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A Water Quality Protection Plan for Darwin Harbour region

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Abstract: This paper presents an overview of the development of components of a plan to maintain the water quality in the Darwin Harbour region, Northern Territory, Australia. The paper overviews water quality monitoring and modelling components that helped evaluate water quality objectives and improve decision-making. Successes, potential limitations and lessons learned during the process are also discussed.

The Water Quality Protection Plan for Darwin Harbour (WQPP) aims to ensure that water quality of the region's water resources is maintained and that the community's values and beneficial uses (e.g. primary and secondary recreation) associated with waterways are protected. The water quality of Darwin Harbour is regarded as in a near-pristine or slightly modified condition. A key component of the WQPP includes development of water quality objectives (water quality guidelines for local waterways) for waterway protection. Water quality objectives will be scheduled under legislation. Monitoring and modelling were essential to help evaluate how increasing population growth and industry expansion may affect water quality and water quality objectives in the future.

Load-based data is necessary in the WQPP to help evaluate (i) diffuse source pollutant quantities; (ii) the impact of diffuse and point source loads from the catchments to the harbour and upper estuaries on water quality and water quality objectives; and (iii) potential future load-based targets. Empirical catchment scale pollutant export coefficient modelling indicates that non-urban diffuse sources are an important source to overall loads. Urban areas had much greater pollutant export coefficients than non-urban areas. The load data were used to help evaluate the effects of five scenarios of current or increased urbanisation and sewage treatment plant (STP) discharges on water quality using a hydrodynamic model for Darwin Harbour.

Darwin Harbour hydrodynamic and associated nutrient modelling has also been an important component in the WQPP to aid understanding of harbour and estuarine processes, particularly of poorly flushed estuaries. A component of the WQPP is to gain understanding of how STP discharge scenarios may affect water quality, and are therefore of interest for management of water quality objectives. The Darwin Harbour hydrodynamic model is the two dimensional RMA-2 model, and is suitable to simulate flow in the harbour and estuaries over a finite element mesh. Water quality in the harbour has been simulated using the two-constituent RMA-11 sediment transport model.

During the development of the WQPP, water quality studies and harbour hydrodynamic modelling indicates that, notwithstanding the large macro-tidal movements, the transport and dispersal of nutrients and pollutants is less than might have been expected. This, in turn, highlights concern about nutrient input from diffuse sources, STPs, and licenced discharges into the upper reaches of the harbour's estuaries. Harbour hydrodynamic modelling indicates that these upper reaches are poorly flushed. Scenario modelling using the Darwin Harbour hydrodynamic model shows for the N concentrations in the harbour during the wet season, increases in urbanisation have a greater effect on water quality than increases in STP discharges. The development of modelling and monitoring to improve process understanding, aid management of the harbour and catchment, and improve on-ground decisions are key components in the WQPP.

Keywords: *water quality, nitrogen, phosphorus, catchment modelling, watershed, nutrient export*

1. INTRODUCTION

The water quality of Darwin Harbour, Northern Territory, Australia, is regarded as in a near-pristine or slightly modified condition, but some areas of concern exist around some urbanised areas. The population of the Darwin region is approximately 117 000 (ABS 2008). By 2026, around 165 000 people are predicted to live in the Darwin region (ABS 2008). Increasing urbanisation, horticulture and agriculture can result in increased erosion, water runoff and extraction, and increased loads of pollutants entering waterways, which are of importance particularly at a localised scale, such as upper estuaries where there is limited tidal flushing. Tidal trapping of sediment in the upper harbour arms can occur, with some estuaries poorly flushed (Williams et al. 2006). On a whole-of-harbour basis, the tidal oceanic inputs and outputs of nutrients are very large compared with land-derived inputs (Burford et al. 2008). However such oceanic influences may be less relevant in upper estuary areas that are poorly flushed and may be subject to eutrophication, than in open harbour areas.

A Water Quality Protection Plan for Darwin Harbour (WQPP) is being developed to ensure that water quality of the region's water resources is maintained and that the community's values associated with various waterways are protected. A key aspect of the Darwin Harbour WQPP includes development of water quality objectives (WQOs; water quality guidelines for local waterways) to protect estuarine and freshwater waterways in the region.

Catchment scale modelling and event-based water quality monitoring is being used to increase understanding of catchment pollutant sources and help identify key sources and priority areas for management actions to protect the water quality in the region. Components of a separate Darwin Harbour hydrodynamic model are being developed and parameterised to help understand estuarine and harbour transport process understanding and improve decision-making a the population grows. This paper presents an overview of the WQPP project and related selected monitoring and modelling activities to protect water quality in the region, and improve understanding of catchment sources and harbour processes. It is beyond the scope of this paper to describe all components of the WQPP development. The paper also discusses successes, potential limitations and lessons learned during development of the monitoring and modelling to improve future investment.

2. THE DARWIN REGION

The Darwin Harbour and surrounding catchments are located in the wet-dry tropics of northern Australia. Darwin Harbour's catchment covers an area of approximately 3 230 km^2 comprising a land area of 2 010 km^2 and an estuary area of 1 220 km^2 at the high water mark. Darwin Harbour is a large tidal estuary that experiences tidal variations of up to 8 m. Tidal movement is likely to be the dominant process affecting water quality in the harbour. Features of the harbour are shown in Figure 1.

The climate is tropical with distinct wet and dry seasons. The monsoonal wet brings rainfall averaging 1 700 mm per year, with 79% falling between December March inclusive (data from BOM 2009). The period May to September inclusive only contributes 2.6% of mean annual rainfall (data from BOM 2009). Savannah woodlands and forest dominate the catchment, with approximately 80% of the catchment uncleared.

3. THE WQPP PROJECT

3.1. Overview

The WQPP project aims to ensure that water quality of the region's water resources is maintained and that the community's values associated with various waterways (beneficial uses) are protected. An overview of the process is shown in Figure 2. A key aspect of the WQPP includes development of water quality objectives (WQO; sometimes called water quality guidelines for local waterways). The National Water Quality Management Strategy promotes the sustainable management of water resources by determining environmental values (human or beneficial uses e.g. primary recreation or aquatic ecosystem protection) of waterways and corresponding water quality objectives for water quality indicators. Beneficial uses have been declared, and WQOs determined (see below). WQOs are designed to protect water quality for beneficial uses and will soon be scheduled under the Northern Territory *Water Act* (part 7 amended) legislation, and therefore included in future policy and planning initiatives (Figure 2).

Figure 1. Location and features of the Darwin Harbour region.

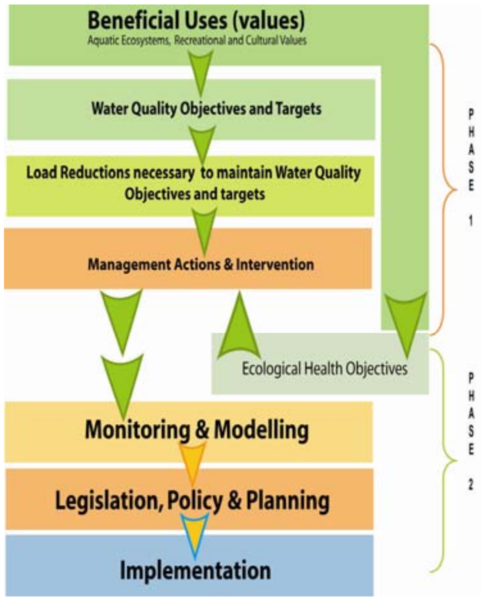

Figure 2. Diagram of the development of the WQPP for Darwin Harbour, and the contribution of monitoring and modelling.

3.2. Water Quality Objectives

Development of state (e.g. EPA 2006), and regional-scale water quality guidelines such as WQOs and targets are considered more appropriate than national guidelines (e.g. ANZECC) in Australia (Drewry et al., 2008; Bennett et al., 2002; EPA 2006) and internationally (Ulén and Weyhenmeyer 2007). WQOs are a useful reference for strategic planning and development assessment. WQOs are long-term goals for water quality management.

WQOs are defined as numerical concentration levels or narrative statements of indicators established for receiving waters to support and protect the designated environmental values or beneficial uses (e.g. aquatic ecosystem protection) for those waters (EPA 2007). WQOs are based on scientific criteria or water quality guidelines but may be modified by other (e.g. social, cultural, economic) inputs (EPA 2007). A WQO is for a specific waterbody and agreed by stakeholders.

The WQPP provides an approach to develop and set WQOs for reducing pollutant loads or maintaining current water quality in the region. In contrast, Water Quality Improvement Plans in other Australian states and agriculturally dominated catchments, such as reported by Drewry et al. (2008), aim to maintain current good water quality, or improve degraded water quality via long-term WQOs and short-term water quality targets. WQOs in the Darwin region have been determined for selected freshwater and estuarine waterbodies by the Department of Natural Resources, Environment, the Art and Sport (NRETAS). Methods for developing WQOs in Australia are described in detail elsewhere (e.g. Drewry et al. 2008; EPA 2006). Briefly, local data is used to determine WQOs taking into account undisturbed reference sites. WQOs were developed for physico-chemical parameters and pollutants for the outer, mid and upper estuarine areas of the Darwin Harbour as a component of the WQPP, and are presented in further detail in Fortune and Maly (2008). An example of a draft WQO for freshwater streams in the Darwin region is total N <230 μm g/L. WQOs will provide local government, planners, managers and developers with water quality guideline levels to be sustained or achieved when considering or assessing coastal developments.

3.3. Catchment Pollutant Load Monitoring and Modelling

As a component of the WQPP, event water quality monitoring combined with empirical export coefficient modelling has helped evaluate catchment loads and effects of future land use. The pollutant export coefficients are presented and discussed in this section. Load-based data is necessary in the WQPP to help evaluate (i) diffuse source quantities; (ii) the impact of diffuse and point source loads from the catchments to the harbour and upper estuaries on water quality and water quality objectives; and (iii) potential future load-based targets. The use of catchment diffuse and point source pollutant load data was also required in the modelling using the Darwin Harbour hydrodynamic model – that component of the WQPP is briefly presented in section 3.4.

To improve load estimates to the harbour for current and future modelling projects, water quality monitoring has included ambient and event-based monitoring from telemetered stream gauge network sites. Diffuse source pollutant monitoring has included predominantly urban, rural or undeveloped catchments (Table 1). Monitoring data collected during the 2006/07 wet season from the Moil, Howard, Elizabeth, Bennetts, Peel and Berry hydrographic stations were used to estimate diffuse loads by Skinner et al. (2009). Water quality samples for the 2006/07 and previous wet seasons (see below) were collected using a flow weighted composite sampling technique, or by automatically collected discrete sampling equipment. The number of discrete samples in the composite sample, typically varied from about 20 to >100 depending on event size.

An estimate of longer term pollutant export coefficients standardised for rainfall, i.e., per meter of rainfall, to help account for variability of rainfall between years, has also been determined as a key component of the WQPP project. The average pollutant export coefficients based on data from up to six years of wet season data, standardised for rainfall, are presented in Table 2. The number of wet seasons data for urban catchments was 2-3 and for non-urban catchments was 1-6; the year varied from 1990/91 to 2006/07 depending on site. Urban land use contributes greater rainfall-standardised pollutant export coefficients than non-urban land use in the Darwin Harbour region (Table 2). Similarly, pollutant flow-weighted mean concentrations for the 2006/07 wet season for urban land use were greater than for non-urban land use (Table 3).

Table **1**. Land use for selected Darwin Harbour urban and rural catchments used to estimate (adapted from Skinner et al. 2009).

Category	Catchment name	Land use (% range)			Area (ha)
		Undeveloped	Rural	Urban	
Undeveloped	Bennetts, Peel, Celia, Manton	86-100	0-12	0-2	940-5 670
Rural	Berry, Howard, Elizabeth	53-56	39-41	2-6	9 000-14 600
Urban	Moil, Karama	0	2-23	77-96	36-49

Table **2.** Pollutant export coefficients (2006/07 wet season) and rainfall-standardised pollutant export coefficients for Darwin Harbour catchment categories (adapted from Skinner et al. 2009).

Season	Pollutant	Category		
		Undeveloped	Rural	Urban
2006/07 wet season[1]	TSS (kg/ha)	85	73	930
	TN (kg/ha)	4.7	2.6	14
	TP (kg/ha)	0.06	0.08	1.5
		Non-urban		Urban
Average rainfall standardised [2]	TSS (kg/ha/m)	57		440
	TN (kg/ha/m)	1.65		5.50
	TP (kg/ha/m)	0.06		0.59

[1] Data for Peel, Bennetts, Berry, Howard, Elizabeth, and Moil catchments. Rainfall for 2006/07 wet season varied from 1.46 m for Peel catchment to 1.81 m for Bennetts. Average rainfall is 1.67 m. [2] Data for urban: Moil and Karama catchments; data for non-urban: Peel, Bennetts, Celia, Berry, Howard, Elizabeth, and Manton catchments. Rainfall varied with catchment and year; six years data was used for Elizabeth catchment for example. Rainfall range over these catchments was 1.27-2.31. Average rainfall for urban catchments 1.8 m; for non urban catchments 1.82.

Table **3.** Pollutant flow-weighted mean concentrations for 2006/07 wet season catchment categories (unpublished data). Catchments as in note 2 above.

Pollutant	Category		
	Undeveloped	Rural	Urban
TSS (mg/L)	16	18	56
TN (mg/L)	0.61	0.41	0.82
TP (mg/L)	0.01	0.01	0.09

An evaluation of the impact of diffuse and point source loads from the catchments to the harbour and upper estuaries, via hydrodynamic modelling, is presented in the next section.

3.4. Darwin Harbour Estuarine Hydrodynamic Modelling

Integration Within The WQPP Project

Harbour hydrodynamic modelling has also been an important component in the WQPP to aid understanding of harbour and estuarine processes, and evaluate potential effects of increased pollutant catchment loads from increasing population. Parts of Darwin Harbour are poorly flushed, particularly in the dry season which may have implications for estuarine water quality from impacts associated with point sources such as STPs. Consequently, the aim of this component of the WQPP was to gain understanding of how urbanisation and STP discharge scenario discharges may affect water quality, and therefore the practical implications to maintaining the WQOs.

Model Description

A brief description of the Darwin Harbour hydrodynamic model developed by the Northern Territory Government is presented here. As a component of the WQPP, the water quality submodel was further developed by Water Research Laboratory (WRL) to aid understanding of harbour and estuarine processes. Hydrodynamic processes in the harbour are reported in detail by Williams et al. (2006) and the model is described by Wolanski et al. (2006). The tides are asymmetric, where they move to the upper reaches of the estuary, and the peak flood tides currents are about 25% larger than at ebb tides. Tidal trapping of sediment in the upper arms of Darwin Harbour can occur. The model is the two dimensional RMA-2 model, and is suitable to simulate flow in estuaries, and predicts water flow and depth over a finite element mesh (Williams et al. 2006). Sediment-related water quality in the harbour has been simulated using the two-constituent RMA-11 sediment transport model (Williams et al. 2006). Water velocities and depths simulated in RMA-2 are used as inputs for the RMA-11 model. The model then solves advection diffusion transport equations.

Application Of The Model In The WQPP Project - Scenarios And Modelling Results

This section presents a brief overview of the application of the hydrodynamic model in the WQPP project. As part of the WQPP project, the resolution of the finite element mesh was recently improved to cover East Arm and the Elizabeth River and smaller creeks to improve simulations of the water quality where effluent discharge occurs and future development is predicted. Additionally, the model was refined around West Arm, Middle Arm and Blackmore Estuary. Inputs into the RMA-2 model include tidal elevations, STP inflows, and catchment inflows. N and P have been included recently as part of the WQPP project to evaluate scenarios on water quality and WQOs. N and P were modelled in the project as independent constituents with a single decay rate. The concentration of N and P in the harbour from catchments and sewage discharge was simulated to estimate the total maximum pollutant loads to maintain WQOs. The monthly discharge concentrations of N and P into the harbour from each STP were obtained. Catchment loads were estimated as in Skinner et al. (2009) and section 3.3.

The use of this data and the RMA-11 model enabled scenario modelling to evaluate and simulate the likely effects of increased STP discharges and urbanisation on the receiving water quality. Five scenarios below were simulated for 12 weeks, for both the wet season (January to March) and dry season (June to August). Although catchment diffuse loads at gauge stations were not monitored in the dry season (i.e. no flow), monitoring of estuarine water quality has been undertaken and modelled. This is important given that point source discharges are likely to have their greatest impact in poorly flushed areas when there are no rainfall inputs. It should be noted that comparison of modelled water quality with WQOs is constrained by the absence of set boundary conditions and modelled data are likely to be significantly underestimated.

Scenarios modelled with the Darwin Harbour model for the WQPP were:

1. a base case representing the condition for the year 2005-06 (average rainfall year);
2. a doubled STP discharge scenario to simulate an increase in population;
3. an increase in urbanisation surrounding the Elizabeth Estuary
4. an increase in urbanisation and doubled STP discharge scenario for catchments surrounding the Elizabeth estuary; and
5. a 100% urbanised catchment with five times STP discharge assumption scenario.

As no initial N or P concentration was used in the water quality simulations the results cannot be directly compared to observed water quality data or WQOs. Scenarios can only be compared to the base case scenario. A summary of selected results for site B (located in the upper Elizabeth estuary; Figure 3) and site 2 (located south of East Arm wharf; (see Figure 3) are presented in Table 4.

Table **4**. Effect of modelled scenarios on site B and site 2 (see Figure 3) in the Darwin Harbour. Mean TN concentrations (mg N/L) are presented for spring tide modelling. Scenario results can only be compared to the base case scenario, not observed data.

Scenario	1	2	3	4	5
Wet season					
Site B	0.11	0.01	0.07	0.08	0.21
Site 2	0.02	0	0.01	0.01	0.04
Dry season					
Site B	0.02	0.01	0	0.02	0.06
Site 2	0.01	0	0	0.01	0.02

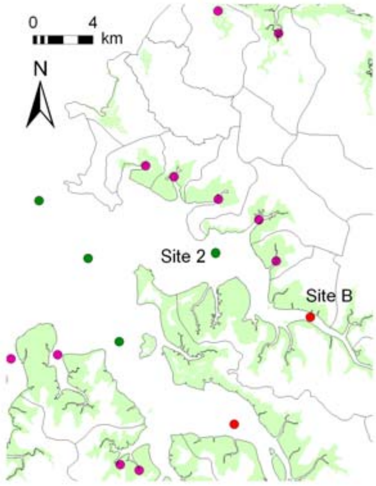

Figure 3. Selected harbour monitoring sites. Modelled water quality results in Table 4 are presented for site 2 and site B

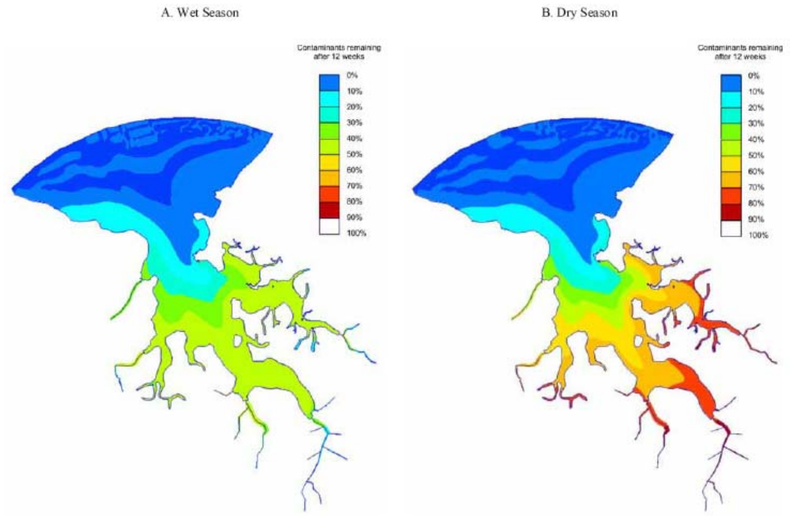

Figure 4. Percentage of nutrient constituent remaining after 12 weeks using the Darwin Harbour Receiving Water Quality Model in the WQPP (Wasco and Miller 2008).

The modelling results (Table 4; Figure 4) indicate that the wet season results are of main concern rather than the dry season. The variability in N concentration due to tidal variation is not as great for the dry season as it is for the wet season. For the N concentrations modelled in the harbour during the wet season, increases in urbanisation have a greater effect on the water quality than increases in STP discharge. N concentrations are largest in the upper part of the Elizabeth River estuary at site B. Sites in the middle of the harbour had much lower concentrations. Overall, the results suggests the concentration of N and P in Darwin Harbour is likely to increase in the future due to the increasing population of Darwin. Estuarine pollutant concentrations are likely to increase most during the wet season due to increased catchment diffuse source inflows.

4. DISCUSSION AND CONCLUSIONS

The research developed as integrated components of the WQPP suggests that increasing urbanisation will have significant impacts on water quality on a localised scale, particularly in poorly flushed upper estuaries. However, there are several limitations of the Darwin Harbour Receiving Water Quality model. A zero boundary condition has been adopted for the scenario modelling described above. This allows the direct comparison of different scenarios on water quality, but the results of the water quality simulations cannot be directly compared to sampled values or WQOs. Modelled scenario values are likely to be significantly underestimated. So far the nutrient component of the hydrodynamic modelling has been largely qualitative with further research required to provide further quantitative data for harbour and catchment management.

Several experiences in the WQPP highlighted the need for adequate data. Long-term time series hydrographic and water quality data from gauged catchments with appropriate infrastructure was vital to the development of empirical modelling approaches in estimating catchment pollutant loads. A preliminary evaluation of data to ensure aptness, spatial, seasonal, temporal variation or comprehensiveness in informing WQOs was valuable. This highlighted the need for consistent data with good temporal and spatial extent to inform the development of WQOs, particularly in the harbour waters. Much of the historical data permitted broad assessment of water quality at specific sites, however, the data imparted limited information for the parameterisation of the receiving water quality model. Future effort is proposed which will inform the model, in particular, water-sediment-nutrient interactions and temperature specific rates. The development of the receiving water quality hydrodynamic model specific to Darwin Harbour for the WQPP has been time consuming and expensive. Managing expectations in relation to this component has been challenging. Although much effort has been dedicated to the development of this modelling tool, much more work is necessary. Additionally, a more realistic approach to what can be feasibility delivered with limited data should be communicated to stakeholders.

In conclusion, water quality monitoring and modelling have increased our understanding of pollutants, loads and water quality delivered to and transported within harbour waterways. Further research is essential to improve understanding of harbour and catchment processes to support decision-making and ongoing maintenance of the WQOs to protect the region's waterways.

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