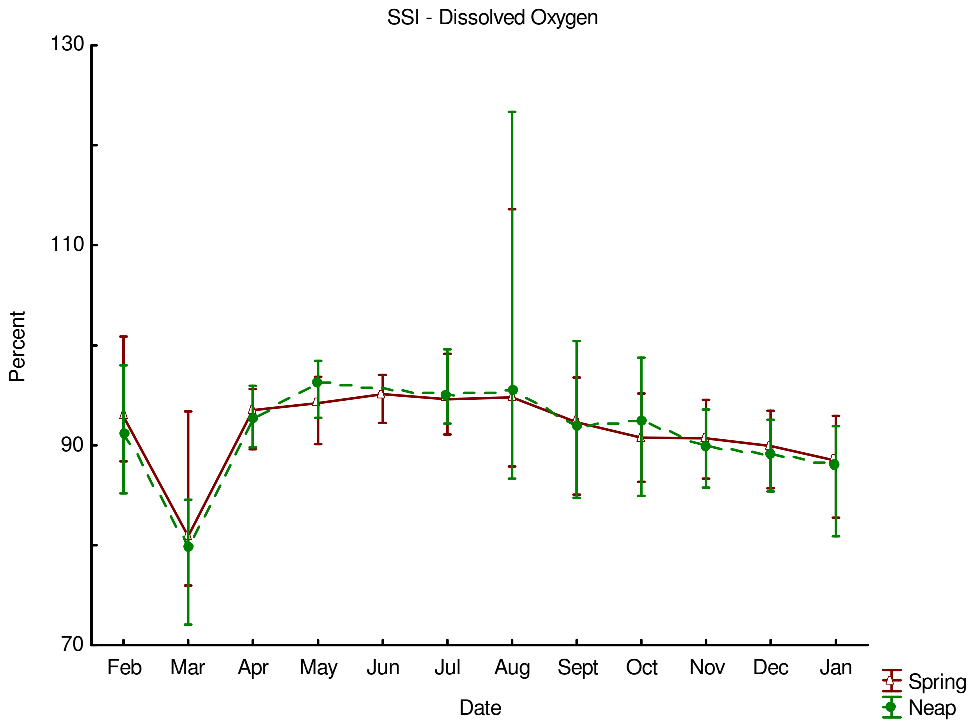


Figure 3-10 Monthly spring and neap tide dissolved oxygen levels from February 2010 to January 2011 at North East Wickham Point and South Shell Island (median with 5th and 95th percentile error bars)

3.2.6 Turbidity

Over the duration of the monitoring program, turbidity levels ranged from 0 NTU to 145 NTU, the latter being recorded at Weed Reef. Seasonal mean turbidity levels ranged from 3.9 NTU (North East Wickham Point, Dry Season) to 15.6 NTU (Weed Reef, Wet Season) (Table 3-2).

High turbidity is characteristic of Darwin Harbour, although maximum values in this investigation are above the typical range found in the main body of water (Padovan 1997, URS 2009). Duggan (2006) found that shallower sites located closer to mangroves exhibit higher turbidity than those in the middle and outer Harbour due to the tidal resuspension of mangrove muds. The distribution of resuspended mangrove sediment in the water column in Darwin Harbour also diminishes towards the surface and as a result, the highest turbidity values are typically recorded near the seafloor (Padovan 1997, URS 2009). Therefore, elevated turbidity values exceeding 100 NTU are not uncommon near the seafloor in East Arm and Middle Arm during the Wet Season. For example, turbidity values recorded in a water quality monitoring program conducted near Channel Island in 2003 reached 108.1 NTU (Munksgaard & Parry 2003), comparable to the maximum value of 113 NTU recorded at the Channel Island site during the present study.

Seasonal mean turbidity values in the present study are lower than turbidity averages measured at Channel Island over six two-week periods between October 2002 and August 2003 (Munksgaard & Parry 2003). In addition, the annual mean across the four sites in Middle and East Arms for the 2010/11 survey period (7.7±11.8) is less than the average across nine sites recorded in 2004 (14.7±12.2 NTU) (Duggan 2006).

Seasonal mean turbidity values varied between sites. The highest mean Wet Season turbidity level (15.6 NTU) was recorded at Weed Reef, the site closest to the Harbour entrance (Table 3-2). This is in contrast to previous findings that turbidity decreases towards the seaward end of the Harbour as the result of the dilution of inner Harbour waters with more oligotrophic, low turbidity waters of the Timor Sea (McKinnon et al. 2006). However, Weed Reef is more exposed to wind-generated waves than are the other three sites, hence mobilisation of seafloor sediments during periods of strong winds may have contributed to the higher turbidity levels. Dry Season mean turbidity levels were slightly higher at Channel Island (5.8 NTU) than at the other sites (3.9 - 4.4 NTU). Despite the variability in mean turbidity levels between seasons, all sites exhibited fluctuations of high and low turbidity levels that were within a similar range.

Within each site, turbidity also varied between seasons, with median values at the “peak” of the Wet Season (January to March) clearly exceeding those in the early Dry Season (May to July) (Figure 3-11 and Figure 3-12). This seasonal pattern in the turbidity of the water in Darwin Harbour is closely correlated with rainfall and run-off. These findings are in contrast to Padovan (1997), who found no evidence of elevated turbidity during periods of high rainfall. Rainfall data from 2010 indicate a lag effect between highest rainfall and elevated turbidity levels. For example, the high rainfall in January and February 2010 (630 mm and 428 mm respectively) resulted in peak turbidity levels in February and March. The 390 mm that fell in December 2010 was not reflected in the turbidity levels until January 2011. Substantial run-off of sediment laden water enters the waterways leading into Darwin Harbour through the upper creeks.

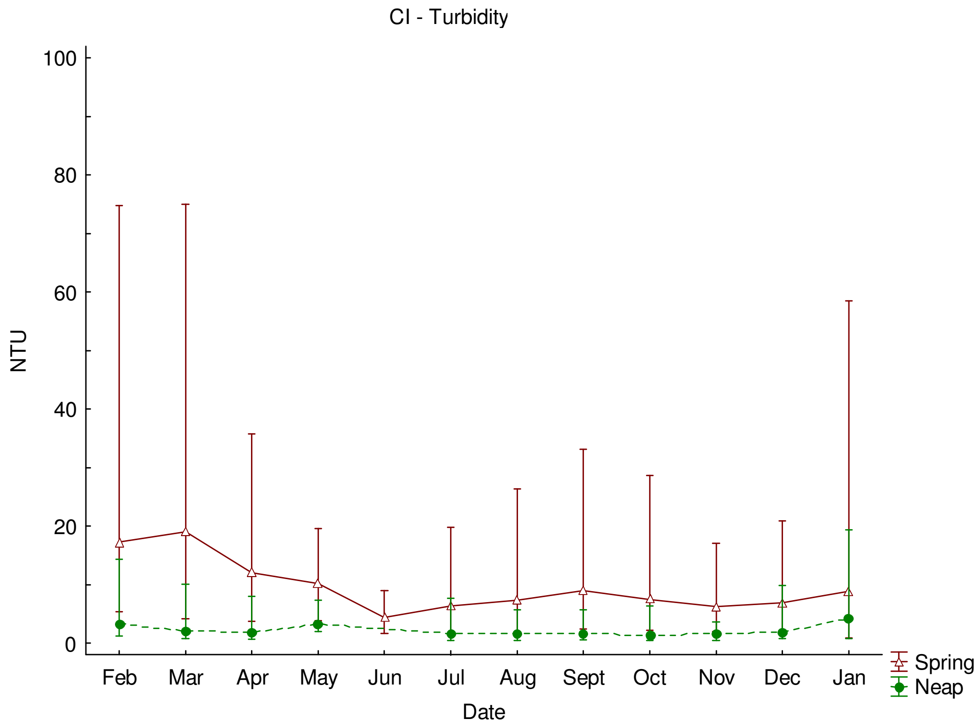
Differences in turbidity between ebb tides and flood tides, due to natural suspension of sediments within Darwin Harbour, were exhibited across all sites (Figure 3-11 and Figure 3-12). The survey data indicate that turbidity exhibits a strong relationship with tidal phase; i.e. for each month of the survey period, turbidity was generally lower during neap tides than during spring tides.

However, due to poor flushing of the upper reaches of the Harbour, the onset of spring tides is required to effectively exchange the turbid creek water with the surrounding water mass (Munksgaard & Parry 2003, Boggs et al 2007). This is supported by the observation in the present study that, following the substantial rainfall events between January and March 2010, there were marked increases in turbidity only when the difference between low water and high water within a day exceeded ~6.5 m.

A more gradual increase in turbidity was evident during spring tides across all sites from June onwards, generally peaking during the spring tides in September, prior to the onset of any substantial rainfall event (Figure 3-11 and Figure 3-12). Despite increasing rainfall in subsequent months, turbidity gradually declined until November when monthly rainfall exceeded 200 mm. The increase in turbidity between June and September may have been due to increased biomass (e.g. cyanobacteria or plankton) in the water column, rather than to meteorological events. Between June and October 2010, nuisance blooms of cyanobacteria (*Lyngbya majuscula*) and elevated levels of enteric bacteria led to closures of Darwin Harbour beaches (Drewry et al. 2010). As observed by Drewry et al. (2010) in Fannie Bay Creeks, cyanobacteria blooms may have occurred in tidal creeks around the Harbour during the Dry Season and been carried into the water quality monitoring sites on ebb tides. Enteric bacterial abundance has been found to strongly correlate with turbidity and nitrate levels, and to increase in lower salinity waters (Mallin et al. 2000, Shibata et al. 2004). It is plausible that low salinity at the early onset of the Wet Season, combined with elevated nitrogen levels, promoted enteric bacterial abundance which then contributed to higher turbidity levels in September. An increase in phytoplankton may also have occurred with the rapid rise in water temperature in September, and plankton biomass can also increase with inflow of oceanic waters (McKinnon et al. 2006).

Within each month there are two spring tide periods and two neap tide periods. The tidal ranges typically vary in magnitude between the two spring tides and between the two neap tides. In March, six days of turbidity data were not captured at Weed Reef during the two smaller tidal events, hence fewer lower turbidity values were included in the calculations of the monthly mean value, which may consequently have been higher than if the entire dataset was available (Figure 3-11). Similarly, at South Shell Island data were not recorded during the smaller of the spring tides in March, and the high turbidity value shown in Figure 3-12 was derived from only two turbidity readings.

3 Results and Discussion



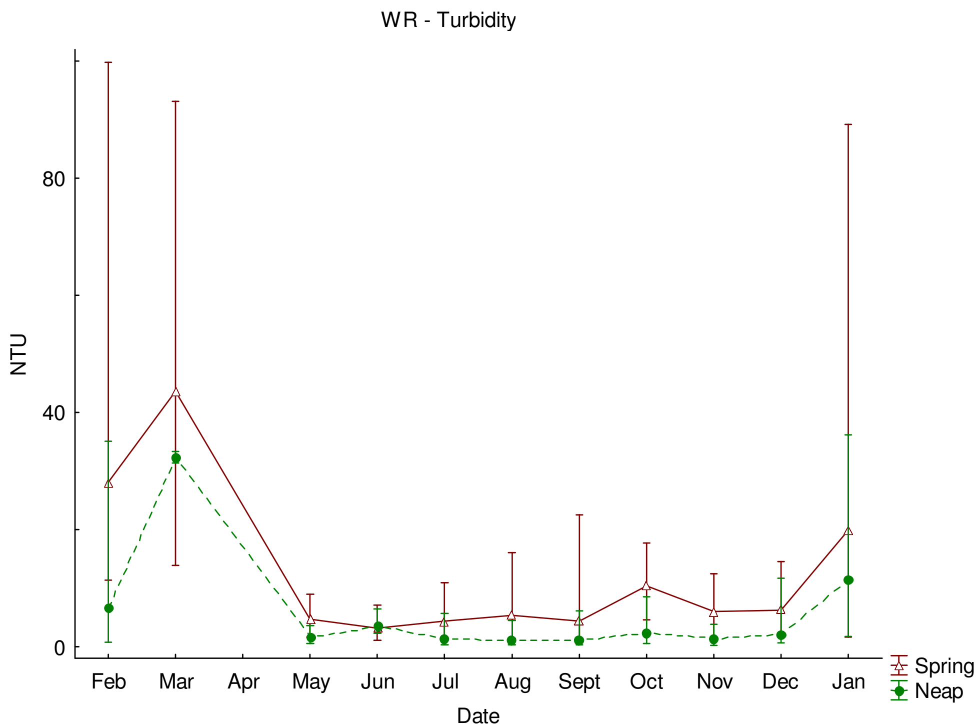
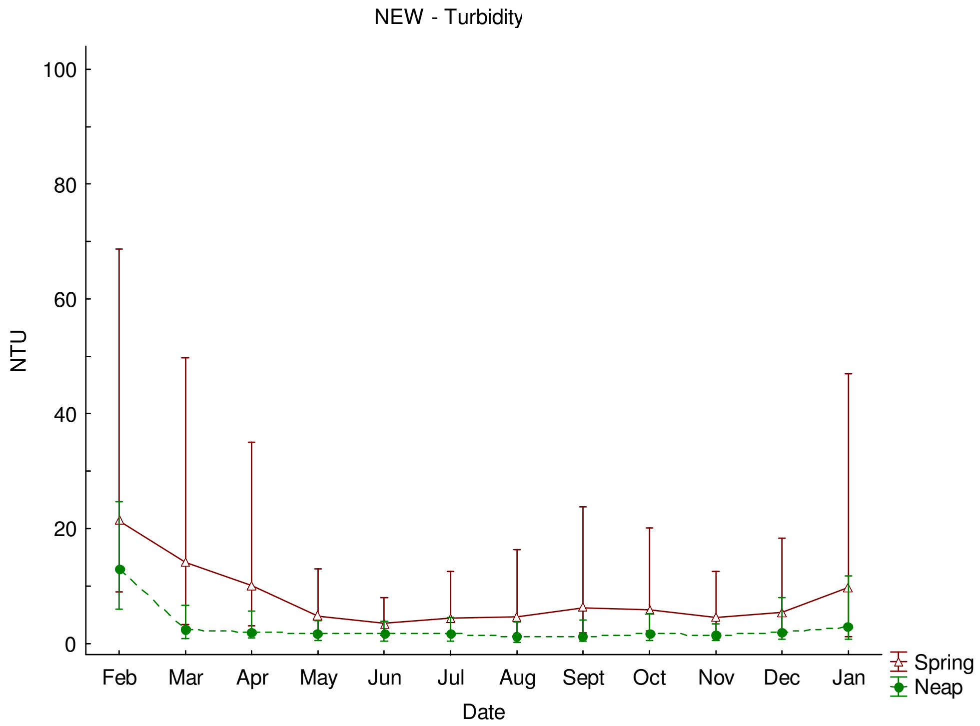


Figure 3-11 Monthly spring and neap tide turbidity levels from February 2010 to January 2011 at Channel Island and Weed Reef (median with 5th and 95th percentile error bars)

3 Results and Discussion



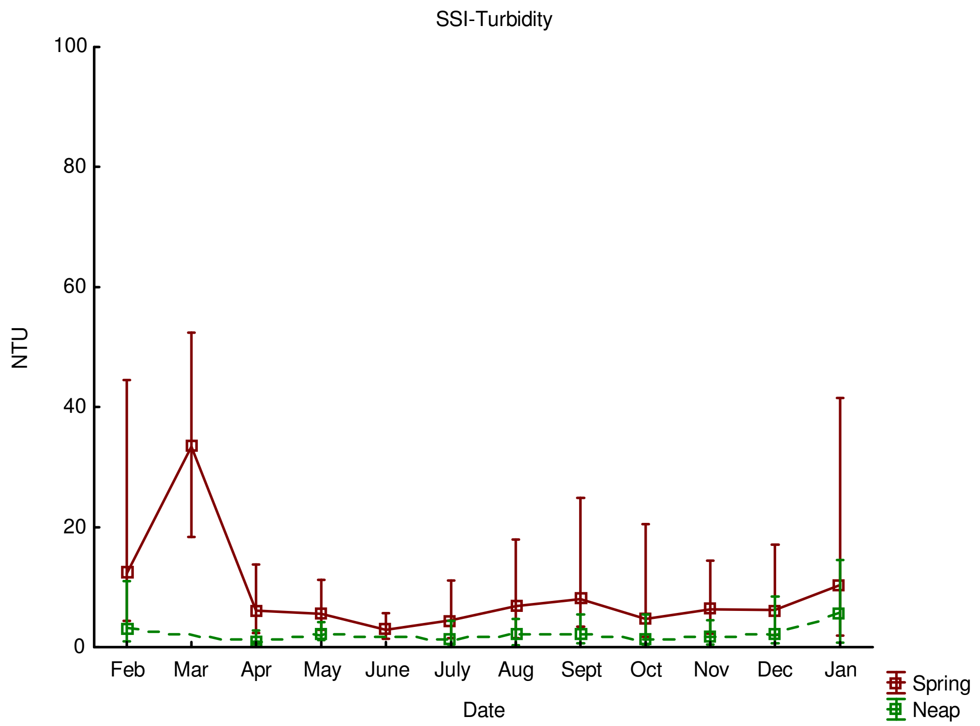


Figure 3-12 Monthly spring and neap turbidity levels from February 2010 to January 2011 at North East Wickham Point and South Shell Island (median with 5th and 95th percentile error bars)

3.3 Turbidity/Suspended Solids Concentration Relationship

Direct relationships between turbidity (measured *in situ* as NTU) and SSC were established from water samples collected and filtered from all four monitoring sites during neap tides between February 2010 and January 2011. Direct relationships between suspended solids of varying concentrations and the corresponding turbidity values (measured as NTU by optical backscatter sensor in the laboratory) were also established from abstracted <75 µm subsamples taken from composite samples of fine sediment collected within East Arm and Middle Arm (Figure 2-1). The NTU/SSC correlation appears to differ slightly between locations, depending on the composition and particle size of the suspended material. The intention of both investigations was to establish NTU/SSC relationships for Weed Reef, Channel Island and sites within East Arm (North East Wickham Point and South Shell Island).

Correlations between turbidity and SSC are summarised in Table 3-3. The positive linear NTU/SSC relationships within the filtered water samples were developed from a dataset with a high representation of relatively low turbidity values, as samples were predominantly collected during neap tides.

To confirm relationships for higher NTU values, fine fraction material (<75 µm) was extracted from samples of surface sediments and the extracted material was suspended in water at known SSCs to allow measurements of corresponding NTU. When SSC was <50 mg/L, this serial dilution approach resulted in a linear equation, with a strong positive correlation coefficient (r^2 = 0.987, Table 3-3), that was similar to that derived from the filtered water samples. However, when SSC was above 50 mg/L, rising NTU values resulted in proportionately smaller increases in SSC. While the entire turbidity range measured in the laboratory (0-2000 NTU) can be described by fitting a power (or logarithmic) function, for <50 mg/L SSC the most accurate descriptions of the NTU/SSC correlations are the linear relationships in Table 3-3.

Table 3-3 Functional relationship and mean correlation coefficients (r^2) between SSC and turbidity (NTU) using different techniques for Channel Island (CI), Weed Reef (WR), North East Wickham Point (NEW) and South Shell Island (SSI) sites.

Location	Filtered Water Samples	Fine Sediment Samples	
		<50 mg/L only	Over entire turbidity range
	Linear	Linear	Logarithmic
CI/WR	SSC=0.9104*(NTU)+6.1108	SSC=0.9254(NTU)+6.2053	SSC=38.804ln(NTU)–95.151
NEW/SSI	SSC=0.8058*(NTU)+6.4315	SSC=0.848(NTU)+7.0477	SSC=46.479ln(NTU)–113.08
Mean r^2 values	0.84335	0.987	0.991

3.4 Suspended Solid Concentration Summary Statistics

The linear equations in Table 3-3 provide the most accurate NTU/SSC correlations for SSC up to around 50 mg/L. For SSC well above 50 mg/L it appears a natural log equation may be appropriate; however this is based on a limited data set and needs further investigation. For waters with SSC substantially higher than 50 mg/L, the linear equations are likely to overestimate SSC and should be used with a degree of caution. Nevertheless, the linear equations have been applied to the entire data set to produce summary statistics in Table 3-4, as applying both equations to the data results in incongruity for values around 50 mg/L SSC (with the linear equation providing a higher corresponding SSC than that from the natural log relationship). The SSC for the maximum values in Table 3-4 (which are generally above 50 mg/L) may therefore be considered potential over-estimates; it should be noted that this has no bearing on development of thresholds for benthic communities, which are based on dry season 95th percentiles and 50th percentiles and are typically well below 50 mg/L SSC.

Data from both sites within East Arm were merged to represent the typical conditions of East Arm. Weed Reef had the highest mean SSC during the Wet Season (20.6 mg/L) with Channel Island having the highest mean SSC during the Dry Season (11.6 mg/L). The mean SSC values for East Arm are slightly lower (14.9 mg/L in the Wet Season, 10.6 mg/L in the Dry) (Table 3-4).

SSC values were determined from NTU statistical measures to evaluate the baseline SSC levels to which benthic biota are naturally exposed. Model outputs of the predicted dredge program (expressed as SSC) will be added to the values in Table 3-4 and the total SSC will be considered in the context of the typical physiological responses of benthic biota and their potential maximum tolerable SSC levels. This will culminate in the definition of predicted areas of impact, and predicted areas of influence, associated with dredging and spoil disposal.

Table 3-4 Summary statistics of seasonal SSC values, calculated from NTU/SSC linear equations, for East Arm and Middle Arm locations

Turbidity Logger Location		Min	Max	95th %ile	90th %ile	50th %ile	Mean
South Shell Island and North East Wickham Point	**Wet**	7.2	83.0	36.5	26.4	11.3	14.9
	Dry	7.1	46.4	17.9	14.7	9.4	10.6
Channel Island	**Wet**	6.3	110.8	43.5	28.0	10.6	15.7
	Dry	6.3	52.7	26.4	19.6	9.2	11.6
Weed Reef	**Wet**	6.3	140.5	63.1	47.1	12.5	20.6
	Dry	6.3	33.0	17.7	14.9	8.8	10.0

Summary

Water quality parameters were recorded close to the seafloor at four sites in Darwin Harbour over a 12 month period between February 2010 and January 2011. The yearly total rainfall during the survey period was above the annual Darwin average, resulting primarily from rainfall events occurring outside of Darwin's typical Wet Season months.

Water quality within the monitoring period varied substantially between locations, tides and seasons. However, at all sites the ranges of values of the water quality parameters were not substantially different from those that, based on the results of other surveys, would be expected within East Arm and Middle Arm. The trends in water quality parameters during the survey period were:

- Warm water temperatures (29 to 32°C) were prolonged throughout the Wet Season in 2010, dropping rapidly by ~3-4°C in June. Typical seasonal patterns in Darwin Harbour are maximum temperatures in October/November, gradually declining until June.
- Conductivity and pH results were slightly reduced and varied less between seasons than in previous studies. The present results indicated a less defined transition from estuarine to oceanic conditions within the Harbour in the Dry Season of 2010, associated with higher and more prolonged rainfall throughout the year.
- Conductivity values further into the main body of the Harbour, at Weed Reef, were slightly higher and more uniform, reflecting its distance from the creeks and rivers where freshwater inflow occurs.
- DO saturation indicated Darwin Harbour was well oxygenated throughout the year, with slightly higher levels during the Wet Season.
- Turbidity varied strongly spatially, seasonally and with tidal phase. The Channel Island and Weed Reef sites exhibited higher turbidity fluctuations than the East Arm sites (North East Wickham Point and South Shell Island), although the results were comparable between the Channel Island and Weed Reef sites, and between the two East Arm sites.
- Following substantial rainfall events between January and March (>300 mm in a month), there were exponential increases in turbidity on days when the difference between low water and high water exceeded ~6.5 m.
- Monthly rainfall < 200 mm appeared to have little influence on turbidity. It is suggested that slight increasing trends in turbidity during the Dry Season may have been related to increased biological activity.

Investigations into the relationship between NTU and SSC yielded the following linear equations, which were used to convert measured NTU values into SSC values:

- Channel Island and Weed Reef: $SSC = 0.9254 * NTU + 6.2053$
- East Arm: $SSC = 0.848 * NTU + 7.0477$

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Limitations

URS Australia Pty Ltd (URS) has prepared this report in accordance with the usual care and thoroughness of the consulting profession for the use of INPEX Browse Ltd and only those third parties who have been authorised in writing by URS to rely on the report. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report. It is prepared in accordance with the scope of work and for the purpose outlined in the Dredging and Dredge Spoil Disposal Management Plan.

The methodology adopted and sources of information used by URS are outlined in this report. URS has made no independent verification of this information beyond the agreed scope of works and URS assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that information contained in this report as provided to URS was false.

This report was prepared in February and March 2011, and is based on the results at the time of preparation. URS disclaims responsibility for any changes that may have occurred after this time.

This report should be read in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. This report does not purport to give legal advice. Legal advice can only be given by qualified legal practitioners.

Appendix A YSI Instrument Specifications

6600EDS Extended Deployment System

Measure over 10 parameters in severe fouling environments
Featuring Patented Clean Sweep® Anti-fouling Technology

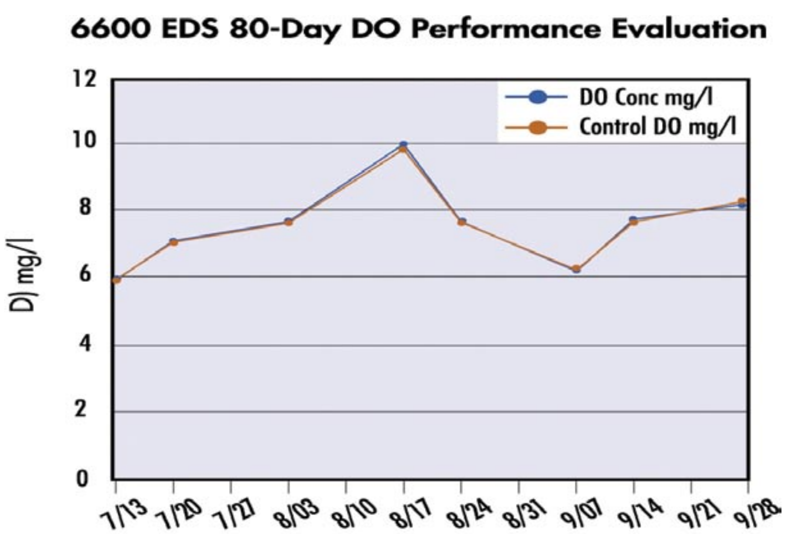
Profile of the 6600EDS depicting (clockwise from bottom) temperature/conductivity, turbidity, Rapid Pulse™ dissolved oxygen, chlorophyll and pH/ORP—all of which (except conductivity) are kept free of fouling by the patented Clean Sweep® universal wiper assembly, as well as individual optical wipers.

Building upon the unprecedented accuracy and reliability of YSI's stirring-independent Rapid Pulse™ dissolved oxygen system, as well as on the improved and proven wiped optical sensors, YSI offers the YSI 6600EDS (Extended Deployment System).

- **Provides unprecedented DO accuracy and longevity in aggressive fouling environments**
- **Patented wiped fouling protection for turbidity, chlorophyll, DO, BGA, pH, and ORP sensors**
- **Ideal for extended, long-term deployments**
- **Virtually maintenance free**
- **Sensors are field-replaceable**
- **Integrates with DCPs (via RS-232 or SDI-12)**

Initial field studies of the YSI 6600EDS show that the system provides unprecedented DO accuracy and longevity in aggressive fouling environments. The 6600EDS was inspected after 80 days of an ongoing deployment performance evaluation. The Rapid Pulse™ DO sensor performed within specifications throughout this deployment without the need for recalibration or cleaning. During this deployment, the instrument was removed once for battery replacement; none of the sensors was cleaned or recalibrated.

A prototype 6600EDS after continuous deployment for 80 days in Buzzards Bay, MA. The sensor in the foreground is the active DO sensor. The sensor at top-right was used as a non-wiped fouling reference. Note extensive fouling by plant and animal species on the non-wiped sensor.



Remarkably close agreement (mean error 0.16mg/l) between the continuously deployed sonde and the control measurements was observed throughout an 80-day deployment.

Pure Data for a Healthy Planet.®

*Sensor Performance verified by the EPA Environmental Technology Verification Program.**

ETV

Sensor performance verified*

The 6600EDS uses sensor technology that was performance-verified through the US EPA's Environmental Technology Verification Program (ETV). For information on which sensors were performance-verified, look for the ETV logo.

YSI 6600EDS Sensor Specifications

	Range	Resolution	Accuracy
Dissolved Oxygen• % Saturation 6562 Rapid Pulse™ Sensor* (ETV)	0 to 500%	0.1%	0 to 200%: ±2% of reading or 2% air saturation, whichever is greater; 200 to 500%: ±6% of reading
Dissolved Oxygen• mg/L 6562 Rapid Pulse™ Sensor* (ETV)	0 to 50 mg/L	0.01 mg/L	0 to 20 mg/L: ± 0.2 mg/L or 2% of reading, whichever is greater; 20 to 50 mg/L: ±6% of reading
Conductivity•• 6560 Sensor* (ETV)	0 to 100 mS/cm	0.001 to 0.1 mS/cm (range dependent)	±0.5% of reading + 0.001 mS/cm
Salinity	0 to 70 ppt	0.01 ppt	±1% of reading or 0.1 ppt, whichever is greater
Temperature 6560 Sensor* (ETV)	-5 to +50°C	0.01°C	±0.15°C
pH 6561 Sensor* (ETV)	0 to 14 units	0.01 unit	±0.2 unit
ORP	-999 to +999 mV	0.1 mV	±20 mV
Depth: Deep	0 to 656 ft, 200 m	0.001 ft, 0.001 m	±1 ft, ±0.3 m
Medium	0 to 200 ft, 61 m	0.001 ft, 0.001 m	±0.4 ft, ±0.12 m
Shallow	0 to 30 ft, 9.1 m	0.001 ft, 0.001 m	±0.06 ft, ±0.02 m
Vented Level	0 to 30 ft, 9.1 m	0.001 ft, 0.001 m	±0.01 ft, 0.003 m
Turbidity• 6136 Sensor* (ETV)	0 to 1,000 NTU	0.1 NTU	±2% of reading or 0.3 NTU, whichever is greater**
Rhodamine•	0-200 µg/L	0.1 µg/L	±5% reading or 1 µg/L, whichever is greater

• Maximum depth rating for all standard optical sensors is 200 feet, 61 m. Also available in Deep Depth option: 656 feet, 200 m.
•• Report outputs of specific conductance (conductivity corrected to 25° C), resistivity, and total dissolved solids are also provided. These values are automatically calculated from conductivity according to algorithms found in *Standard Methods for the Examination of Water and Wastewater* (ed 1989).

**In YSI AMCO-AEPA Polymer Standards.

	Range	Detection Limit	Resolution	Linearity
BGA - Phycocyanin•	~0 to 280,000 cells/mL† 0 to 100 RFU	~220 cells/mL§	1 cell/mL 0.1 RFU	R^2 > 0.9999**
BGA - Phycoerythrin•	~0 to 200,000 cells/mL† 0 to 100 RFU	~450 cells/mL§§	1 cell/mL 0.1 RFU	R^2 > 0.9999***
Chlorophyll• 6025 Sensor* (ETV)	~0 to 400 µg/L 0 to 100 RFU	~0.1 µg/L§§§	0.1 µg/L Chl 0.1% RFU	R^2 > 0.9999****

• Maximum depth rating for all standard optical probes is 200 feet, 61 m. Also available in Deep Depth option 656 ft 200 m.
BGA = Blue-Green Algae
RFU = Relative Fluorescence Units
~ = Approximately

† Explanation of Ranges can be found in the 'Principles of Operation' section of the 6-Series Manual.

§ Estimated from cultures of *Microcystis aeruginosa*.
§§ Estimated from cultures *Synechococcus sp*.
§§§ Determined from cultures of *Isochrysis sp.* and chlorophyll *a* concentration determined via extractions.

**Relative to serial dilution of Rhodamine WT (0-400 ug/L).
***Relative to serial dilution of Rhodamine WT (0-8 µg/L).
****Relative to serial dilution of Rhodamine WT (0-500 ug/L).

YSI 6600EDS Sonde Specifications

Medium	Fresh, sea or polluted water	Software	EcoWatch®
Temperature: Operating Storage	-5 to +50°C -10 to +60°C	Dimensions: Diameter Length, no depth Length, depth Weight, depth and batteries	3.5 in, 8.9 cm 19.6 in, 34.3 cm 21.6 in, 54.9 cm 7 lbs, 3.18 kg
Communications	RS-232, SDI-12	Power: External Internal	12 V DC 8 C-size alkaline batteries

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ISO 9001
ISO 14001
Yellow Springs, Ohio Facility

Printed in USA 0809 E54-04

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*Sensors with listed with the ETV logo were submitted to the ETV program on the YSI 6600EDS. Information on the performance characteristics of YSI water quality sensors can be found at www.epa.gov/etv, or call YSI at 800.897.4151 for the ETV verification report. Use of the ETV name or logo does not imply approval or certification of this product nor does it make any explicit or implied warranties or guarantees as to product performance.

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