6.0 Introduction

Northern Territory's Department of Natural Resources, Environment, the Arts and Sport (NRETAS) engaged the Water Research Laboratory (WRL) at the University of New South Wales to develop a water quality model for Darwin Harbour. The concentration of nitrogen and phosphorus in the harbour, as a result of catchment runoff and Sewerage Treatment Plant (STP) discharge, was simulated to estimate the total maximum pollutant loads to achieve water quality objectives.

A RMA-2 finite element mesh of Darwin Harbour had been previously established by WRL and developed further by NRETAS for assessing the fate of dredge spoil for construction of the East Arm Port. As part of this current study the model mesh, presented in Figure 6.1, was refined around East Arm and Elizabeth Estuary to provide greater detail of the water quality in these areas where effluent discharge occurs and future development is predicted. Additionally, the model was refined around West Arm, Middle Arm and Blackmore Estuary to enhance the water quality predictions throughout the harbour.

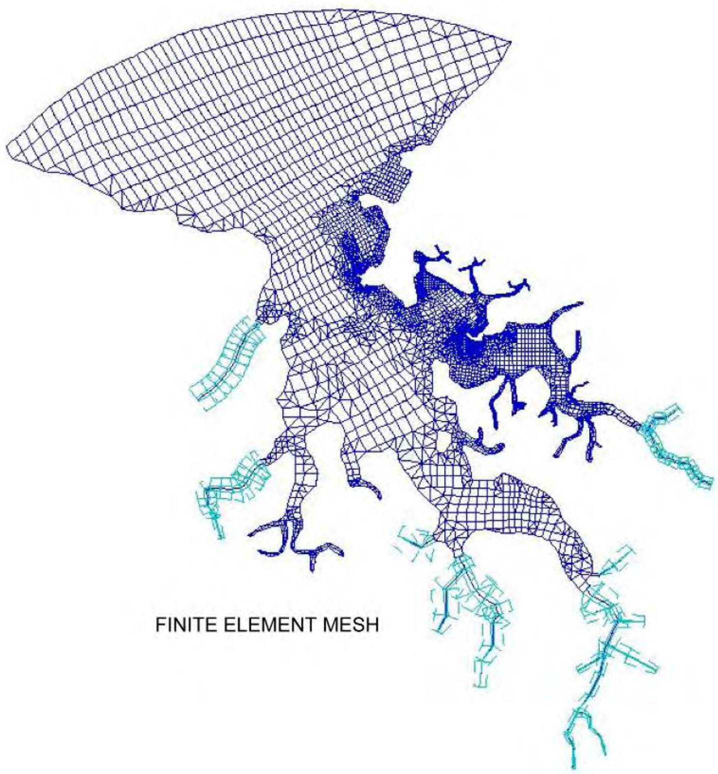


Figure 6.1: Enhanced Finite Element Mesh for the Darwin Harbour Receiving Water Quality Model.

RMA-11 was used to establish a two constituent water quality model of Darwin Harbour. A literature review was undertaken to determine suitable decay rates for nitrogen and phosphorus in the water quality model. Bulk nitrogen and phosphorus were simulated with a single decay rate and were modelled to disperse and diffuse with the tidal currents, catchment runoff, and STP discharge from the RMA-2 hydrodynamic model. Catchment loads were assessed using the methods outlined in the draft report, "The Impact of Urban Land-use on

Total Pollutant Loads Entering Darwin Harbour" (Skinner *et al*., 2008), with STP loads supplied by Power Water Corporation.

6.1 Catchment and STP Loads

The RMA-2 model of Darwin Harbour requires discharges into the harbour from the surrounding catchments and STPs in order to define its boundary conditions. The RMA-11 model boundary conditions require load concentrations to be applied to the RMA-2 inflows to simulate the water quality in the harbour. In this section the data and methods used to calculate these inputs are described.

6.1.1 STP Method

Inflows into the harbour at monthly and daily time periods for each STP were supplied from NRETAS. The discharge of nitrogen and phosphorus into the harbour from each STP was provided by NRETAS in the form of monthly discharge concentrations for the year 2005. As concentrations were provided at monthly time periods, both the RMA-2 and RMA-11 boundary conditions were both specified on a monthly period.

6.1.2 Catchment Method

Hydrographs for Elizabeth River and Blackmore River were supplied. Scaling these hydrographs for the other catchment discharging into the harbour is possible using hydrologic modelling, however the use of these methods was beyond the scope of this study. As no hydrographic data was available for the other catchments discharging into the harbour the following method was applied to estimate discharges. Skinner *et al*. (2008) presents runoff coefficients for selected catchments. Runoff coefficients for Elizabeth and Blackmore were taken as being representative of non-urban catchments with the runoff coefficients for the Karama and Moil catchments taken as being representative of urban catchments. For all the remaining catchments, runoff coefficients were linearly interpolated between these values based on the proportions of area in each catchment, which was classified as urban and non-urban as presented in the following equation:

$$C = C_{urban} x\ U + C_{non\text{-}urban}\ x\ (1 - U)$$

where:

C = runoff coefficient
C urban = representative coefficient for an entirely urban catchment
C non-urban = representative coefficient for an entirely urban catchment
U = percentage of catchment area classified as urban.

6.1.3 Pollutant Load Scenarios

Five scenarios were simulated by the Darwin Harbour Receiving Water Quality Model (DHRWQM). These were as follows:

1. A base case representing the condition for the year 2005-06 (Average rainfall year).
2. A doubled STP discharge scenario, in which the discharge for each STP is doubled to simulate an increase in population.
3. An increased urbanisation scenario, in which the catchments surrounding the Elizabeth Estuary had their fraction of urban area increased to simulate urbanisation
4. An increased urbanisation and doubled STP discharge scenario, in which the discharge from each STP is doubled and catchments surrounding the Elizabeth estuary had their fraction of urban area increased

5. A 100% urbanised and five times STP discharge scenario.

Each scenario was simulated for 12 weeks, for both the wet season (January, February, and March) and dry season (June, July, August). Bulk nitrogen and bulk phosphorus were simulated for each scenario. The bulk concentration of each pollutant is the sum of the pollutant mass regardless of its organic or inorganic form before it is lost to the atmosphere.

The nitrogen and phosphorus concentrations entering the harbour through catchment runoff were calculated by adapting the method outlined in Skinner *et al* (2008). In this report export coefficients are derived for each pollutant allowing the total nitrogen and phosphorus load for each catchment to be calculated.

The results of all simulations were analysed at the Darwin Harbour Marine Monitoring sampling points in the East Arm of Darwin Harbour extending out towards the ocean boundary. The sampling sites are presented in Figure 6.2 and their chainages, measured from the finite element mesh are presented in Table 6.1.

Table 6.1. Chainage of Darwin Harbour Monitoring Locations.

Monitoring Site	Chainage (km)
DHM B	8
DHM 2	15
DHM 13	23
DHM 6	28
DHM 8a	35

Results for the base case or 'business as usual' and other scenarios are presented in Table 6.2 - 6.6 for each monitoring station as a mean pollutant concentration, a maximum pollutant concentration and a minimum pollutant concentration within the given tidal range. Comparison of modelled results to Water Quality Objectives for upper, mid and outer estuarine water types show little derivation from the benchmark with all mean values below the upper trigger value. Highlighted values indicate where water quality objectives have been exceeded and are typically representative of pollutant maximums. It should be noted that comparison of modelled water quality with Water Quality Objectives is constrained by the absence of set boundary conditions and modelled data is likely to be significantly underestimated.

Figure 6.2: Sampling stations used for modelling scenarios.

Table 6.2. Comparison of modelled base or 'business as usual' with Water Quality Objectives. *(Highlighted values indicate exceedance)*

		Wet Season								Dry Season							
		Spring Tide				Neap Tide				Spring Tide				Neap Tide			
Monitored sites	Chainage (km)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)
Bulk Nitrogen																	
Site B	8	0.110	0.260	0.040	0.300	0.110	0.213	0.070	0.300	0.020	0.020	0.014	0.300	0.020	0.020	0.010	0.300
Site 2	15	0.020	0.030	0.010	0.300	0.015	0.030	0.010	0.300	0.010	0.010	0.002	0.300	0.000	0.010	0.000	0.300
Site 13	23	0.000	0.010	0.000	0.270	0.000	0.010	0.000	0.270	0.000	0.000	0.001	0.270	0.000	0.000	0.000	0.270
Site 6	28	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.001	0.270	0.000	0.000	0.000	0.270
Site 8a	35	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440
Bulk Phosphorus																	
Site B	8	0.009	0.015	0.005	0.026	0.008	0.012	0.007	0.026	0.004	0.005	0.002	0.026	0.004	0.005	0.003	0.026
Site 2	15	0.002	0.004	0.001	0.026	0.002	0.003	0.001	0.026	0.001	0.003	0.001	0.026	0.001	0.002	0.001	0.026
Site 13	23	0.000	0.001	0.000	0.020	0.000	0.001	0.000	0.020	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.020
Site 6	28	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.020
Site 8a	35	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.016

The base case scenario for wet and dry seasons represents the discharges from each STP for the year 2005, and the estimated runoff from each catchment for an average year of rainfall for Darwin. Table 2 presents the results of the Base Case simulations.

Water quality varies significantly with the tide cycle in Darwin Harbour. For the wet season spring tide, nitrogen concentration can vary from 0.04 mg/L to six and a half times that value of 0.26 mg/L. Water quality fluctuates inversely to the tide, so that when the water depth is low, the pollutant concentration is high.

Table 6.3. Comparison of modelled scenario for doubled STP discharge with Water Quality Objectives.

		Wet Season								Dry Season							
		Spring Tide				Neap Tide				Spring Tide				Neap Tide			
Monitored sites	Chainage (km)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)
Bulk Nitrogen																	
Site B	8	0.010	0.000	0.010	0.300	0.010	0.010	0.020	0.300	0.010	0.020	0.012	0.300	0.010	0.020	0.010	0.300
Site 2	15	0.000	0.010	0.000	0.300	0.000	0.010	0.000	0.300	0.000	0.011	0.002	0.300	0.000	0.010	0.000	0.300
Site 13	23	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270
Site 6	28	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.001	0.270	0.000	0.000	0.000	0.270
Site 8a	35	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440
Bulk Phosphorus																	
Site B	8	0.003	0.001	0.004	0.026	0.003	0.002	0.003	0.026	0.004	0.006	0.002	0.026	0.004	0.005	0.002	0.026
Site 2	15	0.001	0.002	0.000	0.026	0.001	0.002	0.001	0.026	0.001	0.003	0.001	0.026	0.001	0.002	0.000	0.026
Site 13	23	0.001	0.000	0.000	0.020	0.001	0.000	0.001	0.020	0.001	0.001	0.000	0.020	0.001	0.001	0.000	0.020
Site 6	28	0.001	0.001	0.000	0.020	0.001	0.001	0.001	0.020	0.001	0.001	0.000	0.020	0.001	0.001	0.001	0.020
Site 8a	35	0.000	0.001	0.000	0.016	0.001	0.001	0.000	0.016	0.001	0.001	0.000	0.016	0.000	0.001	0.000	0.016

For the doubled STP discharge scenario, the discharge from each STP is doubled to model an increase in the population of Darwin. Nonetheless all catchment parameters remain identical to those in the base case scenario. In this simulation only the impact of an increased STP discharge on water quality in Darwin Harbour is assessed.

Doubling STP discharge has little affect on the concentration on nitrogen, with the mean increasing only by 0.01 mg/L at DHM 2 and DHM B, both of which are in the upper reaches of the Elizabeth River estuary. The relative impact on phosphorus concentration is marginally larger with an increase of 0.003 mg/L in the mean phosphorus concentration in the wet season at DHM B, and 0.004 mg/L in the dry season. This represents a doubling of the phosphorus concentration in the wet season at this monitoring station. Phosphorus concentration decrease seawards and is almost undetectable beyond DHM 13 within the main body of Darwin Harbour.

Table 6.4. Comparison of modelled scenario for increased urbanisation with Water Quality Objectives.

		Wet Season								Dry Season							
		Spring Tide				Neap Tide				Spring Tide				Neap Tide			
Monitored sites	Chainage (km)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)
Bulk Nitrogen																	
Site B	8	0.070	0.170	0.020	0.300	0.070	0.150	0.040	0.300	0.0000	0.0010	0.0010	0.300	0.0010	0.0000	0.0020	0.300
Site 2	15	0.010	0.020	0.000	0.300	0.010	0.010	0.000	0.300	0.0001	0.0000	0.0000	0.300	0.0001	0.0010	0.0000	0.300
Site 13	23	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	-0.0006	-0.0010	0.0000	0.270	0.0000	0.0000	0.0000	0.270
Site 6	28	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	-0.0006	-0.0010	0.0000	0.270	0.0000	0.0000	0.0000	0.270
Site 8a	35	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440	-0.0005	-0.0010	0.0000	0.440	0.0000	0.0000	0.0000	0.440
Bulk Phosphorus																	
Site B	8	0.010	0.024	0.003	0.026	0.010	0.021	0.006	0.026	0.000	0.001	-0.001	0.026	0.0000	0.0000	0.0000	0.026
Site 2	15	0.001	0.002	0.000	0.026	0.001	0.002	0.001	0.026	0.000	0.002	0.000	0.026	0.0000	0.0000	0.0000	0.026
Site 13	23	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.020	0.0000	0.0000	0.0000	0.020
Site 6	28	0.000	0.001	0.000	0.020	0.001	0.001	0.000	0.020	0.000	0.000	0.000	0.020	0.0000	0.0000	0.0000	0.020
Site 8a	35	0.000	0.001	0.000	0.016	0.000	0.001	0.000	0.016	0.000	0.000	0.000	0.016	0.0000	0.0000	0.0000	0.016

In the increased urbanisation scenario the catchments surrounding East Arm had the percentage of their catchment classified as urban increased. The Hudson Creek, Myrmidon Creek, Palmerston South, Mitchell Creek and Elizabeth Arm catchments all had their percentages of urbanised land increased by approximately 40-50%. The purpose of this was to simulate the effects of urbanisation on water quality in Darwin Harbour, while isolating the increases in urbanisation from increases in STP discharge due to an increased population.

The results in this case are appreciably different from those observed when the STP discharge was doubled. There is almost no change during the dry season for the any of the pollutant concentrations. This is likely to be as a consequence of negligible flow occurring during the dry season, so increasing urbanisation does not increase pollutant loads enough to cause an increase in the concentration in the harbour. There is one parameter where the minimum recorded phosphorus concentration at DHM B actually decreases. This is most likely a result of the increase in flow outweighing the effects of an increase in the pollutant load (Wasko & Miller, 2008). The trends for the wet season are in contrast to those in the dry season. Generally, there is a doubling of phosphorus concentrations in the upper reaches of Elizabeth estuary, and a 60 % increase in the mean nitrogen concentration recorded at DHM B. Seaward of Wickham Point the changes in nitrogen and phosphorus concentrations are insignificant.

Table 6.5. Comparison of modelled scenario for increased urbanisation and doubled STP discharge with Water Quality Objectives.

		Wet Season								Dry Season							
		Spring Tide				Neap Tide				Spring Tide				Neap Tide			
Monitored sites	Chainage (km)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)
Bulk Nitrogen																	
Site B	8	0.080	0.170	0.040	0.300	0.080	0.150	0.060	0.300	0.020	0.020	0.010	0.300	0.010	0.020	0.010	0.300
Site 2	15	0.010	0.030	0.000	0.300	0.010	0.020	0.010	0.300	0.010	0.010	0.000	0.300	0.000	0.010	0.000	0.300
Site 13	23	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270
Site 6	28	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270	0.000	0.000	0.000	0.270
Site 8a	35	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440	0.000	0.000	0.000	0.440
Bulk Phosphorus																	
Site B	8	0.013	0.025	0.007	0.026	0.013	0.022	0.009	0.026	0.004	0.006	0.003	0.026	0.004	0.005	0.002	0.026
Site 2	15	0.002	0.004	0.000	0.026	0.002	0.003	0.002	0.026	0.001	0.003	0.001	0.026	0.001	0.002	0.000	0.026
Site 13	23	0.001	0.000	0.001	0.020	0.001	0.000	0.001	0.020	0.001	0.001	0.000	0.020	0.001	0.001	0.000	0.020
Site 6	28	0.001	0.001	0.001	0.020	0.001	0.001	0.001	0.020	0.001	0.001	0.000	0.020	0.001	0.001	0.001	0.020
Site 8a	35	0.000	0.001	0.000	0.016	0.001	0.001	0.000	0.016	0.001	0.001	0.000	0.016	0.000	0.001	0.000	0.016

The increased urbanisation and doubled STP discharge scenario is a combination of both the increased urbanisation scenario (Table 4) and the doubled STP discharge scenario (Table 3). The Hudson Creek, Myrmidon Creek, Palmerston South, Mitchell Creek and Elizabeth Arm catchments all had their percentages of urban land increased by approximately 40-50%. In addition all the STP's had their volume of discharge for each month doubled, while the concentration of total nitrogen and phosphorus exiting the plants was unchanged. The purpose of this was to simulate the effects of urbanisation on water quality in Darwin Harbour.

Relative to the base case, mean nitrogen concentrations for the dry season have doubled, and for the wet season increased by 70 %. Phosphorus concentrations are also doubled for the dry season, however for the wet season, the increase in mean phosphorus concentration at DHM B is 150 %. The increases in concentration are less pronounced seaward and at DHM 13 the change in both contaminant concentration is slight. The increase in the maximum pollutant concentration observed over the tidal cycle is similar in magnitude to that observed for the average concentrations.

Table 6.6. Comparison of modelled scenario for 100% urbanised catchments and five times the STP discharge with Water Quality Objectives.

		Wet Season								Dry Season							
		Spring Tide				Neap Tide				Spring Tide				Neap Tide			
Monitored sites	Chainage (km)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)	Mean (mg/L)	Max (mg/L)	Min (mg/L)	WQOb (mg/L)
Bulk Nitrogen																	
Site B	8	0.21	0.37	0.11	0.300	0.21	0.34	0.16	0.300	0.06	0.08	0.05	0.300	0.06	0.07	0.04	0.300
Site 2	15	0.04	0.07	0.02	0.300	0.03	0.06	0.03	0.300	0.02	0.04	0.01	0.300	0.02	0.03	0.01	0.300
Site 13	23	0.01	0.02	0.01	0.270	0.01	0.01	0.01	0.270	0.01	0.01	0.00	0.270	0.01	0.01	0.00	0.270
Site 6	28	0.01	0.01	0.00	0.270	0.01	0.01	0.01	0.270	0.01	0.01	0.00	0.270	0.01	0.01	0.01	0.270
Site 8a	35	0.01	0.01	0.00	0.440	0.01	0.01	0.00	0.440	0.00	0.01	0.00	0.440	0.00	0.01	0.00	0.440
Bulk Phosphorus																	
Site B	8	0.034	0.055	0.020	0.026	0.034	0.050	0.028	0.026	0.016	0.022	0.010	0.026	0.016	0.021	0.010	0.026
Site 2	15	0.007	0.014	0.003	0.026	0.007	0.011	0.005	0.026	0.005	0.012	0.002	0.026	0.004	0.008	0.003	0.026
Site 13	23	0.002	0.002	0.002	0.020	0.002	0.002	0.002	0.020	0.002	0.002	0.001	0.020	0.002	0.002	0.001	0.020
Site 6	28	0.002	0.002	0.001	0.020	0.002	0.002	0.002	0.020	0.002	0.002	0.001	0.020	0.002	0.002	0.002	0.020
Site 8a	35	0.001	0.002	0.000	0.016	0.001	0.002	0.001	0.016	0.001	0.002	0.000	0.016	0.001	0.002	0.001	0.016

In the 100% urbanised and five times STP discharge scenario all the catchments surrounding Darwin Harbour have their percentage of urbanised land set to 100%. STP discharges are magnified five fold from the base case, however the concentration of pollutants remains unchanged.

At DHM B mean nitrogen concentrations for the dry season quadruple, however they are still less than those of the base case in the wet season. Mean wet season nitrogen concentrations at DHM B triple, with the maximum nitrogen concentration observed increasing by 140 % as compared to the base case. Mean phosphorus concentrations at DHM B are approximately 5 times that recorded for the base case. Although the modelled phosphorus concentration is quadrupled at DHM 2, it is still similar to that at DHM B for the base case. Similar trends are observed for phosphorus concentrations in the dry season.

6.2 Modelled Loads and Receiving Water Quality

As a result of the forecasted increase in population and urbanisation of Darwin, the nitrogen and phosphorus loads entering the harbour from catchment runoff and STP discharge will increase.

Scenarios simulated illustrate that urbanising the catchments surrounding the Elizabeth River estuary have a much greater impact on the overall water quality than doubling all STP discharges. In approximate terms, the cumulative effect of these two changes resulted in a doubling of the mean nitrogen concentration in the upper reaches of the Elizabeth River estuary (DHM B). However, the magnitude of this change was less than the tidal variation for the base case wet season spring tide. Mean phosphorus concentrations at the same location increased by 150%. The magnitude of this change was greater than the tidal variation of phosphorus for the base case wet season spring tide. For the extreme scenario of all catchments 100% urbanised and STP discharge increased five fold, mean nutrient concentration levels for the wet season spring tide at DHM 2 did not exceed the mean base case levels at DHM B. Further towards the mouth of the harbour, the change in the concentration of pollutants decreases to levels similar to that of the detection limit for normal laboratory nitrogen and phosphorus analyses. Although increasing urbanisation appeared to have greater impacts on broader modelled water quality this does not negate the potential for localised impacts around point discharges in the harbour, particularly where they emanate into smaller tidal systems.

In order to accurately simulate the concentration of nitrogen and phosphorus in Darwin Harbour and compare modelled results with water quality guidelines, regular water quality sampling is required with knowledge of the level of the tide at the time of sampling. Water quality in the harbour is highly influenced by tides, and the amount of water entering from surrounding catchments. Higher inflows into the harbour result not only in pollutants being dispersed more, but the pollutant loads also increasing. To accurately calibrate the water quality model decay rates for nitrogen and phosphorus also need to be experimentally determined, as both the nitrogen and phosphorus water quality cycles are highly dependent on the local aquatic environment (Wasko and Miller, 2008).

6.3 DHRWQM Toolbox

For each scenario tested the boundary conditions must be established. The methods described in WRL technical report 2008/22 for land use and STP changes are repeated for each scenario, and as flows differ in the dry and wet season, these inflows must also be recalculated. The methods described in these sections lend themselves to be implemented using a computer algorithm, hence a toolbox was developed to create the RMA-2 and RMA-11 input files for each of the scenarios simulated. Figure 6.3 presents the Graphical User Interface (GUI) of the RMA inflow toolbox.

The toolbox requires the following user inputs:

- A rainfall hyetograph in csv format;
- STP hydrographs and pollutant concentrations in csv format; and
- A data file with catchment areas and the relevant inflow nodes in the RMA finite element mesh in csv format.

Each of these files has a ready-to-use template which is easily modified. The hydrographs and hyetograph were formatted on a monthly time period, however any time period can be used in the toolbox.

In the graphical interface a number of parameters can be modified so different scenarios can be modelled without the need for updating the input files. The percentage of area in each catchment which is urbanised can be modified, as well as the rainfall factor. Runoff coefficients as well as export coefficients, termed load factors in the toolbox, can also be updated.

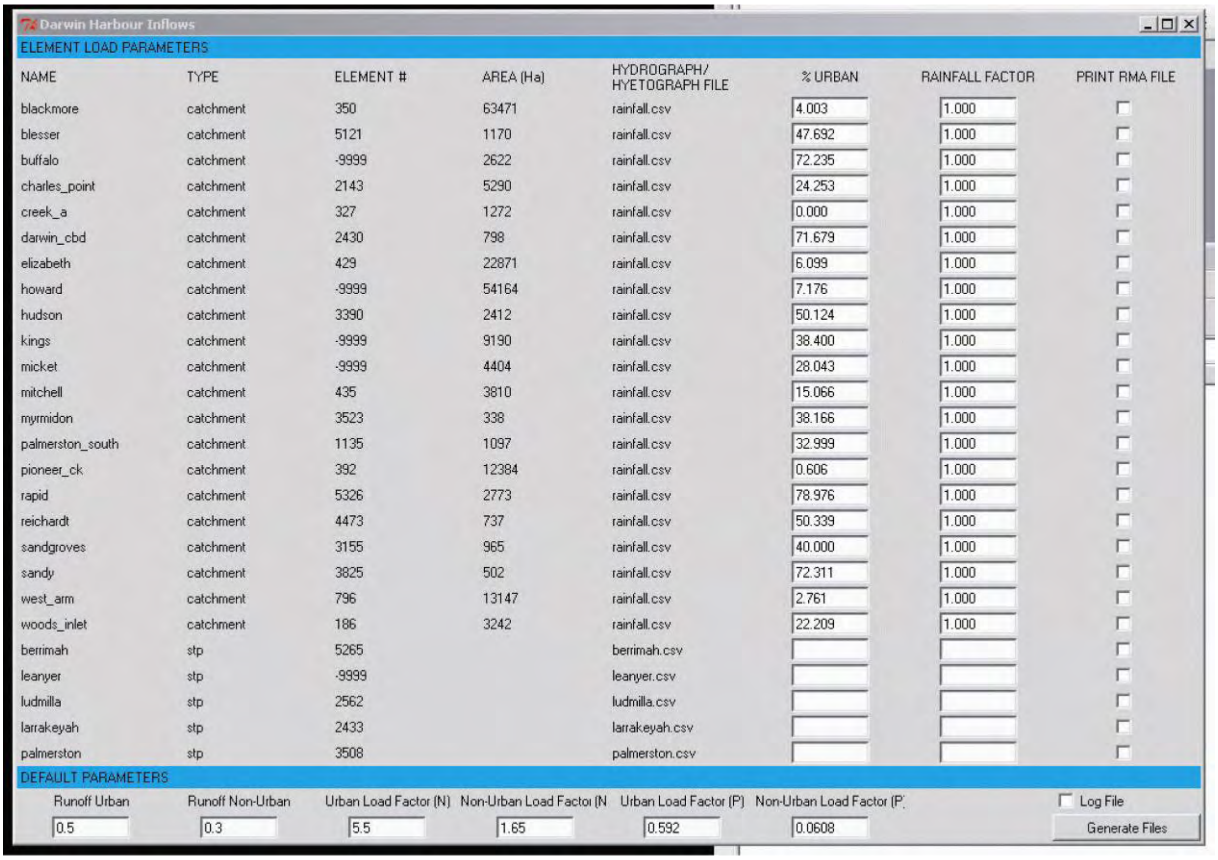


Figure 6.3: Graphical User Interface of DHRWQM Toolbox.

6.4 Model Simulations and Uncertainty

6.4.1 Enhanced finite element mesh.

The finite element mesh for Darwin Harbour is shown in Figure 6.1. The mesh was previously established by the Water Resources Laboratory (WRL) and has been improved by NRETAS in conjunction with the need to model port developments in the Harbour. For the purposes of the WQPP the mesh has been further refined throughout the East Arm of Darwin Harbour and the upper reaches of Elizabeth estuary. The resolution was particularly refined around the areas of Sadgroves Creek, Reichardt Creek, Blesser Creek, Hudson Creek and Myrmidon Creek to allow modelling of water quality in these estuarine reaches with the provision of wetting and drying for the estuary with tidal cycle. STP discharge is also associated with two of these tidal tributaries, Blesser Creek and Myrmidon Creek, and as a consequence these creeks were refined for suitable predictions in the vicinity of the point discharges. However, the upper reaches of the Harbour Arms require further bathymetry to adequately reflect hydrodynamic processes in these reaches. Currently these reaches exist as 1D elements until further data is available and refinement possible.

6.4.2 Decay Rate

Water quality was simulated in Darwin Harbour using a two constituent RMA-11 model (King 2006). Bulk nitrogen and phosphorus were modelled as arbitrary constituents within the RMA-11 model with a single decay rate applied to each constituent.

It was deemed appropriate to use a single decay rate to encompass all the individual processes for both the nitrogen and phosphorus cycles as site specific data for each is unavailable. A more detailed study including all the sub processes within the N and P cycles including the settlement of particles as well as temperature were not appropriate given the paucity of data. Single decay rates for both wet and dry seasons were chosen as the level of uncertainty in the chosen decay rate was larger than the potential change in the decay rate due to temperature effects.

The rationale for choosing a decay rate was to select a key step in the nutrient cycle and use its decay rate. Ammonification was chosen with a typical value of 0.1/day. Similar decay rates for phosphorus are published with a similar degree of variability. The use of a single rate enabled concentrations for each pollutant to be independently calculated.

6.4.3 Boundary Conditions

Two boundary conditions are required for the RMA-11 water quality model. The first is the ocean boundary, which corresponds to the initial concentration in the harbour. The second is the N and P loads which are discharged into the harbour from surrounding catchments as diffuse sources and other point sources such as STP's.

A zero boundary condition has been adopted for the scenario modelling. This allows the direct comparison of different loading scenarios on water quality. It is recognised that as a consequence of adopting this approach that the results of the water quality simulations cannot be directly compared to sampled values. Although comparison is made in the above tables the values modelled are likely to be underestimated.

Priority research undertaken in conjunction with TRaCK (Tropical Rivers and Coastal Knowledge Consortium) has found that oceanic sources entering the harbour are significant and likely to represent a net import of nutrient. Although limited, data collected in the outer estuary region suggests reasonably high organic Nitrogen concentrations which support current research on sediment and nutrient sources in the harbour. Future simulations with appropriate boundary condition settings may result in more comparable simulations for water quality.

6.5 Sensitivity Testing

The sensitivity of the DHRWQM to decay rate is presented in Figure 6.4. A time series of the concentration of Nitrogen at monitoring station DHM 2 in East Arm is plotted for two different decay rates, 0.1/day and 0.05/day. The concentration of Nitrogen in the harbour is inversely proportional to the decay rate, with the magnitude of the change in decay rate being equal to the magnitude of change in the concentration of N at the station. The concentration of P is identically sensitive to the decay rate. Due to the absence of data, a rate of 0.1/day is adopted based on available literature.

Comparison of modelled water quality in the absence of data to inform complex nutrient processing, particularly for phosphorus and modelling runs without boundary condition have resulted in an under-estimate of resultant receiving water quality. However simulations have broadly provided a better appreciation for the resultant water quality for modelled scenarios and their magnitude.

Flushing rates and the diffusivity parameter were also tested. An absolute diffusion was chosen over the use of scaled diffusion as both East and Middle arms have similar flushing rates.

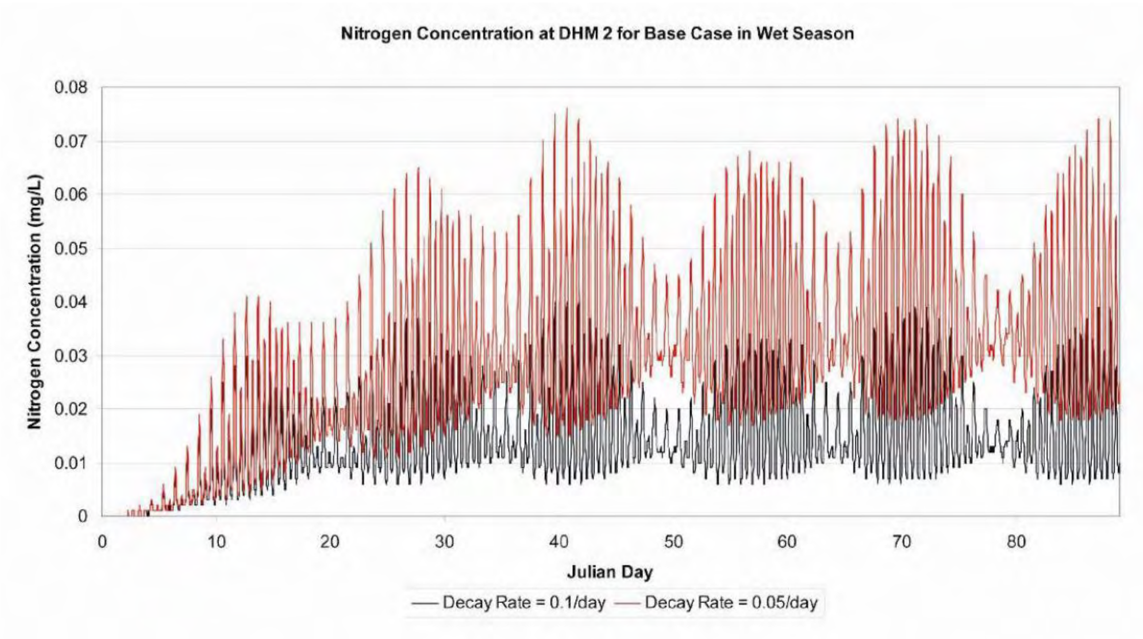


Figure 6.4. Sensitivity testing of decay rates for nitrogen at DHM site 2.

Flushing index was also produced to estimate the relative residence times of a pollutant or constituent within the harbour over time. The index values represent the time in days it takes for a conservative constituent to be removed from the harbour by advection and/or diffusion. The comparison of the flushing index with available water quality data is reasonably analogous and supports the categorisation of estuarine water types (Fig 6.5).

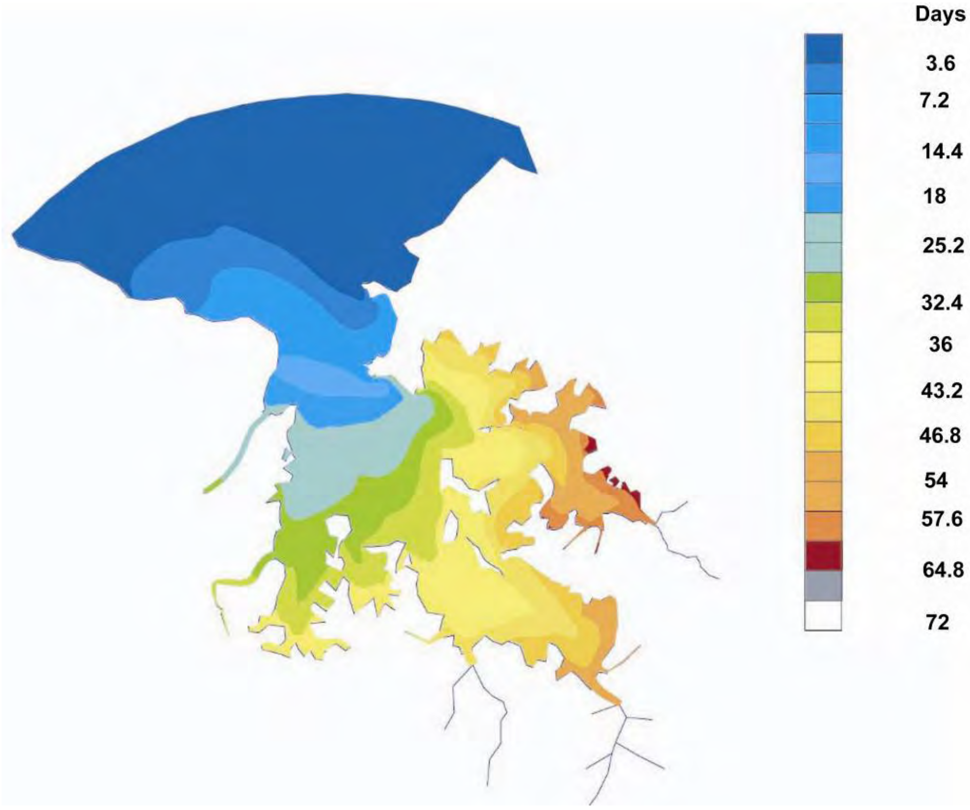


Figure 6.5: Flushing zones for Darwin Harbour during the dry season. The index values represent the time in days it takes for a conservative constituent to be removed from the harbour by advection / diffusion.

Sensitivity of model results to the initial concentration of nitrogen in the harbour was also tested (Wasko & Miller, 2008). For an initial elevated concentration scenario the nitrogen in the system quickly decays back to levels similar to those of the simulation where a zero initial concentration was specified. The increase in concentration between these scenarios ranged from 2-50% depending on tide highlighting the variability associated with tidal cycle in Darwin Harbour.

6.6 Improving Model Predictions

Refinement of models will continue as monitoring data is collected and specific research addresses critical parameter inputs. Given the specialised nature of model development and enhancement ongoing expertise will need to be sought. The ongoing costs associated with such expertise will necessitate the dedication of funds and resources on an ‘as needs’ or priority basis.

Further coding of the RMA model has been sought to allow the model to better simulate the complex water and sediment quality interactions and processes broadly addressed above. Future iterations of the model will provide enhanced sensitivity to better reflect water quality conditions making use of the priority research outcomes.

Section 7. Priority Research

7.0 Receiving Water Quality Model

Although a range of values for modelling parameters have been produced, the appropriateness of these will require further research given the unique nature of Darwin Harbour and its catchment. Focus on the following elements to inform and calibrate the receiving water quality model was recommended by the Water Quality Modelling Program (WQMP):

- Chlorophyll a and algae growth and settling rates
- Algal nutrient relationships
- Nitrogen Cycle
- Phosphorus Cycle
  - Understand nutrient dynamics their biogeochemical role, important oxidation-reduction reactions and the affect on other variables such as oxygen.
  - Key processes: Ammonification – release of ammonia due to decay processes, nitrification oxidation of ammonia to nitrate (NO_3) directly or to nitrite (NO_2).
  - Uptake – accumulation of inorganic nitrogen by plants during photosynthetic growth. Nitrogen fixation – reduction of N_2 to ammoniated compounds.
- Sediment, nutrient and algae cycling and interaction.

A series of research projects have been initiated to provide insight into key water quality processes in Darwin Harbour and inform model parameters. Outcomes of these projects are detailed below. It should be noted that not all of the research undertaken to date will necessarily inform all requirements of the receiving water quality model. Ongoing refinement of models and investment in future monitoring and research effort will be required.

7.1 Key outcomes of priority research, model calibrations and verification.

7.1.1 Sampling for bulk stable isotopes, lipid markers and pigments was undertaken to allow for a direct comparison of organic matter sources and algal species between the "impacted" and un-impacted sites. (TRaCK Project, Leader: Michele Burford) Results found that:

- Phytoplankton biomass, as indicated by chl-a concentration, covers a range from about 1.3 mg m^{-3} to about 2.9 mg m^{-3}. Biomass was similar at the reference creek and Frances Bay sites with 2.34 and 2.40 mg m^{-3} respectively, and slightly lower at Myrmidon Ck sites with 1.87 mg m^{-3}. At all sites, the pigment composition is similar indicating similar phytoplankton communities. Diatoms as indicated by fucoxanthin are the dominant algal group with green algae (chl-b), possibly euglenophytes or type 2 prasinophytes; cyanophytes (zeaxanthin) and cryptophytes (alloxanthin) present at all sites.

- Microphytobenthos biomass, as indicated by chl-a concentration, covers a range from about 0.76 $\mu g\ g^{-1}$ wet wt. to about 5.14 $\mu g\ g^{-1}$ wet wt. Biomass at Myrmidon Ck and the reference creek sites were 3.41 and 3.78 $\mu g\ g^{-1}$ wet wt. respectively, with lower average biomass at the Frances Bay sites with 1.07 $\mu g\ g^{-1}$ wet wt. The average biomass at the sewage discharge site, was approximately 2 – 2.5 times less than the biomass at the other sites at the same impacted tidal creek. The pigment composition at all sites was dominated by fucoxanthin indicating that benthic diatoms dominated the MPB community.

7.1.2 Determination of water column respiration, benthic nutrient fluxes, denitrification, nitrogen fixation and phosphorus retention in the sediments was undertaken. (TRaCK Project, Leader: Michele Burford). Results reveal that:

- A comparison between wet and dry season revealed differences in the benthic fluxes in the un-impacted creek with higher respiration rates (115 mmol C m^{-2} d^{-1}) and net nutrient influxes in the wet season compared to lower respiration rates (67 mmol C m^{-2} d^{-1}) and net nutrient effluxes in the dry season (under dark conditions). The water column nitrogen concentrations were significantly higher in the wet season (2.5 uM) than the dry season (0.4 uM) but there was no difference in the P concentrations. However, these concentrations are still low compared to the nutrient concentrations measured at the sewage outfall of Myrmidon Creek (34 uM N and 25 uM P).

- At the sewage outfall site, benthic fluxes in the wet season were similar to those measured in the dry season (both measured under high tide conditions) with low respiration rates (69 and 86 mmol C m^{-2} d^{-1} in the wet and dry season respectively) and a net efflux of nutrients. Benthic fluxes were also measured at this site in the wet season at low tide when the water column nitrogen and phosphorus concentrations were over 100 and 25 times higher respectively, with the N and P most likely sourced from the sewage outfall. At low tide, sediment respiration rates were much higher (236 mmol C m^{-2} d^{-1}) and there was a net influx of NOx-N and P.

- Measured nitrogen fixation rates were insignificant in the intertidal sediments.

- Denitrification (measured as net N_2 fluxes) appears to be an important process for removing nitrogen from the system, accounting for approx. 90% of the DIN flux from the sediments. At the sewage outfall site, there was no difference in denitrification between the wet and dry seasons under high tide conditions (approx 7 mmol N m^{-2} d^{-1}) but there was net N_2 uptake (-1.4 mmol N m^{-2} d^{-1}) under low tide conditions.

7.1.3 Primary productivity studies were also undertaken to compare productivity between impacted and un-impacted sites. (TRaCK Project, Leader: Michele Burford) Preliminary results reveal that:

- Primary productivity, standardised to chlorophyll *a,* was higher overall in February 2008 (wet season) than in October 2007 (dry season). This coincided with higher ammonium concentrations and lower salinities in both creeks. Water temperatures did not vary substantially between sampling occasions. It should also be noted that there were substantial differences in primary productivity at the sewage outfall site (Ma) on different stages of the tide (one week apart). High tide productivity values were lower than those on the outgoing tide.

- The depth-integrated areal primary productivity values were similar between wet and dry seasons, and between the creek receiving sewage and the reference creek. The exception was the second day of sampling on the outgoing tide at the sewage discharge site which was substantially higher than the other sites and times.

- Primary productivity rates were highly variable for the microphytobenthos within sites reflecting the greater heterogeneity of sediments compared with the water column. In February 2008 (wet season), primary productivity rates appeared to be higher in Myrmidon creek than the reference creek, but the high variability within sites make it difficult to draw clear conclusions.

7.1.4 Algal bioassays were used to determine whether phytoplankton and microphytobenthos were nutrient limited, and whether sewage inputs affect this. (TRaCK Project, Leader: Michele Burford).

- In October 2007, phytoplankton responded to nitrogen addition. In February 2007, phytoplankton also responded to nitrogen addition at all sites except the sewage discharge site. The response at this site was variable. On the first occasion there was a response to nitrogen and phosphorus, on the second occasion there was only a response to nitrogen. This probably reflects changes across the tidal cycle.

- Bioassays for the microphytobenthos showed a different response to the water column. There was no evidence of a response to nutrient additions, with much greater variability between replicates that that seen in the water column. This reflects the heterogeneous nature of the sediment.

7.1.5 AIMS and Griffith University synthesised previously collected data to establish estimates on net ecosystem production and biogeochemical fluxes in Darwin Harbour. (TRaCK Project, Leader: Michele Burford)

- This study examined a tropical macrotidal estuary, Darwin Harbour, in northern Australia to identify the key sources of production and characterize the biogeochemical processes in the subtidal water column and sediment (Burford *et al*, 2008).

- Production and nutrient cycling in the mangroves and intertidal mudflats surrounding the harbour were estimated based on more limited data. Darwin Harbour is adjacent to the city of Darwin, a rapidly growing urban area. During the two year study, material fluxes were dominated by tidal exchange with net import of C, nitrogen (N) and phosphorus (P).

- The main source of primary production was the extensive area of mangroves and resulted in a net autotrophic system (P_G:R = 2.1). This ratio is considerably higher than temperate estuaries throughout the world, but comparable with other tropical, mangrove-dominated estuaries. The system is likely to be more nitrogen than P-limited, based on low N:P ratios, low dissolved bioavailable N concentrations (ammonium (NH_4^+), nitrate (NO_3^-), urea), high particulate carbon (C):N ratios and evidence that phytoplankton growth in bioassays was stimulated by NH_4^+ addition.

- The largest source of new N input to the system was the dissolved oceanic source, with N fixation on the intertidal mudflats and subtidal sediments of less significance, and river and sewage being minor inputs (Fig 7.1).

- Primary productivity in the water column was relatively high and coupled with low dissolved bioavailable N resulted in high rates of N recycling in the water column.

- Nutrient inputs from urban development are unlikely to have major effects on water quality in the short term. However, this study highlights the importance of maintaining mangrove and mudflat intertidal zones in supporting productivity and biogeochemical cycling in the harbour.

- On a whole-of-harbour basis is it unlikely that increases in human impacts, i.e. sewage and river inputs, will substantially affect biogeochemical processes in the short term, given that loads are relatively small compared with oceanic inputs.

- Localised effects in less flushed areas of Darwin Harbour adjacent to urban inputs are possible. Additionally, this work suggests that mangroves are the major source of productivity and provide an important habitat for many fish and other aquatic species.

- Recreational fishing is an important activity in this region, and protecting key habitats for fish and crustaceans, as well as protecting water quality and aesthetics is central to ensuring the future sustainability of Darwin Harbour.

7.1.6. Sources of sediments and sediment inputs to Darwin Harbour and sediment transport. (TRaCK Project, Leader: Prof David Parry)

- Parry *et al* (unpublished) suggested that 40 % of the fine sediment in the harbour emanates from the catchment. This approximation has been questioned on three grounds i.e. small number of samples, representativeness of the entire catchment area and Darwin Harbour and the limited geochemical tracers in data analysis.

- Wasson *et al* (2007) reported that the topsoil tracers ^{210}Pb (excess) and ^{137}Cs show that most fine sediment being transported in the creeks and rivers that flow into the Harbour comes from the channels rather than from sheet erosion of hillslopes. This is an important conclusion for land managers, but needs to be verified by taking additional samples which will also be used for the sediment input study**.**

- Further work will aim to collect a greater range of sediment inputs from the catchments as end members for mixing models; quantify lead isotope ratios and metals for the additional samples to add to the REE (Rare Earth Element) profiles and quantify sediment sources in the catchment.

- Preliminary research supports work undertaken on net ecosystem production and biogeochemical fluxes (Burford *et al*, 2008) in Darwin Harbour where significant nutrient (Carbon & Nitrogen) loads may be emanating from the oceanic boundary.

7.1.7 Nutrient absorption to suspended sediment (Charles Darwin University, Leader: Prof David Parry).

- The rate at which nutrients are absorbed to sediments is an important parameter for the DHRWQM and little information on such rates for tropical estuarine systems exists. The relationship between sediment and nutrients of Darwin Harbour and just how much is absorbed is a question which requires laboratory investigation.

- Charles Darwin University has been engaged to undertake a series of experiments to ascertain maximum absorption rates of nutrients to suspended sediment.

- Given the inherently turbid macrotidal waters of Darwin Harbour and its associated wet season flood events suspended sediment is expected to play a chief role in the export of particulate bound nutrients.

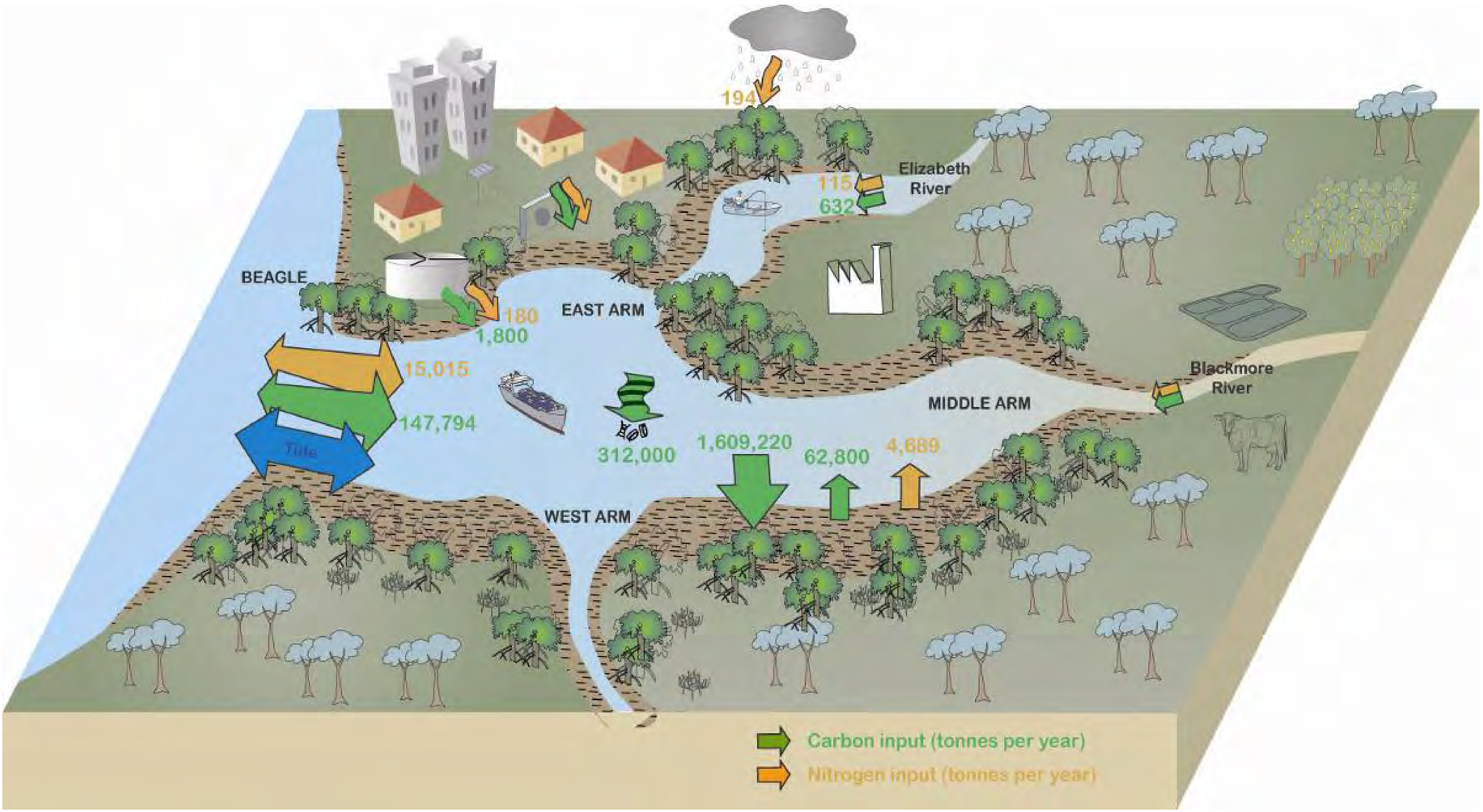


Figure 7.1: Conceptual diagram of estimated load contribution drawn from priority research activities (AIMS and Griffith University)

7.1.8 Development and calibration of a water quality model for Buffalo Creek to enable comparison with the broader receiving water quality model for Darwin Harbour (Charles Darwin University, Leader: Prof Eric Valentine).

Buffalo Creek is a tidal creek receiving wastewater discharge from nearby Leanyer-Sanderson Sewage Ponds. This creek is on occasion subject to minimal tidal flushing and as a consequence experiences regular events of eutrophication.

Little is known about the assimilation of excess nutrients to this creek or the hydrodynamic nature of Shoal Bay, the terminus of Buffalo Creek. To aid our understanding of the fate of nutrients entering the creek and its capacity to assimilate excess nutrients a water quality model will be developed. This tool will also build on our ability to determine locally derived guidelines and objectives where there is a paucity of data.

Additionally, the comparison of this model with that of the broader harbour will be valuable given the likely disparity of these systems based on spatial location and hydrology.

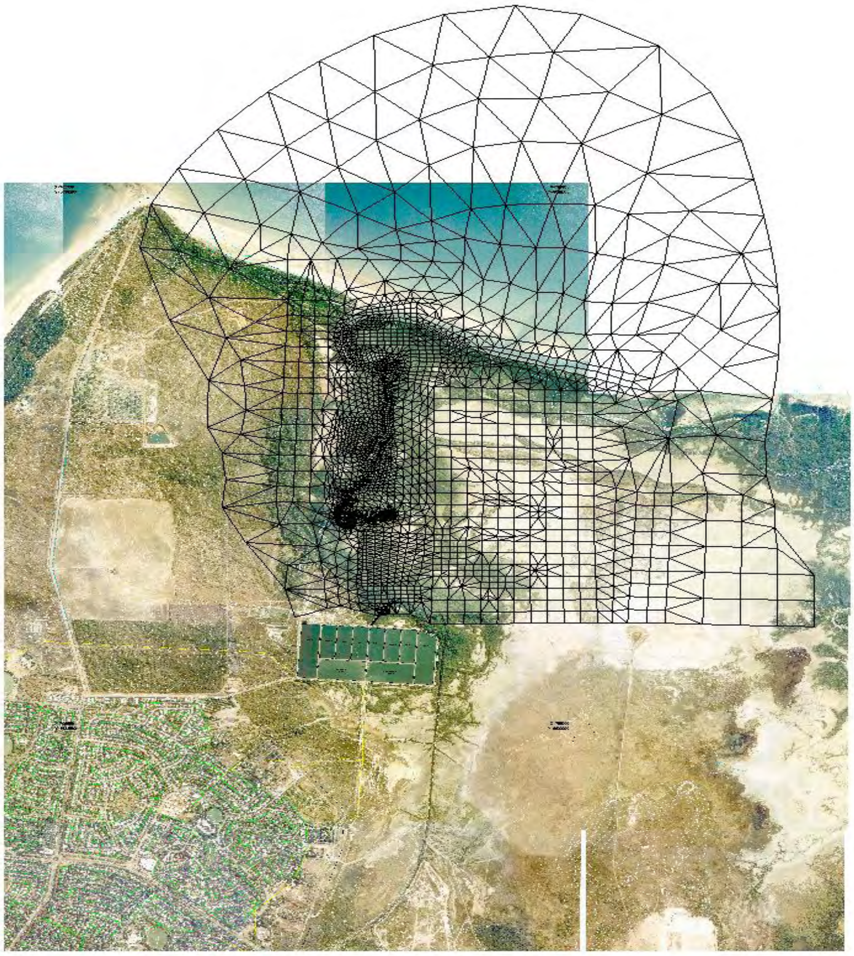


Figure 7.2: Finite element mesh of the Buffalo Creek Water Quality Model.

Outcomes of this priority research and model development include:

- The development of a basic hydrodynamic model which has been constructed for the creek, salt flats and coastal waters. The model uses the Research Management Associates RMA10 software. The mesh for the model is shown in Figure 7.2. The model is a combination of one-dimensional and two-dimensional representations. Most of the area modelled is described in two dimensions.

- Initial testing and calibration. Further work will improve the topographical and hydraulic roughness description and develop the verification of the outputs.

- Preliminary testing for conservative constituents. Calibration will be based on existing field measurements. Future work will develop the model description for pathogens and nutrients which will be informed by other work being carried out for this project in December 2008 as an extension to the TRaCK estuarine research on Darwin Harbour.

7.1.9 Power Water Corporation investment in monitoring effort at STP discharge sites (PWC, Leader: Alex Donald).

In July 2008 the Power Water Corporation funded a series of water quality surveys with a focus on wastewater discharge points associated with the Larrakeyah and East Point outfalls in Darwin Harbour. This data will contribute to improving model calibration and validation in the vicinity of these outfall discharges and extend our understanding of the hydrodynamic influences on mixing zones and constituent decay.

7.2 Catchment Event Monitoring & Improving Loads Assessment

Continued monitoring effort in key tributaries representative of core land uses in the catchment will be important to verify modelled loads. In particular some attention to soluble fraction nutrients, continuous flow time-series data and establishing sound empirical relationships particularly for suspended sediment are necessary.

However, the consistency of this sampling regime has been intermittent due to difficulties associated with equipment failure and availability, inadequate infrastructure (stations), inappropriate stage-flow ratings and inadequate resources have constrained attempts to maintain an annual wet season sampling regime.

Regardless of shortcomings available data and current commitments to ongoing event based monitoring is proposed to aid the development of event based water quality objectives.

Event-based WQOs will be based on similar approaches undertaken in the wet-dry tropics of Queensland. These have been typically derived from several years of data, where flow and water quality data are available. Similar to the methodology used to derive ambient water quality objectives, event-based WQOs are based on the following:

- An appropriate level of protection for a catchment or catchments is determined (HCV, SMD, HD or other);
- Event mean concentrations (EMC) where flow data is available; or
- 80th percentiles of data where flow data is not available.

There is likely to be some uncertainty associated with the use of event mean concentrations (EMC) given the variation in sediment and pollutant supply over the course of an event, the extremes in seasonality and antecedent conditions. Data collected over several years in a number of catchments in the Darwin Region will be used to derive these interim objectives. Further refinement of these objectives would be expected as more data becomes available.

7.2.1 Importance of Event Sampling.

An important feature of freshwater inflows from catchments in Australia is that the variance in rainfall in Australia is high, and for many catchments the majority of the water, nutrient and sediment exports occur for a few days of the year (Webster and Harris, 2004). In tropical Australian catchments such as Darwin, 50% of the annual discharge can occur in 3% of the time (Letcher *et al*., 1999). Capturing these events is vital to quantifying catchment loads as most variation in sediment and nutrient concentration occurs during this period. Kernohan and Townsend 2000 found that a large proportion of nitrogen was transported early in the wet season, owing to high base flow concentrations. More recent work (unpubl) has also found high proportions of suspended sediment also entrained with the first flush and more generally the mass of contaminants transported throughout the wet season is generally dependent on the volume of water rather than contaminant concentration. Particular focus on these sampling events is required to ensure loads are captured and data input to any catchment model is representative of stream flow and constituent characteristics.

7.2.2 Performance of Rating Curve and discharge measurements.

A rating curve for a specific stream location is developed by making discharge measurements at many different stream stages to define and maintain a stage-discharge relation. Discharge can be measured based on a cross sectional assessment using velocity meters or can be determined using a boat-mounted doppler techniques. Once this relationship is developed, it is possible to obtain estimates of discharge simply by obtaining stream depth data. At most gauged sites long term ratings have been determined. However, for more recently established gauge stations such as Peel and Bennett Creek additional gauging is needed to determine rating curves with some confidence. The industrialised catchment of Winnelle also requires additional attention. Discharge at sites where lined drains terminate large urban and industrial subcatchments such as Winnellie and Moil are usually transient. Obtaining sound discharge measurements at these sites is difficult and further assessment using a doppler velocity technique is warranted to improve the existing rating curve.

7.2.3 Sampling Regime Improvements.

The cost of analysis for catchment loads is substantial. Discrete sampling regimes provide improved precision of load estimates however the ongoing costs of such a regime is far more substantial than composite or flow proportional sampling. In order to reduce unnecessary sampling datalogger programs will require further refinement of stage height parameters. The highly variable wet season flows can make this task difficult particularly at newly established stations where only a few seasons have been experienced. Alternatively where over sampling might have occurred samples can be selected based on stage height fluctuations and time, however ideally datalogger programs will need to be revised to alleviate excessive sampling.

7.2.4 Priority Stations for monitoring focus.

Stations at Peel and Bennett Creek's have only recently collected hydrological and water quality data. Therefore, characterising stream flow and load contaminant behaviour at these sites is still underway. Establishing a sound rating curve via an adequate gauging regime for these sites in conjunction with water quality data will enable better load estimation and parameterisation of the model.

A number of stations have recently been improved to enable water quality sampling and remote telemetry. The performance of new dataloggers at these stations will require ongoing review to ensure consistent data collection.

7.2.5 Opportunities to Extend Monitoring Networks.

A number of stations in the catchment do not have water quality capacity. More often than not the infrastructure does not allow the installation of samplers or the existing logger configuration is unable to accommodate samplers. In some cases access during the wet season is significantly restricted posing issues for servicing, sample preservation and safety.

As far as practicable, station placement is based on representative land use in the region and the main tributaries entering Darwin Harbour. A number of existing hydrographic stations in the catchment may further contribute to the current water quality monitoring network. Opportunities to extend water quality capabilities of stations in the catchment, particularly where load estimations and models might identify significant load sources should be examined.

Due to the undeveloped nature of western side of the harbour and absence of major stream networks, gauge stations have not been dedicated to this region. However, historical and current data for undisturbed catchments have allowed estimates from this region through appropriate export coefficients. Catchments to the west and south of Darwin are relatively large and uniform in the land uses they represent.

Historical loads assessment from the industrial catchment of Winnellie has provided limited insight into export coefficients for loads assessment. A more contemporary examination of the catchment is required given the degree of additional development in the largely industrial and commercial estate.

8.0 Introduction

Water quality monitoring data is reasonably agreeable with WQO's, however a number of areas show localised deviations from benchmark values. In some areas data is limited and further monitoring effort will be directed to these areas to validate the objectives and inform modelling simulations.

To maintain Water Quality Objectives and load targets a number of initiatives will be progressed in addition to the formulation of an Implementation and Adaptation Strategy which will attempt to facilitate protection and improvement in water quality. Many of these initiatives are broadly described below (Table 8.1 & 8.2), however further negotiation with relevant partner agencies and organisations are necessary to achieve adoption and define timeframes.

8.1 Point Source Discharge Management Actions/Interventions.

The primary supply of point source loads enters Darwin Harbour from wastewater treatment plants. At close to average wet season rainfall, diffuse loads were the main source of sediment to Darwin Harbour, and contributed about two-thirds of the phosphorus to Darwin Harbour. By contrast the greater proportion of nitrogen entering Darwin Harbour, where algal growth is most likely to be nitrogen limited, is input from wastewater discharges. However more significant is the contribution of phosphorus from these point sources.

Discharge from wastewater treatment plants in Berrimah, Leanyer and Palmerston flow to tidal creeks systems within the Darwin Harbour. The impact of high nutrient inflows to these receiving waterways is the subject of current research under the TRaCK consortium. Understanding the assimilative capacity of these ecosystems will be vital in developing the underpinning parameterisation of the water quality model for Darwin Harbour and for assessing the fate of nutrients.

Other point sources include a number of aquaculture operations which extend along Middle Arm to the upper reaches of the Blackmore River. An assessment of the impact that these point discharges may have on receiving waterways is yet to be explored as data is limited.

Based on preliminary data some estuarine zones of the Harbour will not be able to maintain water quality objectives in the near future without significant investment in intervention activities. Many of these zones are subject to waste discharge licence.

Table 8.1. Minor and Major Point Sources – Broader Management Interventions.

Recommended activities for implementation:	Lead Agency	Support Agency/Group
Ambient monitoring and modelling of mixing zones for point discharge.	Licensee's/ NRETAS	DAC
Implement Industry Best Practice Environmental Management.	Industry/NRETAS	DPI
Environmental Management Plans (EMP) for discharge licensees/point source dischargers.	NRETAS/ Licensees	

Explore upgrades to tertiary treated wastewater or reuse options (prioritisation of point sources).	PWC	NRETAS/DHAC
Examine other regulatory mechanisms to limit loads including licence limits	NRETAS	DHAC
Incorporate works to reduce pollutant loads.	DPI/NRETAS	Industry/DHAC
Initiate collaborative monitoring/intervention activities to improve water quality and reduce loads.	NRETA	Industry/Community Groups/Indigenous Rangers/PWC/DCC/ DHAC
Public Information – Health of the Harbour reports including point source contribution to receiving waterways	NRETAS	PWC/DHAC
Establish WQOs under the *Water Act 1992* to protect declared Beneficial uses.	NRETAS	Industry/PWC/Councils/ DHAC

8.2 Diffuse Pollutant Load Management Action/Interventions

The chief diffuse pollutants associated with new developments are sediment and nutrients. The primary pollutants of concern for existing urban developments are dissolved nutrients, suspended solids and toxicants.

Table 8.2. Diffuse Urban and Rural Sources – Broader Management Interventions.

Recommended activities for implementation:	Lead Agency	Support Agency/Group
WSUD principles – grey water reuse options, landscape design, treatment systems, water saving fittings/appliances.	DPI	NRETAS
Implement and assess compliance with Erosion & sediment control guidelines.	DPI/NRETAS	DRDPIFR
Implement and audit local/ regional erosion and sediment control plans, including those for specific developments.	NRETAS	DPI
Education and community information/awareness.	NRETAS/DPI	Greening Australia, Local Landcare groups DHAC
Industry best practice management – soil, nutrient, pesticide, herbicide use/application practises.	NRETAS DRDPIFR	Horticulture Industry
Protection of riparian zones and employ adequate buffer zones.	NRETAS/DPI	
Implement Clearing guidelines.	NRETAS	DPI
Litter and gross sediment traps /stormwater	DCC	DPI

management-maintenance.		
Community education/awareness: Litter abatement, minimising water use.	NRETAS/DPI	Community based groups/DHAC
Implement Stormwater Management Plan.	NRETAS	DPI/DCC/Industry/DHAC
Monitor loads and the effectives of management measures including treatments system associated with WSUD.	NRETAS/DPI	DHAC

Incorporation of WSUD in new developments or 'Greenfield's' will enable the capture, treatment and release of water to mimic natural flows and reduce loads to receiving waterways.

Stormwater management planning has been undertaken with a focus on the proposed subdivision of Bellamack in Palmerston. Recommendations for sound contingency planning and treatment systems have been examined. Strategies for monitoring the effectiveness of treatment systems are underway. The wet-dry tropics of the Darwin region present a number of challenges to more traditional WSUD approaches elsewhere in Australia. Trialling the usefulness of treatment systems will establish a robust set of design systems adapted for the region which are effective in ameliorating the effects of suspended sediment and nutrients.

Where feasible 'Brownfield' approaches should attempt to examine and implement options for WSUD (retrofit), attempt to incorporate WSUD into any redevelopment opportunities, minimise impervious surfaces and resulting conveyance of surface flow in addition to identifying options for effective gross pollutant traps. Community education and engagement will be another vital component of any implementation and adoption strategy particularly when promoting total water cycle management where private premises are encouraged to adopt water saving opportunities.

8.3 Implementation activities for achieving urban targets – Bellamack Case Study.

The new urban development of Bellamack will be a showcase of WSUD in the wet dry tropics. Design of treatments systems will aim to achieve 80% reduction in TSS loads and a 45% and 60% reduction in TN and TP respectively.

To ensure the protection of Mitchell Creek and Darwin Harbour, stormwater quality objectives have been established for the operational phase of Bellamack. These objectives require specific reductions in pollutant load based on best practice stormwater treatment. The numerical values of the load-based targets are based on achievable load reductions from current best practice stormwater management infrastructure operating in Darwin climatic and pollutant export conditions and operating near the limit of its economic performance. This means that higher load reductions could potentially be achieved, but substantial extra cost would be incurred to obtain a very small additional water quality benefit.

The specific stormwater quality management objectives that apply to Bellamack were established through desk top analysis and discussion of the results at the WSUD Objectives Workshop held on the 14th June 2007 (Table 8.3).

Table 8.3. Stormwater quality objectives for Bellamack (Operational Phase)

Constituent	Discharge Criteria
Total phosphorus (TP)	60% reduction in post development mean annual load
Total nitrogen (TN)	45% reduction in post development mean annual load
Total suspended solids (TSS)	80% reduction in post development mean annual load
Gross pollutants	90% reduction in post development mean annual load

Because there will be limited commercial and no industrial land uses within Bellamack, other pollutants such as hydrocarbons, metals and anthropogenic litter are not expected to be generated in significant loads and therefore the WSUD management strategy does not specifically focus on these pollutants. However, each of these pollutants would be managed appropriately by the proposed WSUD stormwater treatment systems.

Treatments systems will incorporate bioretention and wetland systems into the subdivision landscape to ameliorate loads entering the nearby Mitchell Creek and Elizabeth River systems (Fig 8.1 and 8.2). Monitoring of these treatment systems will focus on measuring TN, TP and TSS loads via a series of gauge stations located up and downstream of the treatment systems. These stations will be engaged over several wet seasons to assess the effectiveness of these systems and guide WSUD options for future developments.

The implementation of WSUD in the region is a significant intervention action in the protection and maintenance of water quality.

8.3.1 Wetland Systems

Ephemeral wetlands with deep water zones, as described in ‘Water Sensitive Urban Design Strategy for Bellamack’ is the preferred option for this subdivision (Fig 1). This option is the most sympathetic to the climate, location and ecology of Bellamack, in particular the hydrology and high evapotranspiration during the dry season which favours ephemeral waterbodies.

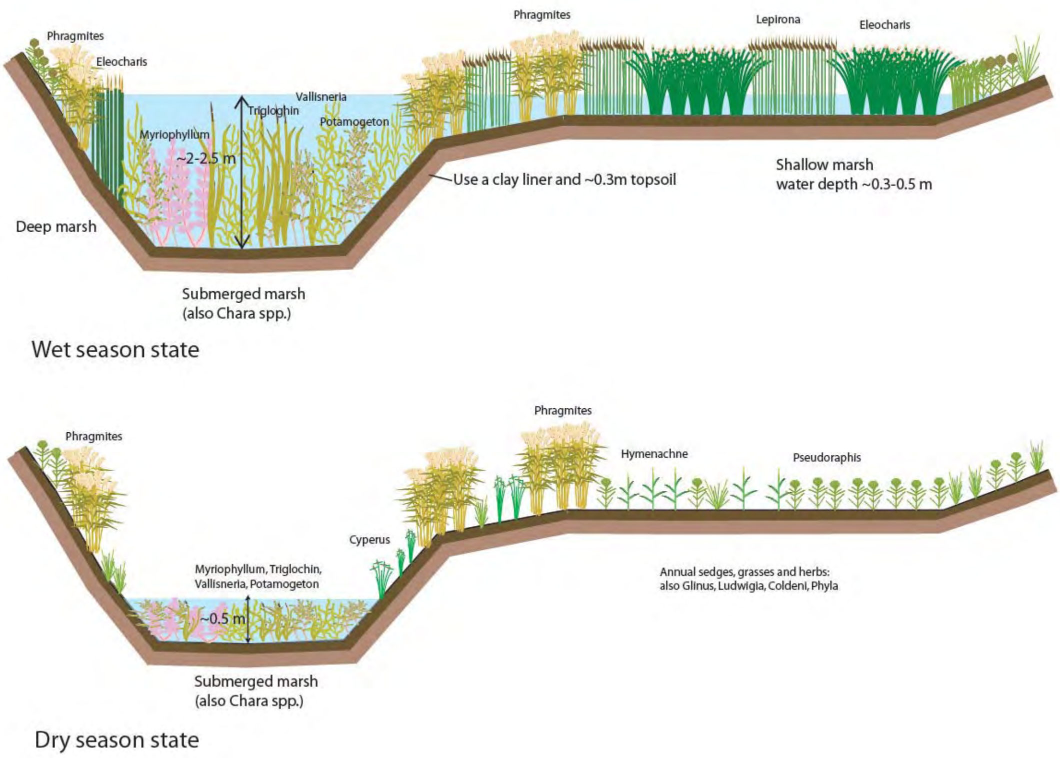


Figure 8.1: Conceptual diagram of an ephemeral wet/dry wetland.

8.3.2 Bioretention Basins (Raingardens)

Bioretention basins are vegetated areas where stormwater runoff is filtered through a soil layer (e.g. sandy loam) as it percolates downwards. It is then collected in a drainage layer via perforated under-drains and flows to downstream waterways or storages for reuse.

Bioretention basins typically use temporary ponding of 0.2-0.4 m depth above the filter media surface to increase the volume of runoff treated through the filter media. The nature of the bioretention basins, being planted soil profiles, means there is a reasonable amount of flexibility regarding the size, shape and location of the systems. As such, there are opportunities to integrate the bioretention basins as landscape features within the overall development layout. Some examples of bioretention systems are shown in Figure 2.

Figure 8.2: Examples of Bioretention systems to be used within the Bellamack subdivision to reduce loads entering nearby waterways.

8.4 Climate Change in the Region

The speed and extent of human induced climate change may have unprecedented impacts on aquatic ecosystems and their vigour in the region. Several of these impacts can be predicted with some confidence and others can be minimised with anticipatory activities.

The most likely consequences of climate change for the NT are:

- Loss of extensive coastal floodplain systems through seas level rise. Floodplain systems are susceptible given their low elevation and proximity to the coast. Changes in salinity can result in marked changes in vegetation and correspondingly the ecological communities they support.
- Loss or retraction of Territory islands.
- Reduced viability of coral reef systems with elevated water temperature and potentially increases in acidity.
- The tolerance thresholds for some species will be exceeded, particularly reptiles such as turtles and crocodiles for which temperature determines the sex of hatchlings.
- The severity of fires may degrade catchments and increase conveyance of surface overflows or runoff bringing with increased nutrient and suspended sediment load.
- Change or loss of suitable habitat for some species or environments.
- Likelihood of new disease, weeds and pests or increased incidence of existing disease, weeds and pests that may impose increasing strain on the regions ecosystems.
- Increase in the intensity and frequency of severe weather events. Increasing runoff events will result in higher than average load contribution, increased erosion and scouring of river and stream channels. All of these processes have the propensity to degrade water quality and undermine set Water Quality Objectives.

Factoring in the potential impacts of climate change to future monitoring and modelling efforts will be sought through the development of monitoring and modelling strategies. Regular review of the implementation and adaptation strategy will allow the consequences of climate change to be recognised and actions undertaken to minimise their effect.

Section 9. Progressing a program of Water Quality Modelling & Monitoring

9.0 Priority Investment Review

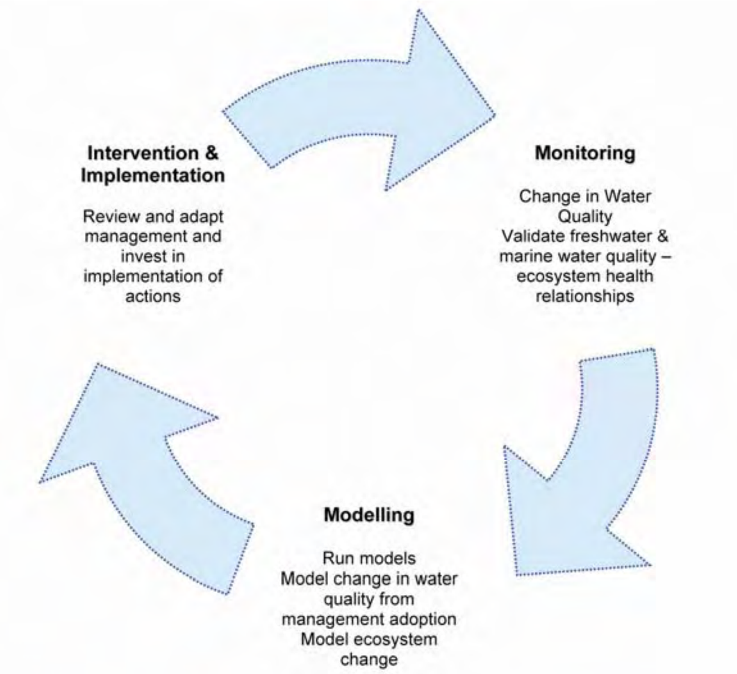
Table 9.1 has been adapted from the document entitled 'Water Quality Modelling Program for Darwin Harbour'. The revised table addresses investment in priority monitoring and modelling activities undertaken as part of the preparation phase of a WQPP for Darwin Harbour.

A large proportion of the proposed activities has been completed or is currently underway. Some of the monitoring and modelling tasks are subject to further funding bids either through Commonwealth and/or NT Government funding streams. The implementation of priority activities will be reviewed annually to ensure research and monitoring activities continue to inform modelling and management in the region.

Refinement of models will continue as monitoring data is collected and specific research addresses critical parameter inputs. Given the specialised nature of model development and enhancement ongoing expertise will need to be sought. The costs associated with such expertise will necessitate the dedication of funds and resources on an 'as needs' basis and will be further addressed in the development of subsequent monitoring and modelling strategies as part of the WQPP.

9.1 Integrated Monitoring and Modelling

It is proposed that modelling and monitoring activities are integrated to determine the effectives of management interventions. Monitoring and models will continue to inform planning and management in the region to ensure the protection of beneficial uses and water quality.



Future monitoring and modelling effort will require ongoing partnership arrangements with research institutions and other stakeholders. Opportunities for collaborative effort will be examined as part of the future development of monitoring and modelling strategies for the region and their implementation.

Table 9.1: Priority Investment Review.

Monitoring/Research Actions	Implementation Status (Nov 2008)
1. Synthesis of existing information Synthesis of historical data and studies will involve a workshop with researchers and agencies previously conducting research in Darwin Harbour to develop a report on the findings. (TRaCK, NRETA and others)	Completed and resulting data made available to modellers.
1.1 Estimate historic rates of sediment and nutrient loads to Darwin Harbour based on sediment cores.	Complete as part of Catchment loads reporting.
2. Intensive field campaigns during the wet season/dry season to quantify the effect of key catchment inputs, e.g. sewage outfalls, on primary and secondary production, and key nutrient and carbon processes on adjacent mudflats and the water column.	Complete in conjunction with TRaCK consortium. An extension to this program of work was funded in June 2008 with Buffalo Creek the subject of study. Field work was undertaken in December 2008 and the results of this work will be reported by March 2009 in conjunction with TRaCK milestone reporting requirements.
3. Examination of potential bioindicators of land based inputs, e.g. fish, crustaceans, molluscs.	To be undertaken – subject to current funding bid.
4. Develop tracing methods for sources of pollutants.	Trialled as part of TRaCK collaborative research.
5. Sediment dynamics (sedimentation, resuspension, transport, bioturbation, sources.	To be undertaken – subject to current funding bid.
6. Algae population dynamics (algal growth / die-off/ biomass). – determined as part of AIMS research in 2004 – synthesis of sediment data required to complete this.	Partially met by AIMS/TRaCK research.
7. Nutrient inputs and availability – budget.	Estimates complete via empirical modeling and research undertaken by AIMS/Griffith University. A conceptual diagram was produced to describe major nutrient pathways (Nitrogen and Carbon).
8. Catchment runoff loads Catchment water budget, notably runoff.	Completed as part of Catchment loads report. The development of a more process orientated model is underway.
9. Development of a conceptual model of the effect of nutrient and sediment loads on the health of mudflats and mangroves.	Conceptual diagram/model completed – to be used with scientific and other communications material.

10. Hydrology Currents Density stratification Exchange with outer Harbour Mixing by wave action Tides Surface water discharge volume Surface water flow rate (Hydrodynamic model improvements)	Partially completed – hydrodynamic model (finite mesh) improvements have been undertaken. Further monitoring of currents and sediment has been undertaken in specific areas of the Harbour subject to dredging.
11. Boundary Conditions – profile nutrient, algae and physical conditions. Spring tide conditions required.	Limited work has been undertaken in the outer estuary. Future work is planned in 2009 to intensify monitoring effort and extend monitoring stations to adequately cater for boundary condition assessment.
12. GIS layers – spatial data requirements for catchment model - Land use (lumped accordingly dependent on model requirements) - Soil types/geology - Stream/drainage networks - DEM - Floodplain extent - Gully density - Hillslope erosion - Annex data/nutrient datasets - Gully Density, Riparian Vegetation, Annual Rainfall, RKLS Factors, Soil Clay %, N in surface Soil, P in surface soil, Air temp, DIN, DON, DIP, FRP. - Time-series flow data	ANNEX datasets are to be compiled and catchment model development pursued in 2009 building on existing empirical approaches. Most of the spatial data requirements for modeling have been met but will require additional preparation.
13. Develop a catchment model which can provide loads data for the receiving water quality model with some confidence and a sound tool for planning and policy formulation purposes.	A more process orientated model such as SedNet will be pursued in 2009. Comparison with empirical based approaches and data already gathered as part of this approach will be used to verify future modelling work.
14. Catchment model development should enable the identification of 'hotspots', which can be examined with finer resolution models if required. i.e. Sediment sources in	The use of Sednet or similar will enable the identification of 'hot spots'. Current data and other research on sediment sources in the catchment suggest that 'in-stream' sources are more significant than hillslope sources. Generally low relief in the region coupled with the extensive lagoon/wetland and dambo type systems in the

catchment.	landscape effectively ameliorate sediment runoff providing natural sediment traps.
15. Focus loads on sampling events at a number of sites and first flush events when most of the variation in sediment and nutrient concentrations occurs.	Intensive sampling will be biennial based on the level of development and/or changes in the catchment.
16. Improve rating curve through more frequent gaugings at Winnellie, Bennett and Peel stations to enable better stage-discharge relationships.	Currently underway.
17. Further development of sound empirical relationships between parameters such as TSS and Turbidity	Data collected to establish these relationships at key sites.
18. Examine collected data for structure and insight into the processes that are operating so that the sampling regime can continue to be improved.	Currently underway.
19. Reduce unnecessary over-sampling caused by fluctuations around sample height by employing minimum time interval before sampling re-occurs at the same height trigger.	Included as part of sampling rationale at each site where discrete sampling is undertaken.
20. Focus sampling on newer stations to build a better understanding of stream discharge and water quality relationships.	Currently Underway and the focus on ongoing loads assessment.
21. Evaluate opportunities to extend water quality capabilities of existing hydrological stations.	Currently reviewing opportunities for other relevant partners within Govt.
22. Engage expertise for catchment model development	Recently appointed staff with relevant expertise.
23. Benthic Habitat Mapping. This task will better define the spatial context of habitats and characteristic ecosystem processes. This whole-system approach will thus support the development and calibration of the water quality model.	To be undertaken – subject to current funding bid

Model Verification and Calibration	**Implementation Status (Nov 2008)**
1. Ambient monitoring– nutrients (NO2, NO3, TKN, TP, FRP…)	Currently underway with intentions to intensify effort in priority zones.
2. Ambient monitoring – Physical water quality conditions (Temp, pH, EC, salinity, DO, Turbidity, PAR)	Currently underway with intentions to intensify effort in priority zones.
3. Ambient monitoring – (Selected sites to minimize cost/time). Phytoplankton/ zooplankton	Under review given costs and resource restrictions
4. Ambient monitoring – Suspended Sediment (TSS/VSS)	Currently underway with intentions to intensify effort in priority zones.
5. Sediment characteristics and mapping (grain size, fall velocity, density, bulk density, shear stress of erosion and deposition & determine diffusion parameters for model)	Under review given costs and resource restrictions. Some recent work undertaken by CDU/TRaCK may inform this work. Further sediment quality is proposed as part of a current funding bid.

10. Conclusion

The Darwin Harbour Region Water Quality Protection Plan aims to maintain water quality suitable for aquatic ecosystem protection and human uses. This first phase of the plan has developed water quality objectives and pollutant load targets consistent with beneficial uses.

A receiving water quality model has been developed which will provide a valuable tool in the assessment of development pressures in Darwin Harbour. A number of proposed management actions including the incorporation of water sensitive urban design have been identified as important intervention measures to ensure diffuse and point sources do not degrade the aquatic ecosystems of the Darwin region.

Significant investment will be required for successful outcomes and implementation will focus on progressing priority actions to maintain water quality and enable aquatic ecosystem assessment to inform ongoing management actions.

The future development of phase two of the plan will integrate monitoring, modelling and implementation strategies and identify opportunities to incorporate legislation and planning. It is expected that these core strategies will be developed by 2010 in conjunction with a comprehensive consultation program.

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Appendix A: Distribution of preferences for Beneficial Uses as part of the Public Consultation Phase.

Beneficial Use / Water body	Agricultural	Cultural				Aquaculture	Public Water Supply		Environment	Riparian	Industry
	irrigation water	food source	spiritual values	recreation (e.g. swimming or fishing)	aesthetics (visual amenity)	aquaculture (both in water or on land)	drinking water source	domestic purposes (not drinking)	habitat for plants and animals	water for stock	industrial (cooling water)
Darwin Harbour and its marine reaches	7	43	25	44	44	26	6	6	52	19	19
Rapid Creek freshwater reaches	4	23	25	40	38	5	4	3	44	21	5
Elizabeth & Howard Rivers Region – surface water	20	28	18	34	34	11	14	19	47	28	6
Elizabeth & Howard Rivers Region – groundwater	30	13	10	14	14	6	36	23	31	18	13
Darwin & Blackmore Rivers Catchment- surface water	34	33	21	34	33	20	24	15	46	29	11
Darwin & Blackmore Rivers Catchment- groundwater	35	15	13	13	15	10	34	27	33	15	14
Shoal Bay & Vernon Islands	2	35	22	36	35	15	3	2	45	18	2
Hudson Creek and Tributaries	3	30	20	29	29	8	5	1	40	15	18

Indicates Beneficial Uses currently declared under the Water Act