Interim Turbidity Water Quality Objectives
for Dry Season Neap Tide Conditions in Darwin Harbour

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The derivation of the interim water quality objective detailed in this report is restricted in its application and only applies to Darwin Harbour as defined by its catchment, estuarine and marine boundaries.

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Front cover: Aerial view of turbid Sadgroves Creek, Darwin Harbour, and Bayview marina.
1. Summary

The Water Quality Objectives (WQOs) for Darwin Harbour currently do not include a trigger value for turbidity. Interim turbidity Water Quality Objectives (WQOs) for the Darwin Harbour Region’s marine environment have been developed to fill this gap. The interim status means that they have not been formally gazetted under the Water Act, which will take place when other water quality objectives are developed specifically for neap tide conditions.

Turbidity naturally varies considerably in Darwin Harbour over time, driven by seasonal conditions and tidal currents. During the wet season or monsoonal conditions, turbidity is highly variable and high turbidity events can persist for periods of days and even longer depending on the severity of weather.

Turbidity also varies over tidal stage (water level elevation), and neap and spring tidal cycle. High current speeds during spring tides resuspend bottom sediments to increase turbidity, whilst under low current speeds suspended material begins to settle out of the water column resulting in decreased turbidity.

Dry season neap tides represent the period of most stable turbidity. Standardising water quality monitoring to this time improves our ability to detect long term anthropogenic change. Surveillance sampling effort undertaken by the Department of Environment and Natural Resources (DENR) has been confined to neap tide dry season conditions since 2012. The resulting dataset presents an opportunity to develop a specific trigger value for turbidity, specifically around neap tide, ‘slack’ water conditions for Darwin Harbour.

Different objectives apply to the three estuarine categories currently nominated by the Darwin Harbour Water Quality Objectives (Fig. 1).

The interim turbidity WQOs are for surface waters (0-50 cm) and neap tides with a range of less than 3 m (at Stokes Hill Wharf) and measured within 1½ hours either side of the neap tide maximum water level.

The WQOs were developed by applying the national protocol that uses the 80th percentile of reference data for a slightly to moderately disturbed ecosystem such as Darwin Harbour, and were based on nearly 2000 data points from over 100 sites collected between 2012 and 2017.

The dry season neap tide standardised turbidity Water Quality Objectives are:

<table>
<thead>
<tr>
<th>Estuarine category</th>
<th>Upper Harbour</th>
<th>Middle Harbour</th>
<th>Outer Harbour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interim turbidity WQO (NTU)</td>
<td>4.5</td>
<td>3.4</td>
<td>3.7</td>
</tr>
</tbody>
</table>

The application of these interim turbidity objectives is limited to the conditions described above and should not be applied to tidal and seasonal conditions beyond neap tides during the dry season. Exceedance of these values provides a trigger for further investigation and should be applied in conjunction with relevant contextual data and expert judgement.
2. Introduction

2.1 Turbidity in the Darwin Harbour environment

Darwin Harbour is characterised by a semi-diurnal (two high and two low tides every lunar day) macro-tidal regime. The tidal range is up to 7.8 m, with mean spring tide variation around 6 m and mean neap tide variation around 3 m (Williams et al., 2006) and within each month there are two spring and neap tide periods.

The climate can be summarised as having two seasons, the wet and the dry, though a transition period occurs lasting typically 2 months. The wet season runs from November until April, and is characterised by convective storms, north-west monsoonal bursts, and cyclones. The dry season, from May until October, is typified by southeast winds with negligible rainfall.

Mangrove forests fringe the harbour. The mangroves’ extensive root systems provide important buffers at the catchment-estuary interface and are a sediment sink (Brocklehurst and Edmeades 1996).

Turbidity is an optical property of water and a measure of the scatter of light caused by suspended and colloidal particles, and can also be affected by large concentrations of dissolved organic matter (colour). The penetration of light through the water column is essential for photosynthesis by plankton and benthic plants, corals and notably seagrass. Turbidity is an important water quality indicator in Darwin Harbour which can have significant bearing on pelagic and benthic productivity. There are also other factors driving productivity including availability of suitable habitat, current speeds, high sedimentation, desiccation due to large tidal range and fluctuations in salinity.

Several studies have found turbidity in Darwin Harbour to be highly variable both spatially and temporally. Key processes controlling turbidity include re-suspension, transport and settling of sediment.

Tides with high current speeds re-suspend sediments from the bottom, with values increasing at high tide and decreasing again at low tide (Cardno, 2015; Frieden and Darnell, 2012; Fortune and Mauraud, 2015; and URS Australia Pty Ltd., 2011). The large tidal movement produces strong currents of up to 2 m s⁻¹, causing re-suspension of fine sediments leading to naturally turbid system (McKinnon et al., 2006). The distribution of resuspended sediments in the water column diminishes towards the surface, with highest values recorded at depth (near seafloor; Padovan, 1997 (see Appendix A); URS, 2009). Water quality however is more uniform during peak neap tide conditions (Fortune, 2015), especially during the dry season.

Episodic meteorological events such as monsoonal weather occur during the wet season to increase turbidity. Elevated wind and wave conditions, tropical storms, and cyclones resuspend seafloor sediments and generate catchment runoff that delivers new sediments to the harbour (Cardno, 2015). Turbidity appears to increase in parts of the outer harbour during these conditions, where waves and wind play an important role in resuspending sediment in shallower parts of the outer harbour and in intertidal areas (Williams et al., 2016).

The highly variable turbidity of the harbour poses a challenge to implementing a water quality monitoring program that distinguishes natural and anthropogenic sources of turbidity. To minimise the variability, principally driven by tides, water quality monitoring by the DENR has been standardised to the period around peak neap tides (Fortune, 2015).

Water clarity, measured by turbidity, is one of four indicators reported for the Darwin Harbour Region Report Card. Nutrients, chlorophyll and dissolved oxygen concentrations are the other indicators and are compared to Water Quality Objectives declared in 2012 (Fortune, 2010). No objective however has been developed for turbidity, instead this has been inferred from
the suspended sediment-turbidity relationship and the suspended sediment water quality objectives. Suspended sediment data for Darwin Harbour is deficient and presents an additional cost to monitoring programs. Turbidity sensors currently used and deployed as part of the Department of Natural Resources and Environment water quality surveillance program presents a valuable source of data to substantiate a new benchmark for turbidity in the absence of spatially extensive suspended sediment data. In particular, a suitably founded benchmark for water clarity as part of the report card production for Darwin Harbour is required.

2.2 Developing Water Quality Objectives

Water quality guidelines for Australian and New Zealand marine waters are drawn from the national framework outlined in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000). This national document published default turbidity trigger values ranging from 1-20 NTU for tropical marine environments. Lower values apply to offshore waters and higher values to estuarine waters. The national document recommends tailoring trigger values to local conditions, and provides guidelines and objectives that can be refined according to local environments. In the case of turbidity a move towards the measurement of light attenuation is preferred (ANZECC, 2000). Similarly the derivation of such values would require data collection across all marine and estuarine types to characterise typical gradients from inshore to offshore waters.

Depending on the significance and present condition of the ecosystem low-risk trigger values for slightly to moderately disturbed ecosystems can be derived based on the approach of ANZECC 2000. Where sufficient data is available for reference type systems low risk trigger concentrations for performance indicators such as nutrients and chlorophyll-a should be determined as the 80th percentile of reference system(s). Alternatively, default to regional trigger values can be adopted particularly where data is deficient or not available.

The national guidelines were applied to develop the Water Quality Objectives for the Darwin Harbour Region – Background document (Fortune, 2010). A tailored WQO for turbidity for marine and estuarine systems in the region was not included in that report due to data deficiency at the time.

This report develops an interim WQO for surface turbidity (0-0.5 m) restricted to neap tides (1½ hours either side of neap high tide) with an approximate 3 m tidal range. The interim status means that they have not been formally gazetted under the Water Act, which will take place when other water quality objectives are developed for neap tide conditions.

2.3 Estuarine Categories

Fortune (2010) developed WQO’s for three estuarine zones in Darwin Harbour (Figure 1). The categorisation of the zones was established using a flushing index output from the Harbour’s hydrodynamic model and available surface water quality data across the estuarine-marine continuum. These described categories (or water types) fall within the ANZECC 2000 Guidelines base estuary types, including; the upper estuary, middle estuary and outer estuary. A summary of these categories and their respective boundaries are further discussed in Fortune (2010). Shoal Bay was previously categorised as containing outer and upper estuary categories only. This categorisation has been reviewed, resulting in an additional mid-estuary zone for Shoal Bay (Figure 1).

**Upper Estuary**: This is the most upstream of the estuarine waters, this zone is poorly flushed with water residence times > 32 days (Williams, 2006).

**Middle Estuary**: The middle estuary covers the majority of the length of Darwin Harbour, with a residence time between 14 - 32 days (Fortune, 2010). The middle estuary has a moderate
amount of water movement and marine and freshwater mixing. A middle estuary zone has been created for Shoal Bay, which was not part of the original zoning of Fortune (2010). Upper reach tributaries terminating in Shoal Bay are not considered mid estuary, however for report card purposes (DENR, 2016) the regional reporting zone of Shoal Bay includes Howard River.

**Outer Estuary:** The outer estuary consists of the most downstream reach of the main channel of Darwin Harbour estuary. Waters are subject to some degree of residual mixing with inflowing fresh water, and water residence time of < 14 days (Fortune, 2010).

![Estuarine categories for Darwin Harbour Region turbidity interim Water Quality Objectives. These are the same as Fortune (2010) with the exception of the inclusion of a Shoal Bay mid-estuary zone.]

**2.4 Report Objective**

The key objective of this report is to develop turbidity WQOs for surface waters during dry season neap tide conditions for the three estuarine categories in Darwin Harbour.
3. Methods

3.1 ANZECC approach

The ANZECC guidelines provide a framework for assessing water quality, based on whether the physical, chemical and biological characteristics of a waterway support nominated community or environmental values. In effect, the guidelines help to define the water quality needed to protect these values.

The trigger values for different indicators of water quality may be given as a threshold value or as a range of desirable values. These values represent conservative assessment levels, not ‘pass/fail’ compliance criteria. Local conditions vary naturally between estuarine and marine regions given the influence of macro-tides and strong seasonal water quality gradients in Darwin Harbour. Consequently it is necessary to tailor trigger values to local conditions where feasible.

Where an indicator is below the threshold value or within the desirable range for this trigger value, the risk to the declared environmental value is low.

Where an indicator is higher than the threshold value or outside the desirable range for its trigger value in a given waterway or area, there may be a risk that the environmental value will not be protected (Figure 2). This may ‘trigger’ either:

1. immediate action to address the likely causes of the value not being met, or
2. further investigation to determine whether the trigger value is too conservative for local conditions, or that local conditions influence the ambient levels.

![Figure 2. Application of locally derived trigger as part of a systematic monitoring program.](image)

The ANZECC guidelines acknowledge that different levels of protection may be appropriate for different water bodies. The guidelines specify three levels of protection, from stringent to flexible, corresponding to whether the condition of the particular ecosystem is:

- of high conservation value
- slightly to moderately disturbed, or
- highly disturbed.
Darwin Harbour has been assessed as a slightly to moderately disturbed ecosystem (Fortune, 2010) with WQO’s developed based on upper trigger value of the 80th percentiles of reference data for indicator parameters of nutrients and chlorophyll-a. For indicators such as Dissolved Oxygen and pH an upper and lower trigger value using the 20th and 80th percentiles of reference data is typically adopted.

In developing a WQO for dry season, neap tide turbidity an upper trigger value representing the 80th percentile of reference data was adopted consistent with the ANZECC approach.

3.2 Data collation and review

Only data collected by AHU staff was used to inform the development of interim turbidity objectives because it is tide standardised, collected according to DENR standard operating procedures and quality checked. The data collection methods included discrete measurements using a handheld turbidity meter, and spatial and stationary sampling by Flow Cell Monitoring (FCM; Patterson 2016). Sampling methods are discussed further below.

Only turbidity data from measurements at the surface (0-50 cm) during 1½ hours either side of the maximum neap tide with a tidal range of less than 3 m (at Stokes Hill wharf) during the dry seasons of 2012-2017 were included.

The final data set comprises 1,935 samples from across the Harbour. These data were collected from sites not overtly influenced by anthropogenic pollution and excluded data from highly disturbed systems, such as Buffalo and Myrmidon Creeks (adjacent to point discharge), which receive treated effluent (Drewry, et al. 2010; Smith and Haese, 2009). Darwin Harbour is a largely unmodified estuary and the effects of treated effluent on water quality are localised to Buffalo and Myrmidon creeks (Smith and Haese, 2009).

All AHU data used to develop the values were quality checked and stored in the Department’s water management database (HYDSTRA). The 1,935 samples used to develop the interim local guideline included 1635 discrete samples and 300 data points from FCM sampling.

3.2.1 Discrete Sampling Data

A total of 1635 discrete samples from 110 sites (Figure 3) was used in the development of the WQO. For each discrete sample two turbidity measurements are taken at the surface (approximately 0 – 0.50 m depth) and averaged for a final value at each site.
Figure 3. Location of discrete turbidity sample sites.
3.2.2 Flow-cell Monitoring Data

The Flow-cell monitoring (FCM) method collects spatially extensive continuous data by driving water through the flow-cell of a water quality sonde while the vessel is moving and measuring water quality parameters at a given time interval (Figure 4). Data can be collected at time intervals as low as 1 second with the vessel moving at high speed, creating data files that can extend across several estuarine categories.

Figure 4. Flow-cell monitoring vessel underway – EXO2 water quality probe mounted to stern of vessel. Data can be collected at 1 second intervals recording location with every value.

FCM sampling took place in all arms of Darwin Harbour over several neap tides during dry season periods from 2015 to 2017. During this period 30 transects with over 89,000 data points were recorded for surface turbidity across the harbour (Figure 5).

Transects were mapped and each record was appended to the relevant estuarine category, resulting in 30 tracks (13 upper estuary, 8 mid-estuary, 9 outer estuary). Areas near point source discharges were excluded from the analysis.

The large FCM data set is biased to a constrained period of time (see Appendix B, Fig A1-A3) and restricted mostly to main channels. To mitigate bias from the large number of FCM records compared to discrete samples, a subset of 10 records for each track was randomly sub-sampled from the dataset using a simple random sampling function in R script. The 300 random sub-samples were integrated with the discrete sample dataset (Figure 6).

The final reviewed data had 1,935 values with samples primarily collected in the upper estuary and fewer for the middle and outer estuary (Table 2). The majority of values were discrete samples.
Table 2. Summary of data used for each estuary category and total data points for sampling year and method. (Dataset used for WQO derivation, \(n=\text{Discrete} + \text{FCM-RS}\)).

<table>
<thead>
<tr>
<th>Year</th>
<th>Category 1. Upper</th>
<th>Category 2. Mid</th>
<th>Category 3. Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCM-RS* data</td>
<td>FCM data</td>
<td>FCM-RS* data</td>
</tr>
<tr>
<td></td>
<td>FCM tracks</td>
<td>Discrete</td>
<td>FCM tracks</td>
</tr>
<tr>
<td>2012</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2013</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2014</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2015</td>
<td>30</td>
<td>2956</td>
<td>3</td>
</tr>
<tr>
<td>2016</td>
<td>30</td>
<td>7621</td>
<td>3</td>
</tr>
<tr>
<td>2017</td>
<td>70</td>
<td>29331</td>
<td>7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>130</td>
<td>39908</td>
<td>13</td>
</tr>
</tbody>
</table>

*FCM-RS (Flow Cell Monitoring – Random Subsamples)

Figure 5. Location of FCM transects in Darwin Harbour.
Figure 6. Conceptual approach to treatment of Flow-Cell Monitoring (FCM) data for dataset and derivation of Water Quality Objective.
4. Results

4.1 Data summary

Mean turbidity for all estuarine categories during neap dry season conditions from 2012 to 2017 was low, ranging from 2.5 NTU in the mid estuary to 3.5 NTU in the upper estuary (Table 1). Medians did not exceed 3 NTU. These low values are consistent with other monitoring and research in the region (DENR, 2013-2016; Fortune and Mauraud 2015; Patterson, 2016; Padovan, 1997).

Table 1. Descriptive statistics of data collated for all three estuaries.

<table>
<thead>
<tr>
<th>Estuary category</th>
<th>n</th>
<th>Mean</th>
<th>sd (σ)</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
<th>Variance 20th Percentile</th>
<th>80th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>1367</td>
<td>3.5</td>
<td>2.9</td>
<td>2.7</td>
<td>0.58</td>
<td>44.8</td>
<td>44.2</td>
<td>8.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Mid</td>
<td>261</td>
<td>2.5</td>
<td>1.5</td>
<td>2.1</td>
<td>0.10</td>
<td>11.6</td>
<td>11.5</td>
<td>2.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Outer</td>
<td>237</td>
<td>3.0</td>
<td>3.0</td>
<td>2.1</td>
<td>0.69</td>
<td>21.6</td>
<td>20.9</td>
<td>9.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Collated and analysed turbidity values for each category revealed a higher median, range and maximum value for the upper estuary compared to both the middle and outer estuary (Table 1, Figure ). These findings may be a result of shallower depths, close proximity to catchment runoff and mangroves.

Higher turbidity values were often observed in the outer estuary. These conditions were typically generated with strong winds driving eddies and resuspension of sediments and may account for the range and variance found for the outer harbour category.

Figure 7. Boxplots for Upper, Mid and Outer estuarine categories, showing median, 25th/75th and 10th/90th percentile.
A monthly breakdown of turbidity data for each estuarine category (omitting outliers) confirmed low variability in median turbidity over the dry season with monthly maxima not exceeding 9 NTU across all estuarine categories (Figure 8).

**Figure 8.** Distribution of turbidity data (2012-2017) in three estuarine categories by month.
4.2 Interim Turbidity Water Quality Objective

Using the 80\textsuperscript{th} percentile of turbidity values for each estuarine category, the interim water quality objectives were determined to be 4.5 NTU for the upper estuary category, 3.4 NTU for the mid estuary and 3.7 NTU for the outer estuary (Table 2).

Table 2. Turbidity Water Quality Objective values, standardised to surface (0 – 25 cm) for the period of 1½ hours either side of a neap tide during a maximum 3 m tidal range; in the upper, middle and outer estuarine categories of the Darwin Harbour Region.

<table>
<thead>
<tr>
<th>Estuary category</th>
<th>Upper Estuary</th>
<th>Mid Estuary</th>
<th>Outer Estuary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interim Water Quality Objective (80\textsuperscript{th} percentile)</td>
<td>4.5</td>
<td>3.4</td>
<td>3.7</td>
</tr>
</tbody>
</table>

5 Limitations of the Turbidity Water Quality Objective.

These interim guidelines are not mandatory standards. They provide an indicative value for the departure from current conditions only for specific seasonal and tidal conditions. Waters that have turbidity values consistently greater than the WQO may suggest anthropogenic or natural variability and should trigger further investigation. The interim values are specific in their application and are developed to assist in water quality monitoring assessment and are not designed for comparison for ‘one off’ sampling.

Caveats for the application of these interim values should be noted. These are:

1. The WQOs apply to dry season conditions only and should not be applied during wet season or other conditions;
2. The WQOs apply to neap tides only and are not applicable under any other tidal conditions;
3. It is essential to acknowledge the importance and influence of other contextual water quality data with any interpretation of turbidity when comparing to WQOs or any other guideline.
4. Interim turbidity water quality objectives are for the waters defined as Darwin Harbour only; and
5. These reported values are not designed to be used for compliance monitoring of licenced point source discharge or determined zone of influence where site specific triggers are typically determined under regulatory monitoring requirements.
6 References


Brocklehurst, P. & Edmeades, B., 1996. The Mangrove Communities of Darwin Harbour.. Technical Memorandum No.96/9, Department of Lands Planning and Environment, Darwin..


APPENDIX A: TURBIDITY VARIABILITY BETWEEN SURFACE AND AT DEPTH

Data used to develop interim standards included only samples taken at surface (approximately 0 – 0.25 m). This approach is a consequence of both consistent available data at surface and Padovan, 1997 and URS 2009 studies finding that the distribution of resuspended sediments in the water column diminishes towards the surface, with highest values recorded at depth (near seafloor).

Padovan, 1997 found turbidity was variable from which depth the sample was taken; turbidity from surface samples was lower and less variable than samples at the bottom of the water column. Data collected by Padovan for the 1997 report presents 80th percentiles of data values increasing with depth for both the upper and middle estuary (Table 5). There was no data from the outer Estuary.

Table A1. Turbidity data sampled for Padovan, 1997 report shows 80th percentiles for each estuary increasing at the bottom of the water column in comparison to surface.

<table>
<thead>
<tr>
<th>Estuary category</th>
<th>Surface</th>
<th>Middle</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper estuary</td>
<td>9.96</td>
<td>16.8</td>
<td>17</td>
</tr>
<tr>
<td>Mid estuary</td>
<td>4.6</td>
<td>7.9</td>
<td>9.02</td>
</tr>
</tbody>
</table>

Note: Data sampled from seven sites located throughout the upper and middle estuary. Sampling was undertaken from October 1990 to November 1991 with particular focus on determining the influence of seasonal, spatial and depth profile on water quality (Padovan, 1997).
APPENDIX B: Plots of FCM and Discrete data distributions

Figure A1. Distribution of FCM data for Upper estuarine category prior to random subsampling.

Figure A2. Distribution of FCM data for Upper estuarine category post random re-sampling technique.
Figure A3. Distribution of turbidity data across sampling years and data source contribution for Upper Estuary.
Figure A4. Distribution of turbidity data across sampling years and data source contribution for Mid Estuary.
Figure A5. Distribution of turbidity data across sampling years and data source contribution for Outer Estuary.
APPENDIX C: Frequency distribution plots with 20th/80th percentile for three estuarine categories.

Figure 11(a). Frequency and notch plot indicating 80th and 20th percentiles – Upper estuary.
Figure 11(b). Frequency and notch plot indicating 80th and 20th percentiles – Mid estuary.
Figure 11(c). Frequency and notch plot indicating 80th and 20th percentiles – Outer estuary.