APPENDIX B

Hydrodynamic and Water Quality Modelling

PowerWater

Appendix B Hydrodynamic and Water Quality Modelling

B.1 Hydrodynamic Modelling of Darwin Harbour, 2005 – 2010, History, Development & Interpretation, Report No. 4

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Hydrodynamic Modelling of Darwin Harbour

2005-2010

History, Development
& Interpretation

Report No. 4

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March 2011

1 EXECUTIVE SUMMARY

This report describes the development of the Darwin Harbour hydrodynamic and water quality modelling carried out by Charles Darwin University (CDU) in collaboration with Power and Water Corporation (Power and Water). Since 2005, CDU has developed and applied a computer based hydrodynamic and water quality model of the Darwin Harbour to determine the dispersion of treated wastewater to the greater Darwin Harbour from Power and Water's wastewater treatment facilities.

Power and Water is licensed to discharge treated wastewater to Darwin Harbour under waste discharge licences issued by the Department of Natural Resources, Environment, the Arts and Sport (NRETAS). In 2010, NRETAS published the Darwin Harbour Water Quality Objectives, providing a basis for delineating mixing zones associated with the discharge of pollutants to the harbour from point sources.

Since its original development by NRETAS, the hydrodynamic model has been further developed and refined over the last 5 years by CDU. It now includes a water quality module that can be used to determine treated wastewater mixing zones to assist Power and Water with wastewater management.

The model shows mixing zones of both non-decaying and decaying contaminants contained in treated wastewater discharges. Model results are illustrated by a range of visual geo-referenced outputs. The delineation of mixing zones relies on a number of assumptions and inputs including background concentrations of contaminants in the Darwin Harbour, trigger values for exceedances of water quality indicators and contaminant load and concentration parameters associated with the discharged treated wastewater. Power and Water and CDU have attempted to define mixing zones for treated wastewater contaminants using the model and various NRETAS' publications. This report attempts to document the development of the model and the methodology associated with defining mixing zones.

The development and application of the model has contributed significantly to Power and Water and NRETAS' understanding of far field hydrodynamic and water quality processes within the harbour. The model is currently being used to address Power and Water's waste discharge licence regulatory requirements and to plan for wastewater treatment and disposal for future development projects in the Darwin region.

Further development of the models is proposed in the forthcoming 12 to 24 months including but, not limited to, the development of the Buffalo Creek water quality model, continued model calibration for Buffalo Creek and modelling the overflow from the creek at the Ludmilla waste water treatment plant. Ongoing development includes refining the intertidal zone of the Darwin Harbour and Buffalo Creek model bathymetry, scenario outfall modelling for the planned extension of the Ludmilla Outfall, and continuing refinement for the existing outfalls in Darwin Harbour.

2 INTRODUCTION

2.1 Background

The Darwin Harbour hydrodynamic model has existed in various forms since 2001. CDU acquired the hydrodynamic model from NRETAS in 2005 and, under funding from Power and Water, continues to develop it for research and wastewater management. Since 2005 the model has undergone development parallel to the improvement of the wastewater disposal facilities in Darwin Harbour. This has included the development of a water quality model that estimates dispersion and advection of contaminants in Darwin Harbour. The development of the hydrodynamic and water quality models to determine mixing zones have largely been instigated by NRETAS through inclusion as conditions in Power and Water's Waste Discharge Licences.

2.2 Power and Water

2.2.1 Regulatory Environment

Power and Water's discharge of sewage and treated wastewater is regulated by NRETAS, although the issuance of Waste Discharge Licences (WDL) under the *Water Act 1992* (NT) WDLs are issued to wastewater treatment plants, or more specifically point-source discharges to waterways which have declared beneficial uses under the *Water Act 1992* (NT) s 74.

Beneficial uses have been declared for all ground, surface, marine and freshwaters in the entire Darwin Harbour Catchment including Shoal Bay, with particular emphasis placed on the preservation of aquatic ecosystems, recreational and cultural values (NRETAS 2010). This is discussed in more detail in section 6.1.2 of this report.

2.2.2 Darwin Harbour Water Quality Objectives

Water quality objectives may be declared according to the *Water Act 1992* (NT) s 73. This declaration allows natural resource managers and regulators to use water quality objectives as benchmarks for regulation to protect beneficial uses and for their use as performance measures for monitoring and reporting (NRETAS 2010). The report "Water Quality Objectives for the Darwin Harbour Region – Background Document" was released in 2010 and provides background references for much of this report.

In many cases treated effluent may be of poorer quality than the receiving environment and the specified water quality objectives. The Australian guidelines for fresh and marine water quality define mixing zones as 'explicit areas around effluent discharges where the management goals of the ambient waters do not need to be achieved and hence the designated environmental values may not be protected' (ANZECC & ARMCANZ 2000, p.2-17). Mixing zones are also often described as exclusion zones. This concept is applied for Power and Water's WDL and will form the basis for the application of the hydrodynamic and water quality models.

Power and Water's WDL for each wastewater treatment plant specifies quantitative discharge limits for a number of physical, chemical and bacteriological contaminants. These quantitative discharge limits are generally specified in terms of median and 90^{th} percentile limits and are assessed and reported on an annual basis.

It should be noted that the quantitative discharge limits specified in current WDLs are based on historical wastewater treatment plant performances. They are not related to the local environment into which wastewater is discharged, the technical capabilities of the individual treatment processes used at each facility, nor the specified water quality objectives. New WDLs will be developed collaboratively by NRETAS and Power and Water and will, in time, better reflect the environmental objectives for the receiving environment.

2.3 Darwin Aquatic Environment

2.3.1 Hydrodynamics

The official boundary of Darwin Harbour can be defined by drawing a line between Charles Point and Gunn Point. This includes Shoal Bay and Buffalo Creek. The model covers the area from Charles Point to Lee Point. A Shoal Bay and Buffalo Creek model has been developed separately. The semi-diurnal tidal patterns and wet/dry seasons contribute significantly to the physical and ecological processes that occur in the harbour. The Harbour has an astronomical tidal range from 0.3m to 7.8m. The existing hydrodynamic model estimates maximum current velocities that reach 2.3m/s and approximately 33 x 10^8 m^3 of water crosses the mouth of the Harbour between a typical spring high and low tide. Tides propagate into the harbour with a time lag of approximately 6 minutes between East Point and Darwin City.

Flushing in Darwin Harbour differs greatly from wet season to dry season and between the upper and lower reaches of the estuary. The mean annual rainfall is 1714mm per year, 97% of which contributes to the freshwater inflow during the wet season (October to April) (McKinnon 2006). A combination of freshwater inflow and tidal cycles flush the harbour during this period. During the dry season rivers and tributaries cease to flow into the harbour. During this time of year flushing is a result of tidal processes. Longshore current velocities dominate water movement in the harbour. Flushing times have been estimated to be in the vicinity of 20 days in the upper reaches of the estuary (Wolanski, Williams et al. 2006). Flushing times at locations in the outer harbour are estimated to be shorter. The upper reaches of Buffalo Creek are inundated only during large spring tides. The complexity of the physical environment there has prompted the development of the second model specific to Buffalo Creek and Shoal Bay.

2.3.2 Water Quality

There have been few long-term studies to obtain seasonal water quality data in Darwin Harbour. However, some short term, descriptive work has been completed to date (Padovan 2003). Salinity in the harbour is usually lower during the wet season due to the increase in rainfall and catchment runoff. The dry season is typically cooler, contributing to lower water temperatures. Depth profiling of temperature, salinity, oxygen and pH during the dry season has indicated that the harbour is generally vertically well mixed (Padovan 1997) High freshwater runoff during the wet season could cause stratification. However, it is unlikely due to the large tidal and wind driven water movement. Turbidity in Darwin Harbour is typically between 1 and 35NTU and depends predominantly on tidal and wind energy, which is mildly affected by the seasons (Padovan 2003). Nutrient studies have historically taken place in areas close to fresh water sources into the harbour and concentrations have been shown to vary spatially and seasonally in some cases. Padovan (1997) found that levels of total nitrogen in the main body of the harbour were similar to those close to the Elizabeth and Blackmore Rivers and varied little with seasonal change. Both Padovan (1997) and (Parry 1999) found that Nitrate concentrations varied seasonally within tributaries and creeks in the surrounding areas of the Harbour. Total phosphorus has been shown to vary weakly with seasonal and tidal variations. Minimal changes in water quality have been measured between monitoring in 1990-91 and 2004 in the main body of the harbour (NRETAS 2005).

The water quality in Buffalo Creek is generally degraded due to minimal flushing and the presence of the Leanyer Sanderson wastewater discharge point in its upper reaches. The water in the upper reaches of the creek exhibits high levels of chlorophyll-a and eutrophication occurs regularly. Water quality in Shoal Bay generally complies with water quality guidelines.

3 MODELLING OVERVIEW

3.1 Model Type

A computational hydrodynamic and water quality model simulates wastewater discharge in Darwin Harbour. This is the common and well documented method for determining the dispersion of effluent in ocean outfalls and has been utilized around the world. In general, developing an environmental model is a time consuming and costly process. The Darwin Harbour model has had a rich history before being applied to waste discharge outfalls. Initially developed by NRETAS and more recently updated and refined by CDU and Power and Water, this model is superior in its developed state. Specific field studies have contributed to empirical parameters used in the model. This is of high value given that field data collection and monitoring in Darwin Harbour has been sparse due to the small population and relatively pristine environment.

Biogeochemical models are of use in certain circumstances, however as with the existing model, they rely on empirical values for valid model output. Many of these parameters are generally poorly understood and rarely quantified, especially in wet/dry tropical environments. Useful data can only be attained through advanced academic research and detailed field experiments, which requires significant time, skill and resources. NRETAS’ Aquatic Health Unit have not developed such biogeochemical models, and similarly to Power and Water and CDU have developed an engineering model based on assumptions and existing knowledge. Assumptions specific to ecological parameters in the model are discussed in section 4.2.3 of this report.

Developing a biogeochemical model may prove useful for the future management of Darwin Harbour, especially as the population continues to grow. However, it is unnecessary to develop a model such as this for determining mixing zones at wastewater disposal points.

3.2 Model History

CDU undertook hydrodynamic modelling of Darwin Harbour commencing in 2005 using an existing model acquired from NRETAS. During the period from 2005 – 2010 the model has been developed specifically for the four wastewater treatment plants discharging to ocean outfalls in Darwin Harbour. In addition to a separate model for the fifth effluent discharge point at Buffalo Creek.

The Resource Management Associates (RMA) Darwin Harbour hydrodynamic model has been adapted to match field data in past studies (Pers comm. David Willaims, AIMS). The model has been used by local government as an environmental planning and decision making tool (Fortune 2009) and an updated and refined version continues to be used for environmental problem solving (Valentine 2006; Valentine 2008). The model is under continuous development as new field data become available. Model development has been dependent on the collection and interpretation of field data, which has in turn been dependent on industry support. There is currently a rising concern for the health of the aquatic environment in Darwin as the population grows rapidly. This has emphasised the importance of a calibrated water quality model to help manage the harbour as a recreational and cultural resource. The most recent and comprehensive field work for data collection has been carried out in 2010 in the form of a tracer study. These data have been used to calibrate and verify the water quality and hydrodynamic model, which have allowed empirical coefficients to be determined for some model parameters. Furthermore, industry support from Power and Water has helped build the capability for water quality modelling research in the Northern Territory.

3.3 Model Development Objectives

The following list provides the objectives of developing the Darwin Harbour and Buffalo Creek models.

- To provide an up-to-date, state of the art model that can be used to manage wastewater discharges from Power and Water's wastewater treatment plants.
- To define regulatory mixing zones associated with the five wastewater outfalls.
- To provide a tool to assist strategic planning and prioritisation of Power and Water's wastewater treatment and disposal upgrades.
- To provide a tool that assists in communication and interpretation of complex engineering problems to a variety of stakeholders.
- To provide a tool that can be continually updated and refined with research as needed.

Defining the mixing zones will help in the development of water quality monitoring programs and will be included in Power and Water's Waste Discharge Licences.

3.4 Model Description

The Resource Management Associates (RMA) enhanced suite is software used primarily for modelling estuaries, bays and rivers. RMA has been in continuous development since 1993 by Prof. Ian King, (King 1993) initially associated with the US Army Corps of Engineers.

Two types of finite element models are used for Darwin Harbour and Buffalo Creek, a hydrodynamic (RMA-10) model and a water quality (RMA-11) model. Generally the models are 2 dimensional (2-D). However an advantage of the RMA modelling suite is the ability to integrate 3 dimensional (3-D) sections into existing 2-D models.

RMA models are far field models. They are designed to cope with large scale environmental factors, such as tidal motion that drives water currents and contaminant dispersion. RMA models have been applied very widely to a range of environmental and engineering problems (WRL 2008) and are available commercially through BOSS (www.bossintl.com). Comparable far field models used for similar applications are; the Danish Hydraulic Institute's MIKE modelling suite, AnuGA (Geoscience Australia and Australian National University) and COHERENS (Royal Belgian Institute of Natural Sciences).

3.4.1 Hydrodynamic Model

The RMA hydrodynamic model uses historical and empirical information for the region where possible. The model is developed and run based on bathymetric and topographic information and tidal data. The hydrodynamic model is used as a basis for the water quality model, as velocity and water depth play a key role in the calculations for the dispersion of water quality constituents. Therefore an accurate hydrodynamic model is necessary for the accuracy of the subsequent models.

The model is constructed using a finite element grid, referred to as a 'mesh' to define the bathymetry of the study area. Triangular and quadrilateral elements are used in an unstructured mesh at different resolutions to define the level of detail in areas of interest. Higher grid resolution depicts more bathymetric detail. Bed material types such as sand, rock and mudflats are also defined in the model mesh. These material types have a bed roughness associated with them which are commonly known as Manning's n roughness coefficients.

Control files define options for coefficients such as shear stress and turbulent mixing for momentum (eddy viscosity) and mass (eddy diffusivity) in the x, y and z Cartesian coordinate directions. There are a number of different turbulence calculation methods which could be used in the model. Other options for parameters such as wetting and drying limits also influence the hydrodynamic model.

3.4.2 Water Quality Model

The water quality model uses output from the hydrodynamic model and the mesh component to drive the advection and dispersion of introduced constituent concentrations. These constituents can take the form of a decaying or non-decaying contaminant and in this case are introduced into the model at a point source location. This is done by allocating a mesh cell in the location of each outfall as the point source. Refining this grid element to the size of the diffuser is a common effluent outfall modelling application (Blumberg 1996). During the model simulation concentrations are calculated by integration across the area of each element in the mesh. A concentration plume diffuses in the x, y and z Cartesian coordinate directions according to the coefficients specified in the model. These diffusion coefficients are also based on field data collected at the study site.

3.5 Existing models

3.5.1 Overview

Two hydrodynamic and water quality models exist for the management of wastewater in the area surrounding Darwin; Darwin Harbour, and Buffalo Creek. Although they are geographically close, they differ significantly in their hydrodynamic description. Model methodology will vary between the two locations given their different characteristics. When the behaviour in Buffalo Creek is well defined it will then be possible to examine potential off-shore sites within Shoal Bay, and possibly extend the harbour model to incorporate Shoal bay should the need arise.

3.5.2 Darwin Harbour

The Darwin Harbour model covers the harbour and extends to a curved line between Charles Point and Lee Point. The Darwin Harbour hydrodynamic model covers a 511 km² surface area, which includes the main harbour water body, mud flats and main tributaries associated with the harbour. The model shows the difference in volume between high and low tide is approximately 32.9 x 10^8 m^3, which contributes significantly to mixing in the harbour. This also supports the underlying assumption that the harbour is well mixed. This assumption was later verified using field data. The extent of the Darwin Harbour model is shown in Figure 1 below.

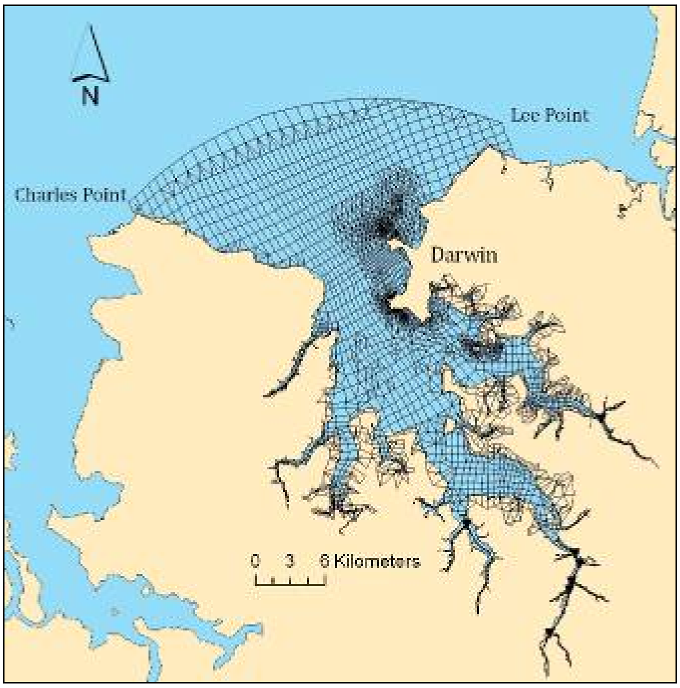


Figure 1 Darwin Harbour Model Mesh

The harbour bathymetry and bed material are represented by 3555 triangular and quadrilateral elements. Most elements are 2-D, with 91 1-D elements used to represent rivers that flow into the harbour. Two material types with different characteristics describe the bed material of the model. Figure 2 shows the distribution of the bed materials.

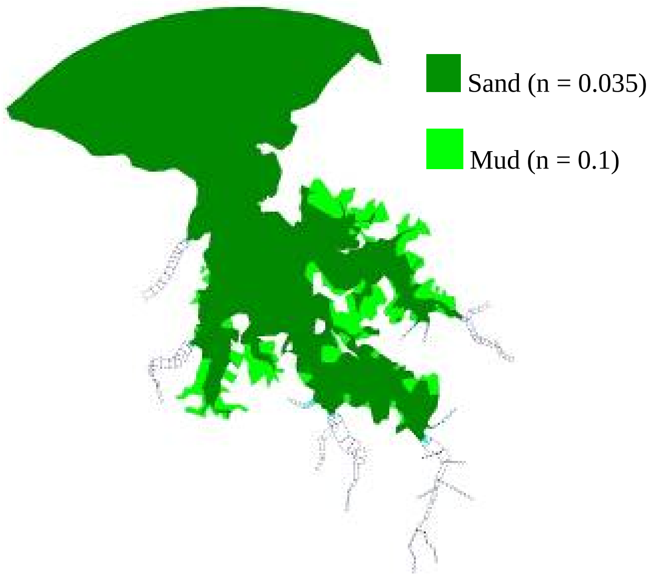


Figure 2 Darwin Harbour model material types and corresponding manning's n values.

3.5.3 Buffalo Creek

Buffalo Creek is of shallow and irregular topography with sand slugs in the river that at times block water movement. The model mesh uses 5815 triangular and quadrilateral elements to describe an area approximately 35 times smaller than the size of the harbour. Six different material types are used to describe the bed material in the model (Figure 3). This provides insight into the complexity and detail of the Buffalo Creek model.

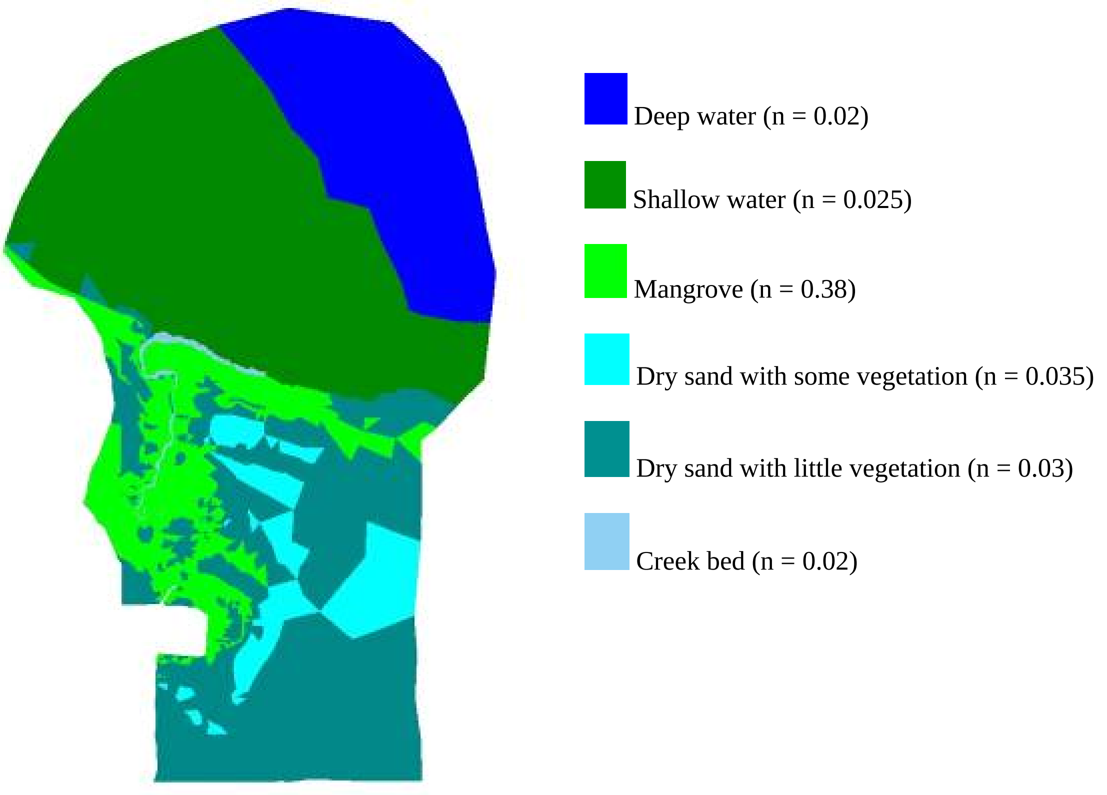


Figure 3 Buffalo Creek model material types and corresponding Manning's n values

4 MODEL DEVELOPMENT

4.1 Data sets

4.1.1 Bathymetry

Bathymetric data for the harbour have historically been sourced from marine charts of the area. More recently, hydro-surveys have been used to collect more detailed data. A localised survey of the area around East Point was completed in early 2009 and a comprehensive Digital Elevation Model (DEM) was constructed from the data. A survey was also carried out at Buffalo Creek but was somewhat limited due to field constraints.

Bed elevations are saved in each model mesh and are used in the hydrodynamic calculations. Recent Light Detection and Ranging (LiDAR) data have become available and will be used to increase the accuracy of bed elevations at the intertidal zone for both the Buffalo Creek and Darwin Harbour models.

4.1.2 Tides

Historical tidal data are used to drive the models. The tidal data set is applied at the specified model boundary (the curved boundary at the open ocean inlet). Using real data allows for some degree of tidal calibration (see section 5.4.2), thus a historical data set was chosen as a standard for all model simulations. Historical data were examined for a range of spring and neap tidal conditions and a period of thirty days during 1994 was chosen to apply to the model (Figure 4). Using standard tidal data for each model simulation allows model results to be compared.

Although the standard thirty day tide cycle is used to drive a model, it is also possible to apply a recorded or predicted tidal data set to analyse model results for a specified day. For example, if an environmental disaster occurred such as a chemical spill, it would be possible to apply predicted tidal data for the coming days to show the spread of the contaminant. Applying forecast tidal data also assisted in preparation for the tracer study (section 5.3.1) carried out to calibrate the model in July 2010.

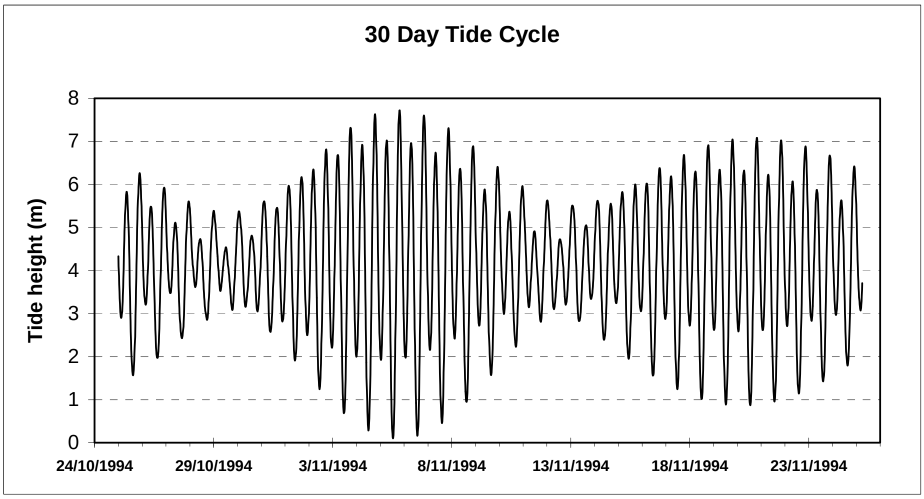


Figure 4 The Fort Hill tide gauge data used to drive the RMA-10 hydrodynamic model.

4.1.3 Meteorological data

Meteorological data can also be applied to the model to incorporate the effects of wind on the water surface. Wind vectors that change over time are applied to the model at a global scale. This means that a time series of wind with direction and magnitude are simultaneously applied to the surface of the entire model area. Wind has not been applied to the standard model for production runs as it would increase surface mixing. No wind represents a worst case for mixing. However a strong onshore wind under certain tidal conditions has the potential to push contaminants towards the shore. The Australian Bureau of Meteorology records maximum wind gusts and directions. Real worst-case scenarios can be extracted from these records and applied to the model as a standard wind file similar to the standard tide file.

Similarly, historical or forecast meteorological data from specific days can be applied to the model to match or predict the real conditions on those days.

4.1.4 Water inflow

The RMA hydrodynamic model can simulate the inflow of water from a point source, which differs from the inflow of ocean water at a tidal boundary. For the Darwin Harbour model, the inflow is treated as a quantity of water entering one mesh element over time. The element selected is at the position of the outfall or proposed outfall. For Buffalo Creek, the inflow is treated as constant flow through a specified boundary, such as the inflow of water from the upper reaches of a river. Both of these 'point source' entries represent mass and momentum inflow to the model. Data used in the models for the effluent flow rates should be extracted from Power and Waters' records. As the population increases, the inflow also increases. It is possible to apply a forecast increase in wastewater inflow to the model to simulate an increase in growth that is probable over the coming years.

4.1.5 Water quality inflow

The paragraph above discusses the mass and momentum of inflow to the model. The quality of this inflow can be adjusted by defining a concentration of any contaminant in the mass of inflow. The contaminant is treated as a parameter which is defined by a set of characteristics in the model. For example, decay, settling time and light sensitivity. These parameters can only be determined by field studies, and little research has been done in the wet/dry tropics. The general method of coping with unknown contaminant characteristics is to take values from the literature where experiments were conducted in similar conditions. If little or no research has been done in this area (as is the case with the rates of absorption of nutrients onto sediment in the wet/dry tropics (Fortune 2009)) the most conservative assumption will be applied to the model. The limitation of this knowledge has been recognised by industry as a matter for research (Fortune 2009).

The momentum of the inflow contributes to the immediate mixing of the contaminant once it enters the water body. From here standard calculations drive the dispersion of the contaminant coupled with the hydrodynamic influence. The RMA far field model calculates the dispersion of the contaminant over a large scale and gives an accurate depiction of the extent of the dispersion in the location. It should be noted that RMA is a far field model and is not designed to be accurate at a small ($<50m^2$) scale. The general lack of detail in near field dispersion can be overcome by refining the mesh elements (see section 4.2.2).

4.2 Model Sensitivity

4.2.1 Wind

A sensitivity analysis to determine the effects of introducing wind to the water quality model was carried out. A global and constant wind speed was applied to the model in different directions to show the effect that wind has on the model hydrodynamics. Figure 5 below shows that a plume responds in a positive direction to the origin of the wind.

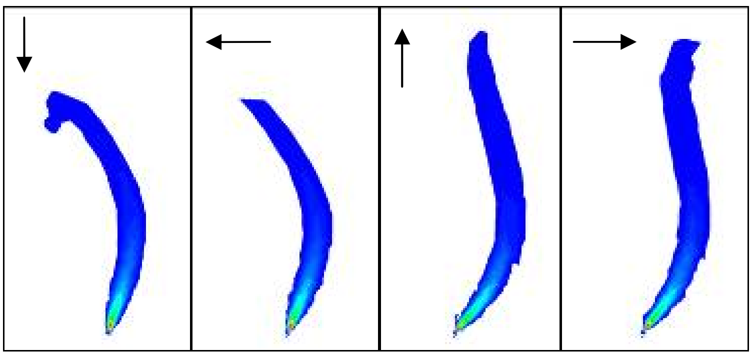


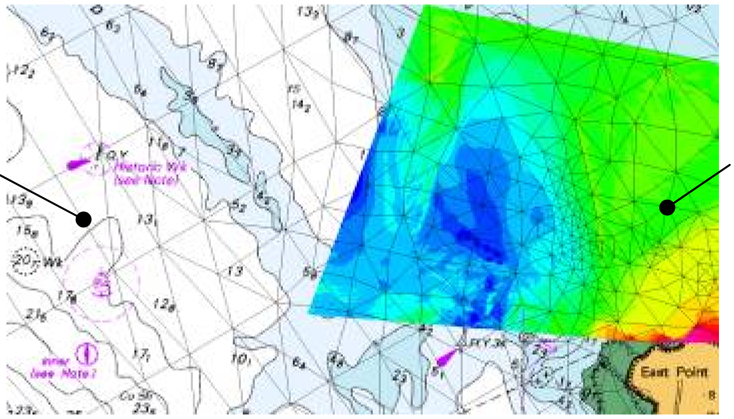
Figure 5 Hypothetical contaminant plumes with constant wind speed applied in four different directions (shown with arrows).

This shows that wind speed and direction make a significant difference to the dispersion of a contaminant. Thus, in assessing impacts of potential plumes it is necessary to take a standard wind speed and direction into account.

4.2.2 Mesh refinement/element size

Model mesh resolution represents the detail of the model bathymetry, as well as the volume of each element. A finer model mesh will more accurately represent the bathymetry given that detailed bathymetric data are available. For example, the Darwin Harbour mesh has been produced using marine charts with low resolution (~100 points per $1km^2$) and hydro-surveys with high resolution (~1 x 10^6 points per $1km^2$) (Figure 6). Refining the mesh in areas of low resolution data will not influence the accuracy of the model bathymetry, but it will change how the model calculates the concentration of an applied contaminant. The model should be refined in the areas of interest such as sewage outfalls to improve the water quality model for both near field and far field results. As RMA models are far field models, high accuracy for near field concentration values are not expected. However, model refinement must still take place so that the far field is represented accurately. There are near field modelling programs such as CORMIX (United States Environmental Protection Agency) that can be used for designing the diffuser to achieve efficient near field mixing.

The marine chart resolution can be seen by the spacing of the elevations. Note the mesh elements are larger here because there is not enough detail to reference in the marine chart.



The DEM is displayed in bright colour. Individual elevations are not shown here because the resolution is too high. Note that the mesh is more refined in this region.

Figure 6 An example of mesh refinement using high and low resolution data sets.

Given that the elements are depth averaged, the volumes of the mesh elements are important when considering the dilution of a contaminant in the near field. Figure 7 below shows the concept of the element volume. The dispersion calculations involve partial integration along the element edges. This means that the smaller the cell, the more accurate the horizontal dilution to a certain degree. Sensitivity analyses and calibration is the most effective method of finding the maximum element size to accurately describe the far field condition.

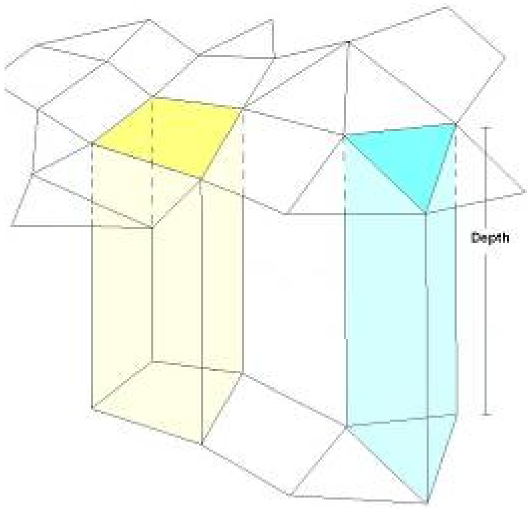


Figure 7 Depth average element concept.

Excessive mesh refinement can be detrimental by slowing down the model calculations, using larger amounts of computer memory and potentially adding more complications to the model. Trials have been carried out on the Darwin Harbour model to show where further refinement no longer influences far field results. An undefined arbitrary contaminant can be used in the RMA-11 model simulation to show a theoretical plume such as the one shown in Figure 8 below.

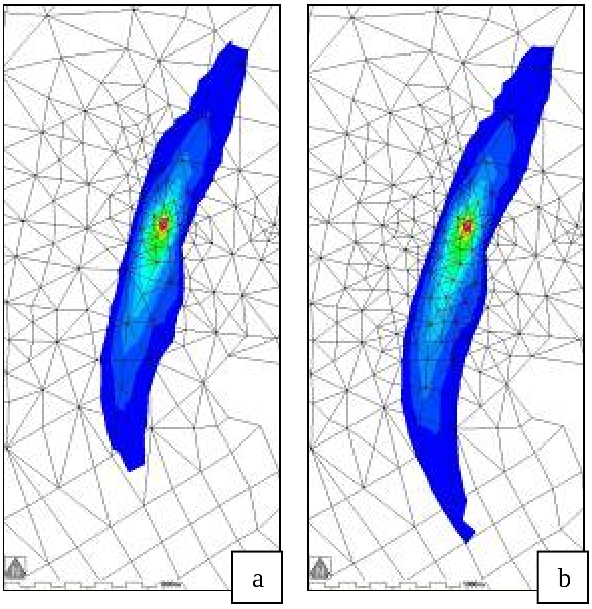


Figure 8 An example of impact on a hypothetical plume of a) a model mesh and b) the same model mesh with some refinement.

Refining the element to the size of the outfall diffuser is a typical method used to accurately simulate near field mixing (Blumberg 1996).

4.2.3 Decay rates

To account for the large number of poorly understood biogeochemical processes, a commonly adopted modelling technique is to apply a 'decay rate' to modelled contaminants. These decay rates do not model a specific process, but are used to account for the reduction in contaminant concentration caused by a range of natural and anthropogenic factors. For example, although E.Coli is a complicated and little understood pathogen, decay due to sunlight, salinity and temperature has been recorded in field studies (Bordalo 2002). Published decay rates of other constituents that have been recorded from similar environments are used where available. Where there are no published data available, no decay rate is allocated for that constituent in the water quality model.

Modelling work undertaken by the Water Resources Laboratory (WRL) on behalf of NRETAS' Aquatic Health Unit also applied the concept of decay rates in the far field modelling of nutrients. Rates were selected from the literature, and adopted from other studies of Darwin Harbour that also use decay rates from the same literature sources (NRETAS 2010), (Wasko and Miller 2008). CDU consulted with a leading professional in the field of marine chemistry in reference to the modelling work undertaken in this study. The advice given was that a simple decay rate should be applied to the parameter to represent the reduction in contaminant concentration during initial and far field mixing (Parry 2010).

The forms of nutrients and nutrient cycles in the tropics are less well understood than in temperate environments. Scientific studies carried out by Aquatic Health Unit (AHU) have adopted the same decay rate for ammonification as independent processes for Darwin Harbour (Wasko and Miller 2008), (Fortune 2009) as the decay rates used in the water quality models.

Figure 9 below shows the comparison between model results for a) a hypothetical contaminant, and b) the same contaminant with an applied arbitrary decay (0.1 per day).

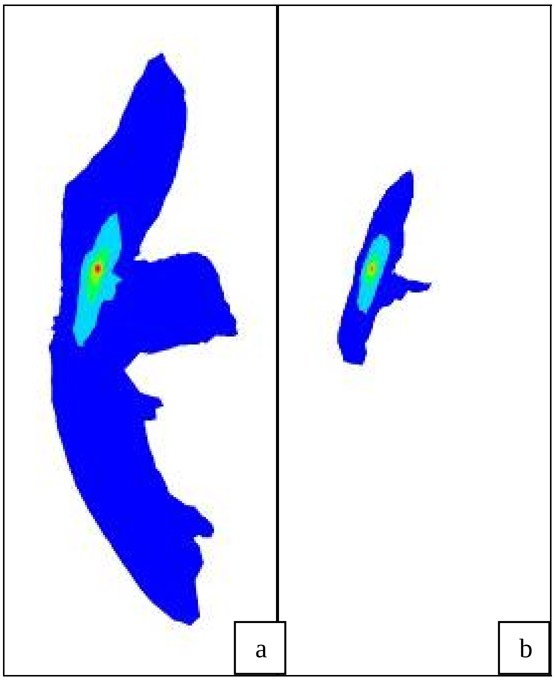


Figure 9 A hypothetical plume with (a) no decay, and (b) 0.1 per day decay

5 MODEL CALIBRATION

5.1 Overview

The accuracy of a model depends on the data used to compile the model. In turn, there are empirical coefficients in a model that can only be determined by collecting field data at that location. The integrity of any model is based on the quality of calibration. The level of calibration can also be determined using statistical analysis to show how well model and field data match. Models are calibrated by altering a combination of different parameters that can be measured or inferred from field observations. These parameters are coefficients that magnify or reduce the effects of physical processes such as shear stress and momentum. Field data were collected for x velocity, y velocity, diffusion, surface currents, wind speed and direction and tides. These data sets were collected during a tracer study and used to calibrate the Darwin Harbour Model. Field data from Buffalo Creek are limited to tidal observations at a point close to the existing outfall.

Calibrating modelled environments require different data depending on the characteristics of the physical processes that occur in that area. The calibration of Darwin Harbour and Buffalo Creek models will be discussed specifically below to describe how these models underwent calibration. Other similar models can be calibrated using, but not limited to the methods described below.

5.2 History

The Darwin Harbour model has been calibrated to some degree in the past by NRETAS (formerly NRETA) before CDU acquired the model. The model has been tested at different periods and locations for depth and velocity and results show that the model matches well with field observations. Figure 10 shows the locations and transects that have been tested against model output in the past.

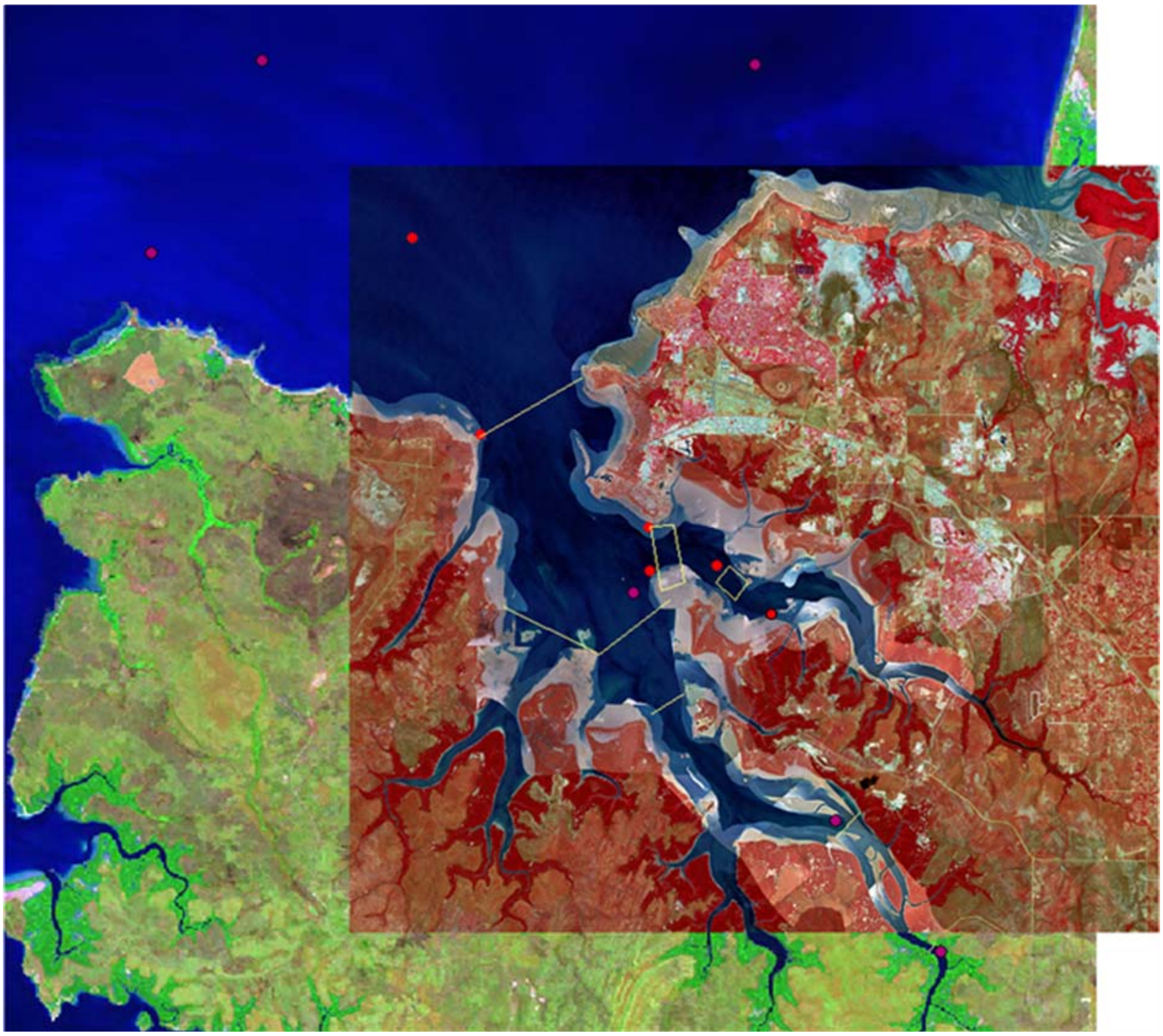


Figure 10 Darwin Harbour mooring and transect sites, red dots represent moorings, yellow lines represent transects, yellow boxes represent a grid of transects (Pers comm. David Williams)

5.3 Method

5.3.1 Tracer study

A tracer study was carried out in July 2010 to measure the calibration parameters. The preliminary model was used to estimate the size of the tracer plume by applying predicted tidal conditions and tracer concentrations. Several field observations were carried out simultaneously to optimise the use of the data collected. The study focused on a time period in July with reliable weather and during spring ebb tides. Two types of tracer, Rhodamine WT and Technetium 99m were released at a known location in the harbour. Rhodamine WT is a red dye designed specifically for water tracing and Technetium 99m is a radioactive isotope and can be detected by its omission of alpha rays during decay. The tracers were injected at the known location from a vessel over 5 minutes. At the same time five drogues were deployed from the vessels at one minute intervals. Each drogue had a GPS receiver attached and recorded time and location for their duration in the water. They tracked currents to two metres below the surface. These drogues moved visibly faster than the dye plume illustrating the need to explore stratification in the water column. An Acoustic Doppler Current Profiler (ADCP) was deployed some weeks beforehand at that location and recorded 60 days of velocity data, including the days of the dye study. The ADCP provides velocities at set intervals (in this case 1m) between the sea bed and the water surface. North westerly winds were present throughout the study periods. The study was repeated on the second day at a location 720m from the location on the first day.

Concentrations of Rhodamine WT and Technetium 99m were recorded by trailing detectors through the water behind the vessels while transecting the plume. Figure 11 below shows the method used.

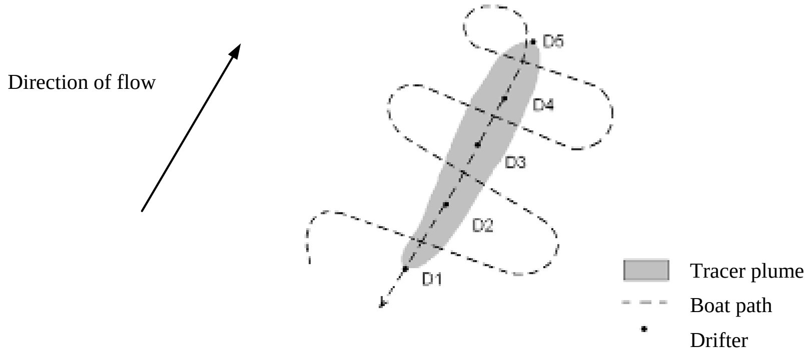


Figure 11 Method used for transecting tracer plume.

The transects were carried out over a period of approximately four hours on each day until tracer concentrations were near background. Rhodamine WT was no longer visible to the eye at a concentration of 2ppb.

5.3.2 Data collection

There were five main data sets collected from the field study. Concentration time series and locations (and depth), drifter time series and locations, ADCP data, wind and tide observations. Wind and tide observations were collected from the Bureau of Meteorology at a later stage. Figure 12 below shows the locations of the various data collection points.

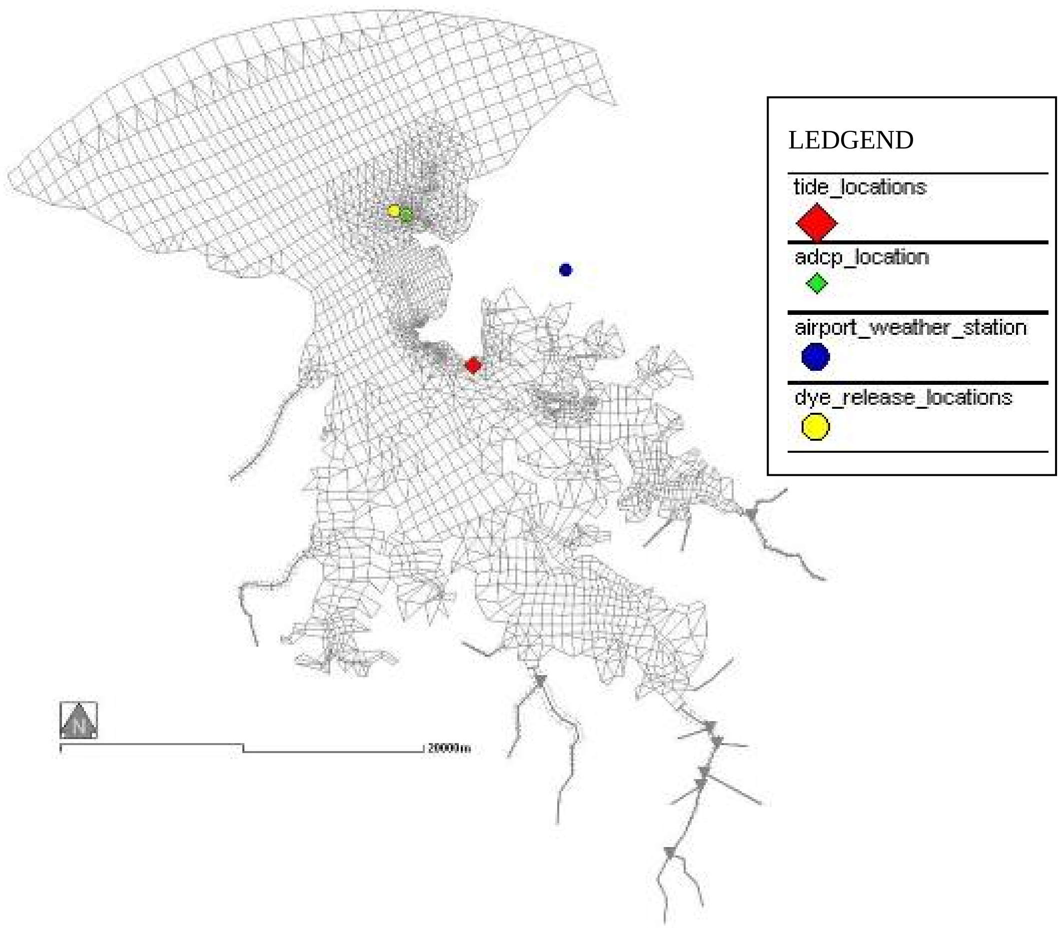


Figure 12 Data collection location points

The results from the tracers Rhodamine WT and Technetium 99m concentrations are illustrated as location and concentration in Figure 13 below.

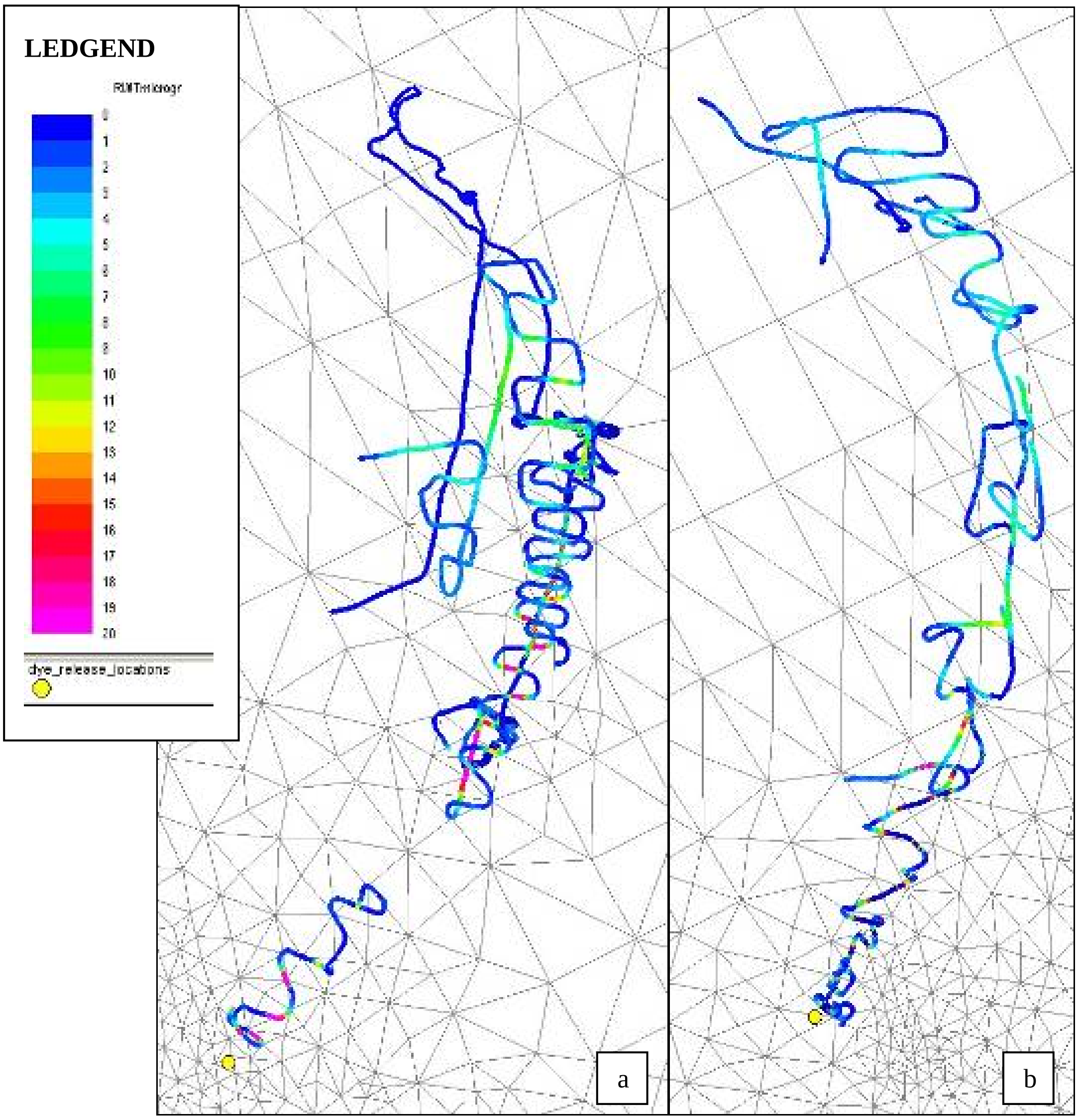


Figure 13 Rhodamine WT dye concentrations and locations (a) Day 1 and, (b) Day 2.

Each concentration can be displayed at a certain time by using filters and highlights in the program.

The drifters' tracks were in the same direction as the plume as illustrated in Figure 14 below. However, in the field, the drifters moved faster than the plume due to the surface water layer being affected by local wind.

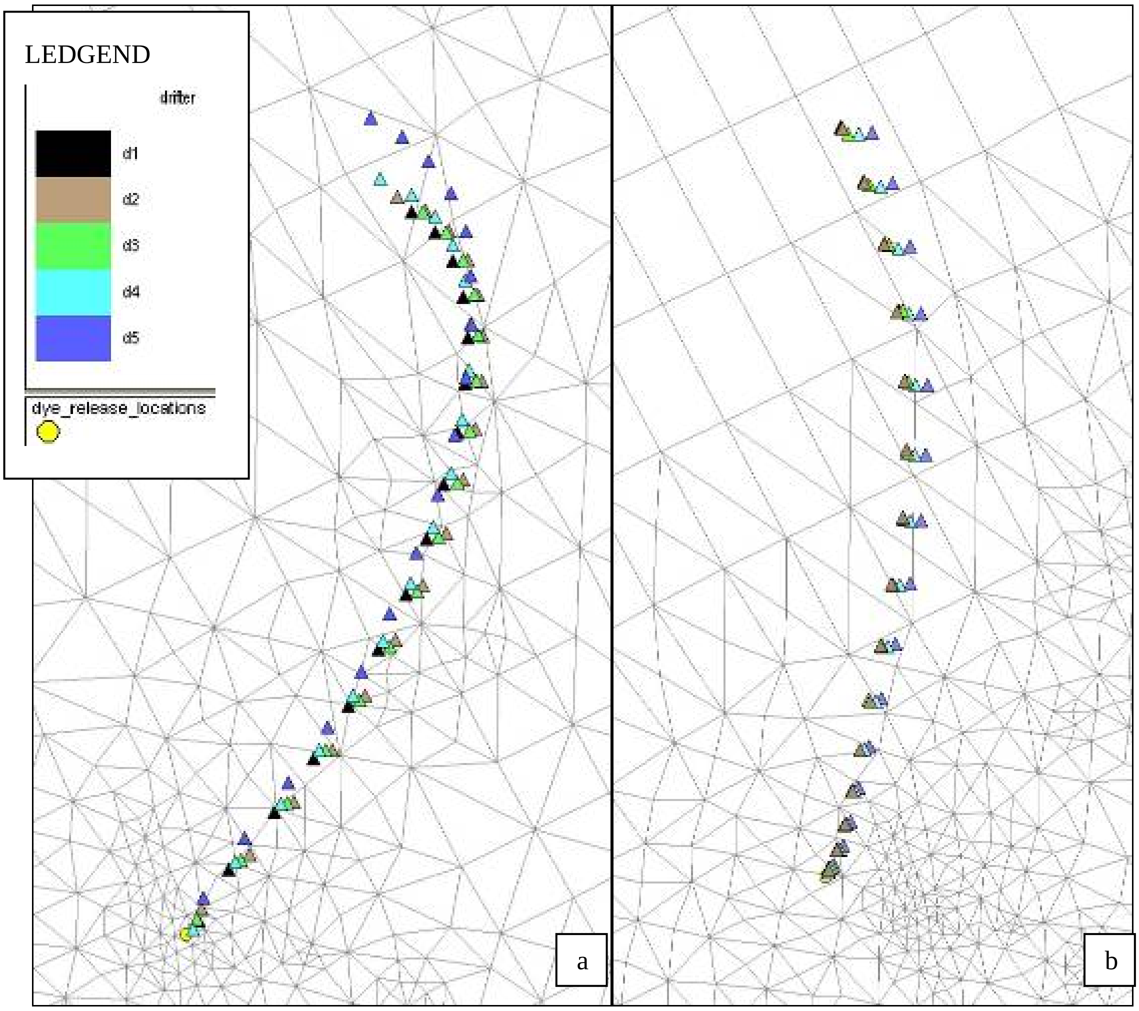


Figure 14 Drifters 1-5 locations on day 1 (a) and day 2 (b)

The ADCP recorded velocity data at 1m intervals between the sea bed and the water surface. A snapshot of about two days is shown in Figure 15 below.

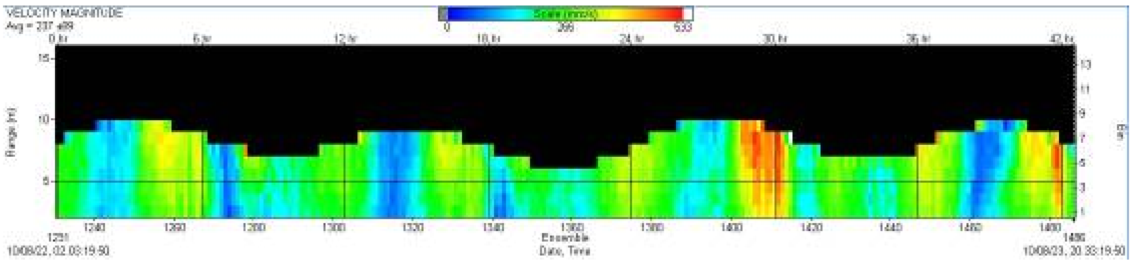


Figure 15 A snapshot of ADCP output showing current speed through the water column.

x and *y* velocity vectors were extracted from the ADCP results and displayed as a time series for comparison with model output. The ADCP was deployed for 60 days. This allows a longer time period (than just the two study days) to be calibrated for velocity. The ADCP data also showed the relationship between the surface and bed layers of the water column. This allowed the assumption of two-dimensional hydraulics to be justified.

5.4 Calibration

5.4.1 Mesh Extension

During dispersion calibration it became clear that the model mesh boundary was not extensive enough to accurately represent the longshore current movement at all locations of interest in the outer harbour. Extending the model mesh at the ocean boundary has an effect on the direction of the plume as it migrates toward the ocean on the outgoing tide. The consequence of the mesh extension was a movement of the plume further to the east. This matched the plume transects carried out by the vessels on the study days.

Figure 16 below shows the difference between the old and new meshes. Figure 17 shows the improvement the extended mesh makes to plume direction.

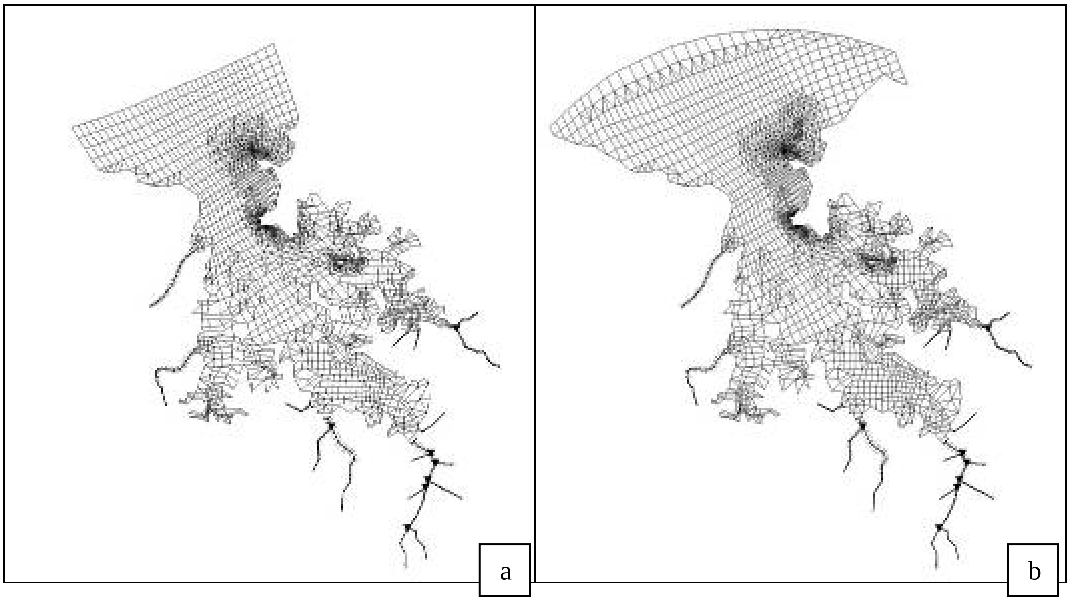


Figure 16 Old (a) and new (b) Darwin Harbour model meshes.

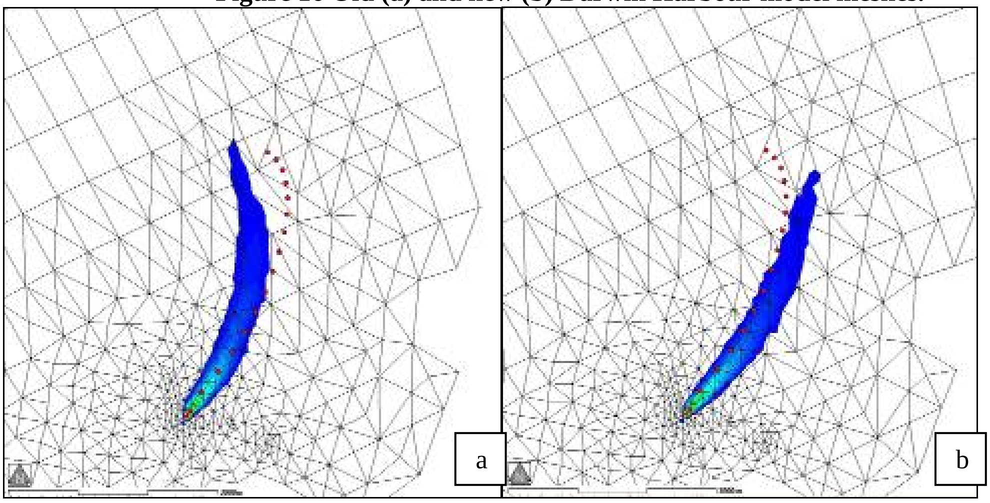


Figure 17 Altering the old mesh (a) by extending to the new mesh (b) alters the longshore flow direction and has a positive effect on the simulated plume.

5.4.2 Tidal Calibration

Tidal calibration has been carried out for both the Darwin Harbour and Buffalo Creek models. Real tidal data were recorded at the Fort Hill tide gauge and used to drive each model at the ocean boundary. Because the tide data are applied at the boundary a time lag must be accounted for (Figure 18). This was corrected by shifting the time that the tide is applied so that the model matches the field data.

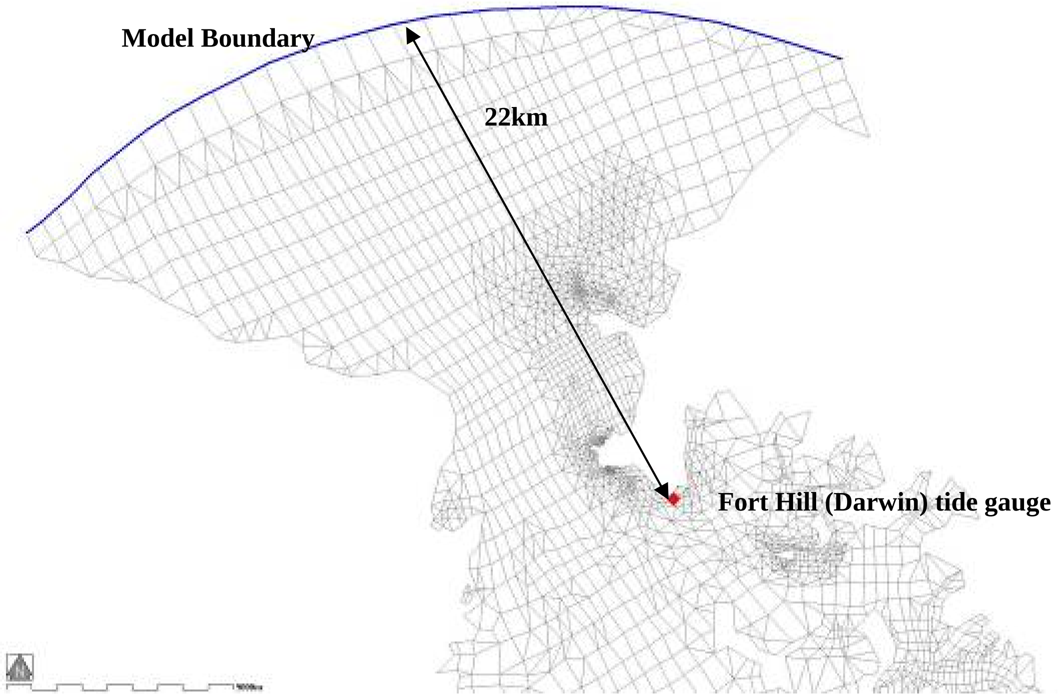


Figure 18 A time lag must be accounted for when calibrating for tides

The time series below shows the modelled tide versus the observed tide at the location of the Fort Hill tide gauge. There is good correlation between the two data sets. There is a small amplitude difference between the depths at low tides (~0.2m). This can be explained by the effects of roughness on shallow water being more significant than in deeper water. The existing model cannot take into account the changing impact of roughness as water becomes shallower, however this can be explored at a later date.

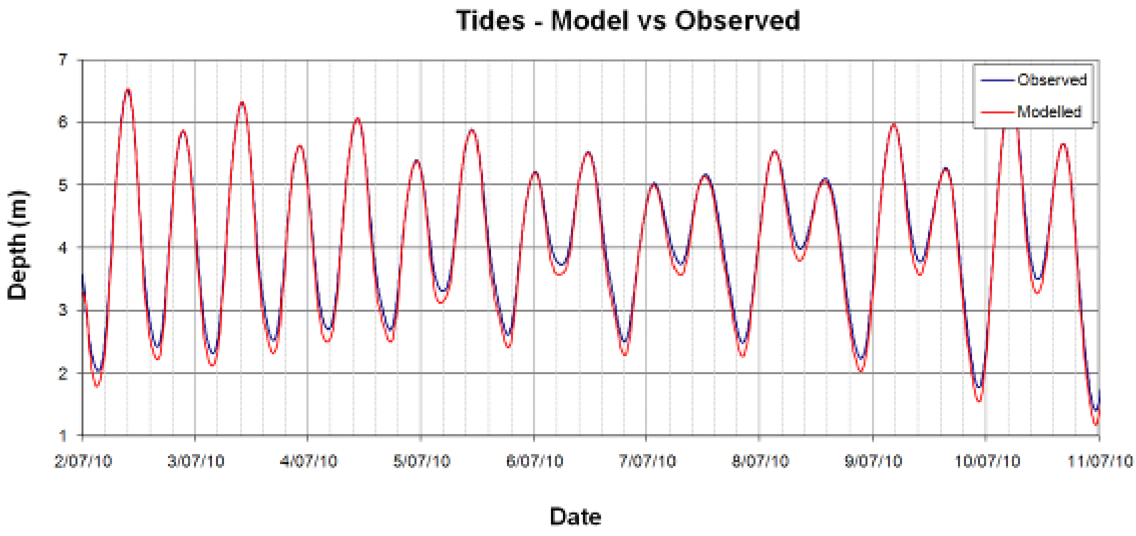


Figure 19 Tidal calibration for the Darwin Harbour model

Buffalo Creek has also undergone tidal calibration using the same method. The Fort Hill tidal data is also used to drive the Buffalo Creek model at the ocean boundary. A tide gauge was placed 50m upstream of the Leanyer/Sanderson sewage outfall. Water level elevations were collected and compared with model data and a time lag of approximately 30 minutes was calculated.

5.4.3 Wind data

The effect of wind in the model is illustrated above in section 4.2.1. These sensitivity analyses indicated the importance of adding wind data to the model of the tracer study. Wind data were acquired from the weather station approximately 9km from the study area (Figure 20).

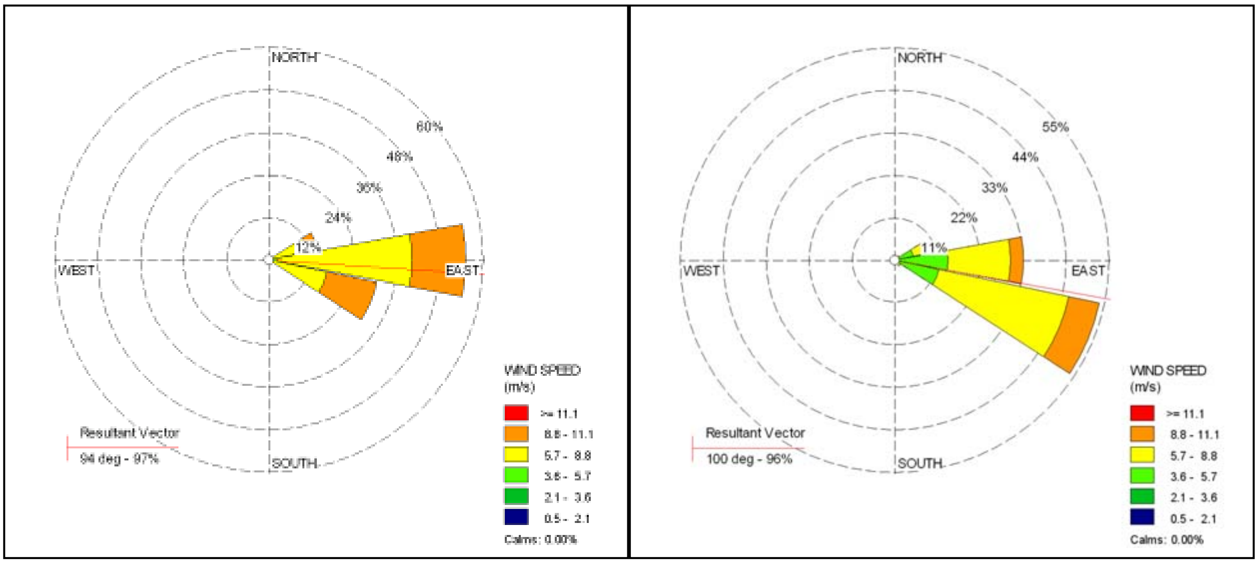


Figure 20 Wind data for day 1 and 2 study periods.

Applying the wind on the field days also had an effect on the velocity as shown below in Figure 21.

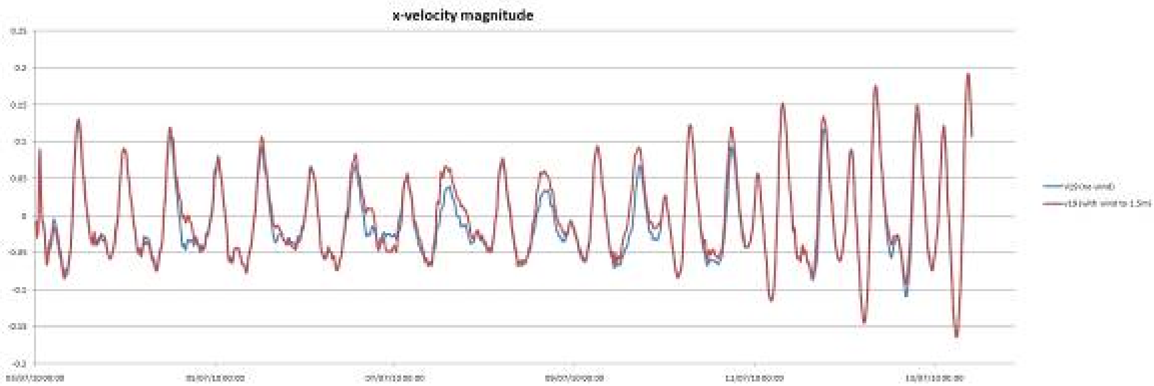


Figure 21 The effect of wind on x-velocity at the ADCP location.

5.4.4 Diffusion Calibration

The diffusion calibration was carried out by adjusting the diffusivity coefficient in the x and y directions until the model plume covered the same area of the concentrations measured during the study period. To do this, the drifter locations and concentration measurements were geo-referenced and overlaid on the water quality model output. The diffusion parameters were then adjusted until the model plume matched the extent of the observations (Figure 22). The parameters were altered to elongate the plume in the direction of flow. It should be noted that these values are within a realistic range for these parameters.

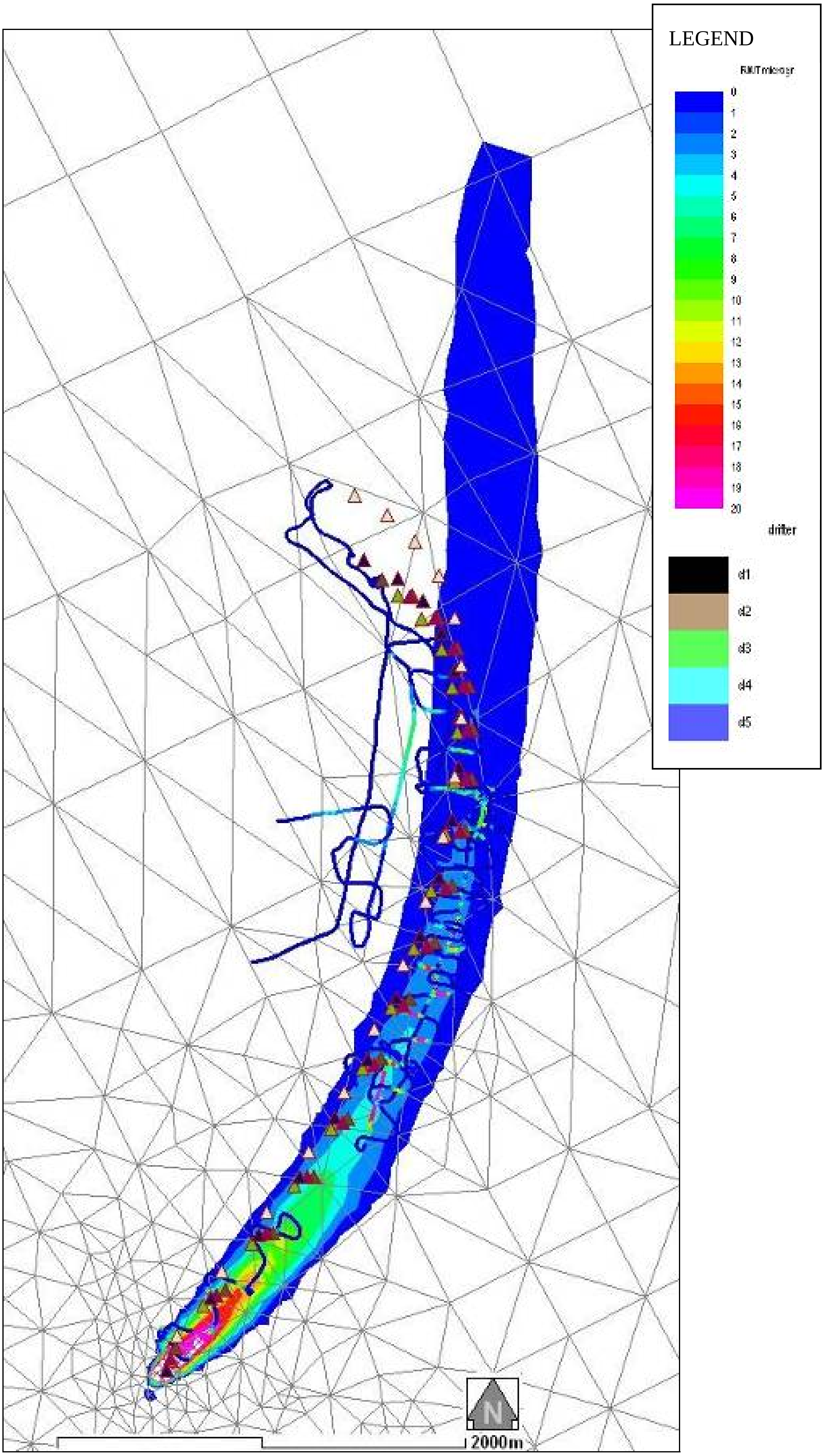


Figure 22 Calibrated dye plume with Rhodamine WT concentrations and drifters.

5.4.5 Hydrodynamic Calibration

Velocity data were collected by deploying an ADCP from 3rd July 2010 until 1st September 2010. The ADCP recorded velocities every ten minutes and at 1m intervals through the water column. These were compared to the model results by plotting time series for x and y velocity directions. Regression analysis was undertaken and showed r values of 0.9597 for y velocity and 0.6661 for x velocity (Figure 23). The r value represents the strength of fit between the two data series.

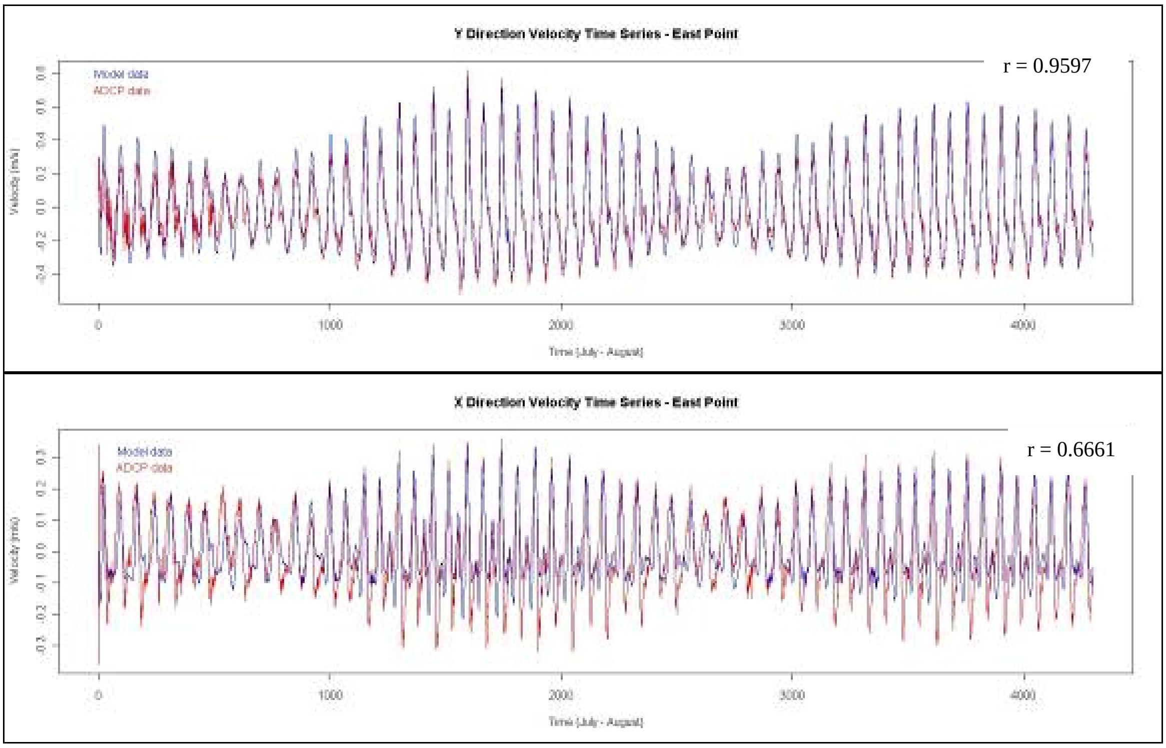


Figure 23. Model and ADCP x and y velocities compared using a time series and correlation.

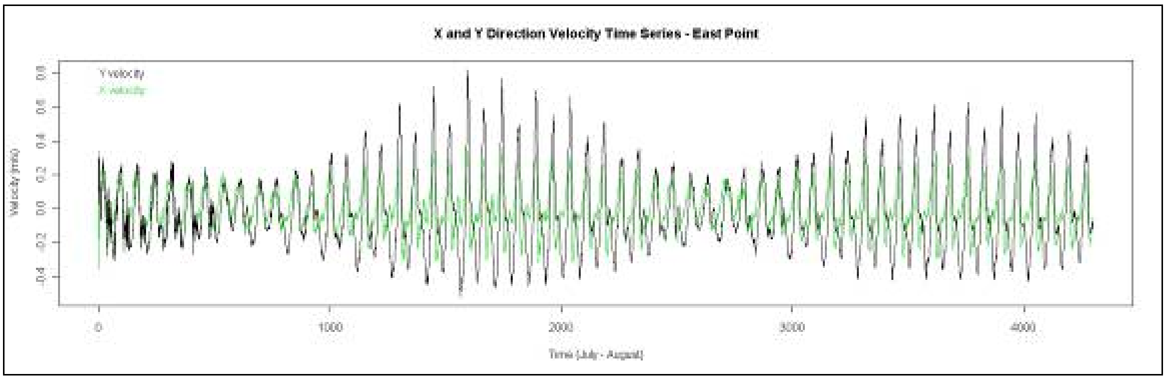


Figure 24. ADCP x and y direction velocities.

Figure 24 shows the ADCP x and y direction velocities on the same time series plot. The x velocity shows a smaller amplitude, illustrating that the current is smaller, and therefore less significant than the y direction velocity. This is expected as the direction of flow in and out of the harbour is primarily in a North-South (Cartesian y) direction. Due to the scale of the finite elements the turbulent scales are not represented at the same scale as the ADCP measurements across the modelled area. Some adjustments can be made in the model to improve the correlation and will continue to be worked on in the future, however there is a limit to the improvement. More importantly, the phasing between the ADCP and modelled x and y velocities are very accurate.

Hydrodynamic calibration at Buffalo Creek consisted of matching tidal data with model output. A tidal water level meter was placed 50m downstream of the Buffalo Creek outfall for 103 days. The data were compared with a model time series of water level. Manning's n values were adjusted for the model output to match the field data. There was a datum anomaly in the field data which was accounted for in the data analysis. A drag coefficient was also introduced to the mangrove material type to improve the model calibration.

5.5 Conclusion Relating to Calibration.

As discussed above calibration has played a key role in providing verification and justification of the assumptions made in developing the model. The level of calibration is now such that the model can be used confidently for treated effluent management at the outfalls in Darwin Harbour. The calibration has been extensive and thorough and will continue to be refined.

The calibration for advection and dispersion is focussed on East Point. It is uncertain exactly how far this dispersion calibration will extend across the model as other areas may differ in terms of turbulence scale. However, a field referenced empirical value is a significant improvement on the values initially used.

Additional LiDAR data has recently become available and it will make further mesh refinement possible at the intertidal zones. In Darwin Harbour other effluent outfalls are positioned in these areas.

The main factors for the model calibration were the extension of the model mesh, and the alteration of the turbulence and diffusion coefficients. This improved the estimation of the preliminary contaminant plume significantly. The ADCP data also confirmed that the hydrodynamic problem can be estimated using depth averaged two-dimensions.

In summary, the calibration was a significant procedure that confirmed past assumptions and improved the estimation of the mixing zones. Previously, a 2-dimensional model was assumed sufficient to accurately model the hydrodynamics and water quality in Darwin Harbour, given that the mixing that occurs due to the large tidal movements within the harbour. This assumption has been supported by field information attained during the tracer study. Calibration of both hydrodynamic and water quality models, means that they can be used confidently in decision making for managing wastewater discharges in Darwin Harbour.

5.6 Model Limitations

Some limitations have been discussed above, although most are insignificant to the end result of the model output in the case of Darwin Harbour and Buffalo Creek. A major and documented limitation for describing the introduction of effluent into a far field model is the ability to accurately represent the near field effluent mixing (the physical area in the receiving environment in which advection and diffusion of the effluent are impacted by diffuser characteristics). Generally the concern is the inability of the model to represent the ‘trap height’. This refers to the height in the water column where the effluent becomes neutrally buoyant and is trapped at this layer. However, this is negligible in Darwin Harbour given there is no stratification in the water column at these locations. The introduction of effluent into the model mesh is described as a point source entry into one grid element that represents the size of the diffuser. Although this is the case, the initial dilution of the effluent is averaged over the element size. This results in an introductory dilution greater than that observed in the natural environment. This is a common and known limitation of a far field model (Blumberg 1996). The capability of a 3D model has been briefly explored during the model development, however will be developed further for the water quality model.

The equations that drive the hydrodynamic and water quality models are the Reynolds form of the Navier-Stokes equations. These equations describe the movement of fluid through time and space. In most engineering problem solving, underlying equations also have assumptions associated with them. The Navier-Stokes method of computing fluid movement, however, is widely used in the field of fluid mechanics and hydrodynamics. The only method to determine how well the model represents the environment is to do a direct comparison of the results. This is the method used above.

Lack of bathymetric data is also a limitation of the model accuracy. The information used in the Darwin Harbour model are taken from previous model meshes and government charts. Furthermore, little is known about the sediment transport processes in Darwin Harbour. It is probable that the topography in the intertidal zone and perhaps in deeper water migrates significantly during high intensity events such as cyclones. The modelling work carried out has taken this into account by performing sensitivity analyses on models with bathymetric differences. Although there are some differences, the end result of the mixing zone does not change significantly. As new data become available the model can be improved.

6 MODEL AND GUIDELINE METHODOLOGY

6.1 Water Quality Guidelines

6.1.1 Overview

Some interpretation of the Water Quality Objectives (WQO) for Darwin Harbour (NRETAS 2010) and Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000) require discussion to describe and justify the model application to Darwin Harbour.

The WQO describe the water quality needed to protect and sustain each of the beneficial uses declared for Darwin Harbour (NRETAS 2010). Currently, most of the WQO for physico-chemical water quality indicators are aligned with local guideline or trigger values for estuarine systems in the Darwin Harbour region (NRETAS 2010). For toxicants the guideline values default to the ANZECC guidelines. The guidelines or trigger values allow statistical assessment of water quality against the WQO – this is discussed in detail in section

WQO and associated guideline trigger values are specified for various water quality indicators for each beneficial use. Three beneficial uses described in the WQO for Darwin Harbour are: Aquatic Ecosystems Protection, Cultural and Recreational. Each of these categories have unique water quality indicators and unique methods for assessment of compliance with water quality guideline trigger values.

It is neither feasible nor practical to model all water quality indicators for each beneficial use. However it is possible to model representative water quality indicators for key contaminants, or contaminants that present known and specific risks for each beneficial use.

Even where stringent effluent limits are set and strict waste minimisation is practised, effluents may be of poorer quality than the receiving environment and not meet the specified water quality objectives (ANZECC & ARMCANZ 2000) .The ANZECC guidelines acknowledge and make allowance for this accepted practice through the concept of mixing zones (ANZECC & ARMCANZ 2000). Mixing zones are often defined as explicit areas around effluent discharges where the management goals of the ambient waters do not need to be achieved and hence the designated environmental values may not be protected (ANZECC & ARMCANZ 2000).

6.1.2 Trigger Values

A water quality guideline is a numerical concentration limit or narrative statement recommended to support and maintain a designated beneficial use (ANZECC & ARMCANZ 2000). Exceedance of guideline values is initially viewed as a trigger for further investigation rather than a failure. Further investigation would be designed to assess the site and its particular local characteristics in more detail leading to a better informed assessment of its true condition (NRETAS 2010).

NRETAS (2010) defines Darwin Harbour as a slightly to moderately modified system and lists priority water quality indicators for marine waters which comprise conductivity, temperature, pH, dissolved oxygen, nutrients (NOx, FRP, TN and TP), turbidity and chlorophyll-a.

Tables 8, 9 and 10 in NRETAS, 2010 (pp. 16-20) list interim ambient guideline values and WQO for priority water quality indicators of the Darwin Harbour Region for three categories of beneficial uses: Aquatic Ecosystem Protection, Cultural Use for Recreation (primary contact) and Cultural Use of Aquatic Food.

The water quality guideline trigger values for physico-chemical indicators for Aquatic Ecosystem Protection specified are based on a range of percentiles of monitoring data at a number of reference sites. Alternatively, where no local reference data are available, the document defaults to the ANZECC Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000) – this is applicable for toxicants.

The type of water quality indicator (eg. physico-chem, toxicants and bacteriological) and the beneficial use (aquatic ecosystem protection, cultural, recreation) determine the procedure and statistical method for assessment against the guideline trigger value.

- Beneficial Use: Aquatic Ecosystem Protection

According to NRETAS (2010) for assessment of physico-chem water quality indicators:

An exceedance will be deemed to have occurred when the ***median concentration*** *of n independent samples taken at a test site exceeds the eightieth percentile (i.e. the derived guideline) of the same indicator at a suitably chosen reference site.*

According to ANZECC (2000) the assessment of toxicant water quality indicators should be similar to physical and chemical indicators, however a more conservative approach should apply to the comparison of toxicant test data with the guideline values. Specifically it is recommended with the:

An exceedance will be deemed to have occurred when the ***95th percentile*** *concentration of n independent samples taken at a test site exceeds the default (guideline) trigger value.*

This approach is more stringent as, unlike physical and chemical stressors, toxicant guideline trigger values are based on actual biological effects data (ANZECC & ARMCANZ 2000).

- Beneficial Use: Recreation (Primary and secondary contact)

The definition of an exceedance according to Table 9 in NRETAS (2010) is unclear with *Note b* contradicting the specified water quality guideline values for both E.Coli and Enterococci.

Water Quality Objectives (NRETAS 2010) generally agree with the water quality assessment criteria specified in the Northern Territory Recreational Microbiological Water Quality Guidelines (DHF 2007), however the latter guidelines provide a number of ‘modes’ for specifying sampling requirements and actions to be undertaken as a result of sampling results.

As a worst case scenario it has been assumed that:

An exceedance will be deemed to have occurred when ***any single*** *independent sample taken at a test site exceeds the guideline trigger value.*

- Beneficial Use: Cultural (Aquatic food collection – shellfish harvest areas)

NRETAS (2009b) specify two criteria for assessment of bacteriological contaminants:

An exceedance will be deemed to have occurred when the ***mean probable number (MPN)*** *exceeds the low guideline trigger value (14 E.Coli / 100mL) or the 10th percentile of samples exceeds the high guideline trigger value (43 E.Coli / 100mL)*

The concept of an exceedance is generally applied to independent water quality monitoring results, taken periodically over an extended period of time at a single location. However the concept of an exceedance can also be applied to modelling results to assess if guideline trigger values are exceeded. Since the concentration of contaminants can be extracted from the model at any location within the model boundary it allows a theoretical mixing zone to be developed. This approach was approved in discussion with NRETAS Environmental Operations and Aquatic Health Unit.

6.1.3 Mixing Zones

It is an accepted practice to apply the concept of mixing zones, an explicitly defined area around an effluent discharge where the management goals of the ambient waters do not need to be achieved and hence the designated environmental values may not be protected (ANZECC & ARMCANZ 2000). Mixing zones must be a defined area, the boundary of which is usually determined in terms of the concentrations of water quality indicators within the effluent (ANZECC & ARMCANZ 2000) which exceed the water quality guideline trigger value. Based on this definition a mixing zone is applicable for each contaminant contained in the effluent which exceeds the water quality guideline trigger value.

The extent and nature of mixing zones depend on hydrodynamic conditions at the outfall site. At high-energy sites effluent may disperse more quickly and the mixing zone may be relatively small. Conversely, in low-energy systems mixing may be slower and mixing zone will be larger (ANZECC & ARMCANZ 2000). The use of mixing zones is not appropriate for managing the discharge of nutrients, bio-accumulatory or particulate substances (ANZECC & ARMCANZ 2000).

Defining the boundary of mixing zones around Power and Water’s outfall sites is required as part of the WDLs.

Generally, mixing zones are determined under worst case environmental conditions (ANZECC & ARMCANZ 2000). In Darwin the worst case conditions are during the dry season where there is little freshwater inflow and the possibility of strong onshore winds at stagnant tidal phases threaten the water quality of the coastline in proximity to the outfalls. Standard conditions have been created and applied to the model as discussed in 4.1 of this report.

The RMA water quality models are used to show geo-referenced mixing zones for various constituents and their trigger values.

A number of mixing zones for each constituent and its corresponding water quality trigger value and beneficial use is modelled. These individual mixing zones may vary in size, depending on the different trigger values of each constituent and the statistical method used to define an exceedance.

Due to the variation in tidal conditions the instantaneous mixing zones continually change over the tidal cycle. To demonstrate this, instantaneous mixing zones for an arbitrary contaminant at half hour intervals during a model simulation is shown in Figure 25 below. The colour gradients in the figures below represent different concentrations.

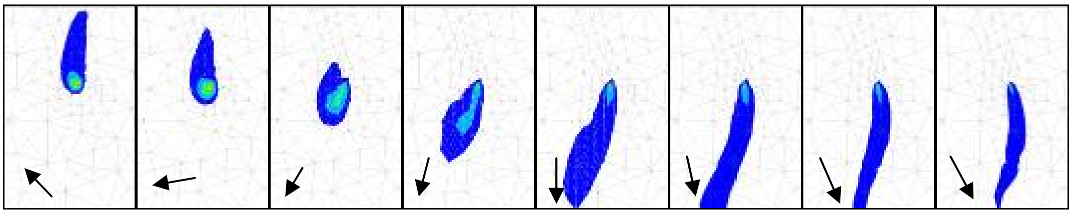


Figure 25. Arbitrary constituent concentration areas and direction of flow at half hour intervals of a model simulation.

Each of the half hour plumes in Figure 25 are instantaneous mixing zones. Based on this concept the entire mixing zone is the spatial accumulation of all the individual mixing zones over a 30-day tidal cycle. To put this into perspective, Figure 25 covers only four hours. If it covered 30 days, the mixing zone for Figure 25 above might look more like Figure 26 below. This is what we call a peak mixing zone. It is defined as the spatially accumulated maximum concentrations through the time period of the model run, displayed in one frame.

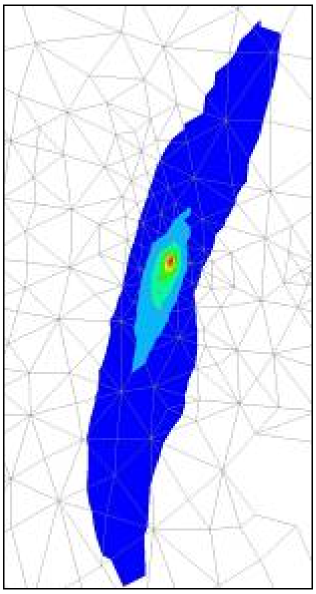


Figure 26. Example of a mixing zone.

As discussed in section 6.1.2, the definition of an exceedance varies for different contaminants and beneficial uses. A statistical function for the water quality model was tailored to a third party viewer program for this purpose. The model output can show a percentile concentration of theoretically independent samples for any peak image. For example the median of the peak values in the 30 day time series can determined using this function. This median concentration is compared with the peak maximum concentration as shown in Figure 27 below.

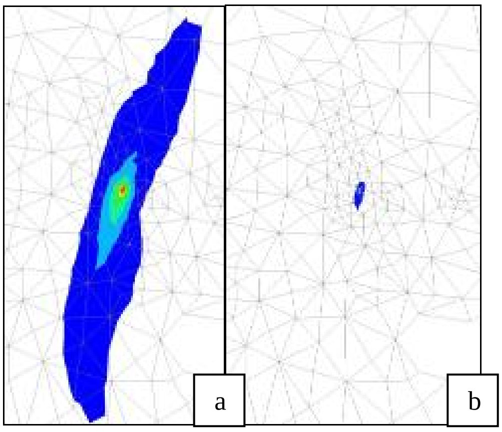


Figure 27. (a) Peak maximum and (b) median values of the peak maximum modelled mixing zone for an arbitrary, non-decaying constituent.

A mixing zone footprint must be developed for regulatory purposes. This regulatory mixing zone may be the maximum spatial extent of all the contaminants' mixing zones combined. This will ensure that all beneficial uses will be protected outside the boundaries of the mixing zone.

6.1.4 Contaminants

Previous modelling work undertaken by CDU (Valentine and Totterdell, 2006, 2008) focussed on the notional conservative metal toxicant zinc, and a decaying pathogen, E.Coli. Since the initial modelling work, other water quality contaminants have been collaboratively identified by Power and Water and NRETAS for further investigation. Initially three individual contaminants (copper, total phosphorous and E.Coli), were chosen for modelling based on three contaminant categories (metal toxicants, nutrients and bacteriological indicator organisms. However since the release of the Water Quality Objective for Darwin Harbour (NRETAS 2010) a more thorough process has identified alternate and additional contaminants for modelling.

A number of requirements and limitations were used in selecting contaminants for modelling, including:

- Adequate historical effluent monitoring data is required to determine inflow characteristics.
- A water quality indicator guideline trigger value must be available against which the contaminant can be assessed.
- The laboratory detection limits must be high enough to allow assessment.
- If the contaminant experiences growth or decay, such values must be available in literature.
- The contaminant must be appropriate for application of mixing zones.

Based on the above criteria the contaminants available for modelling are somewhat limited and for each declared beneficial use a range of contaminants were shortlisted and grouped according to their category of contaminant. These categories include physical and chemical stressors, toxicants and bacteriological indicator organisms. A summary of the shortlisted contaminants is listed in Table 1 below.

Five years of water quality monitoring data were analysed to provide statistical properties of each contaminant, including the median (50th percentile) and 90th percentile concentrations. These are two commonly defined thresholds used in assessment of effluent discharges, including Power and Water's waste discharge licence quantitative discharge limits.

The median concentration of monitoring data is considered to represent the quality of effluent experienced under typical operating conditions. Alternatively, the 90th percentile concentration of monitoring data is considered to represent the quality of effluent experience under atypical operating conditions - that is the small percentage of time where the plant is underperforming and effluent quality is at its worst.

For each contaminant the effluent concentration from both typical and atypical operating conditions was divided by the applicable water quality guideline trigger value. The resulting number provided a required dilution ratio for each contaminant. The contaminant with the highest dilution ration for each category of contaminant in each declared beneficial use is selected for modelling. The process selects the worst case contaminant from each category, resulting in the largest mixing zone.

Metal toxicants are considered non-decaying contaminant, however nutrients (including the toxicant ammonia) and bacteriological indicator organisms undergo decay.

It should be noted that Enterococci is the preferred bacteriological indicator for primary recreation, however until a robust Enterococci data base is established in the NT, the use of E.Coli is acceptable (NRETAS 2010). The input concentrations, background levels and trigger values used in the model are shown in Table 1 below.

Table 1 Summary of contaminants and their respective attributes and trigger values for model application

Beneficial Use WQO	Contaminant Category	Parameter (mg/L, CFU/100mL)	Appropriate for Mixing Zone Definition	Statistical Assessment of Compliance	Contaminant Behaviour	Water Quality Guideline Trigger Value *
***Environmental Use** (Aquatic Ecosystem Protection)*						
	Nutrients	Total Nitrogen (mg/L)	No	Median	Decay	0.44
		Ammonia (mg/L)	No	Median	Decay	0.02
		Total NOx (mg/L)	No	Median	Decay	0.01
		Total Phosphorous (mg/L)	No	Median	Decay	0.016
		FR Phosphorous (mg/L)	No	Median	Decay	0.008
	Toxicants	Copper (mg/L)	Yes	95% ile	Conservative	0.0013
		Zinc (mg/L)	Yes	95% ile	Conservative	0.015
		Lead (mg/L)	Yes	95% ile	Conservative	0.0044
		Ammonia (un-iodised) (mg/L) ^	Yes	95% ile	Conservative	0.068
Cultural Use – Recreation						
Amber Mode	Bacteriological	E.Coli (cfu/100mL)	Yes	Maximum	Decay	200
Primary Recreation		Enterococci (cfu/100mL)	Yes	Maximum	Decay	51
		Pathogenic protozoans (orgs/100mL)’	No	Maximum	N/A	10
Red Mode		E.Coli (cfu/100mL)	Yes	Maximum	Decay	500
		Enterococci (cfu/100mL)	Yes	Maximum	Decay	201
Secondary Recreation		E.Coli (cfu/100mL)	Yes	Maximum	Decay	1000
Cultural Use - Aquatic Food Collection (Shellfish Harvest Areas)						
	Bacteriological	E.Coli (condition 1) (MPN/100mL)	Yes	Median	Decay	14
		E.Coli (condition 2) (MPN/100mL)	Yes	90% ile	Decay	43

* 95% species protection level for toxicants

^ (un-ionised) ammonia is not a conservative metal a toxicant of concern in the ANZECC guidelines. Un-ionised Ammonia is calculated using the transformation formula specified in Appendix 2 of the ANZECC Guidelines (pp161). Ammonia trigger value is 910ug/L for slightly disturbed systems. Conversion based on pH of 8.0 @ 30 deg C

‘ pathogenic protozoans refer to a range of potential fresh and marine organisms

6.2 Water Quality and Guideline Assumptions

6.2.1 Background Levels

Background concentrations for each contaminant were determined using data provided by NRETAS Aquatic Health Unit (NRETAS 2005). These data were used to develop the Darwin Harbour Water Quality Objectives, although several locations which are already impacted by effluent discharges were excluded. The 50th percentile of monitoring data was used to determine the background ambient concentrations.

7 INTERPRETING MODEL RESULTS

7.1 Method

The model output results file and graphical display include contaminant concentrations over the duration of the model simulation at any location within the model mesh. The standard duration of the model simulation is 30 days as described in section 4.1.2. Visual representation of the peak model outputs (defined in section 6.1.3) is used to assess the size and extent of the mixing zone, which is the hypothetical area above the nominated trigger value. The results of the model can be displayed in two ways; peak value images and videos.

Peak images are useful in summarizing the extent of the plume at any one discharge location. They are a tool that will be used to define the mixing zones for regulatory requirements according to their trigger values. Figure 26 is a good example of this, with colour gradients showing different concentrations. It should be noted that if the trigger value concentration is exceeded only once during the thirty day tidal cycle it will still form part of the mixing zone. To illustrate this the time series at a point near the outer boundary of a mixing zone is shown (Figure 28). An arbitrary trigger value that represents a guideline trigger value has been applied. Note that although the guideline trigger value is only exceeded once it still forms part of the mixing zone.

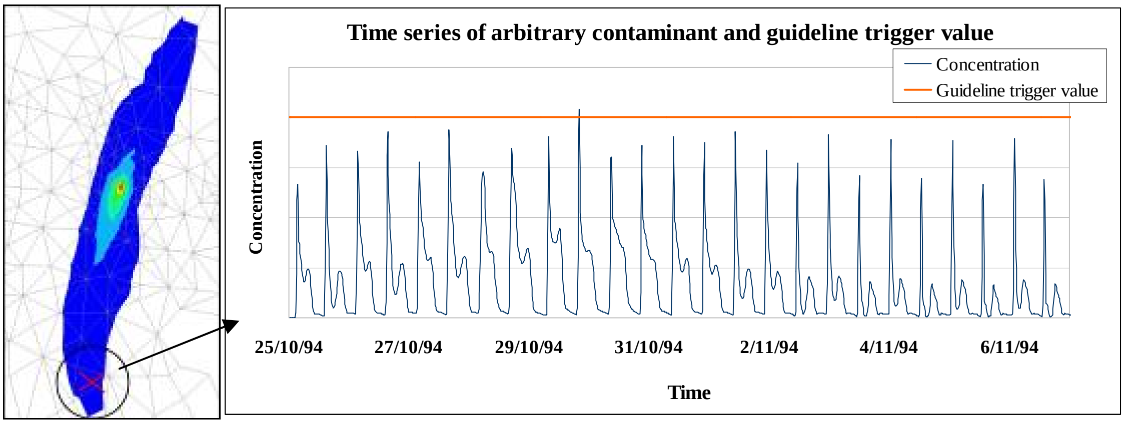


Figure 28 Time series of an arbitrary contaminant near the edge of a mixing zone.

Maps, grids, aerial photographs and landmarks can be added to the model output to show the spatial extent of the mixing zone at a particular region.

A video is another medium used to show the variation in location and extent of selected constituents over the duration of the simulation. This is not possible for display of results in printed media, however can be illustrated though sequences such as those in figure 26.

Water quality monitoring will be used to confirm the extent of the mixing zone determined by the model. The water quality monitoring results will be added to the graphical model output at the location where the tests were performed and will determine over time whether or not the trigger value has been breached. If a trigger value is breached, further investigation and management actions will be instigated.

There is an element of the water quality monitoring that can be applied to improve the water quality model. It must take a specific form if it is to be of use in continual model calibration. Water quality monitoring must consist of long term monitoring at specific sites and times so that long term trends are determined. After these trends are found, they can be compared with the model output. Different stages of the tidal cycle must also be taken into account.

7.2 Continuous Model Improvement

NRETAS have historically undertaken water quality monitoring at various locations within Darwin Harbour, however the frequency of this program has generally been limited to quarterly sampling during ebb/spring tides and the range of parameters monitored is limited (mainly in-situ physico-chemical contaminants and some nutrients and metal monitoring).

The paucity of data, the limited number of locations monitored and the variability associated with random grab samples limits its applicability for calibrating the water quality model.

In 2008 Power and Water undertook an intensive water quality monitoring program in an attempt to provide water quality calibration data for the model at the East Point Outfall and the Larrakeyah Outfall. Water quality monitoring was conducted over two days at seven locations at each outfall site. The parameters monitored included bacteriological indicator organisms (E.Coli, enterococci), nutrients, physico-chemical parameters and a range of metals. The monitoring was conducted at three depths in the water column – bottom, mid and surface. The effluent was also sampled prior to discharge through the outfalls.

This monitoring program provided little benefit to the calibration of the model, primarily due to the extremely low concentrations of contaminants measured. The significant dilution of the effluent from the Larrakeyah Outfall, and the low concentrations in the East Point Outfall effluent resulted in most parameters being below the limit of detection immediately adjacent to the outfall. The outermost sampling locations, some several kilometres away, also showed very low levels. All of the results from this monitoring investigation have been provided to NRETAS Aquatic Health Unit and Environmental Operations.

Since the recent E.Coli detected in Darwin Harbour, NRETAS and Power and Water have been undertaking routine water quality monitoring in the vicinity of the East Point and Larrakeyah Outfalls. The duration of this data set it currently limited, but as the monitoring continues it may provide enough data to assist in model validation.

7.3 Model Limitations for Guideline Applications

While not necessarily relevant to this reports objective of describing the modelling methodology, Power and Water feel it is warranted to include a brief discussion about the limitations of using model-defined mixing zones for regulatory purposes. The above approach to defining mixing zones for regulatory purposes has a number of practical limitations discussed below.

Mixing zones do not necessarily address specific uses at the outfall sites. Environmental values or beneficial uses are defined for the entire area of Darwin harbour and are not based on specific activities at specific locations. As such it is possible that a regulatory mixing zone will be defined based on a parameter that has little relevance. For example, a regulatory mixing zone may be defined around an ocean outfall to meet primary recreational water quality objectives if this parameter (or individual mixing zone) has the largest spatial area. This is not logical if primary recreation is unlikely to occur near the outfall, yet a smaller individual mixing zone for a metal toxicant extends into a sensitive aquatic environment.

The use of regulatory mixing zones to define the spatial extent of water quality monitoring programs is not appropriate. For example, the regulatory mixing zone around the East Point Outfall may be primarily defined by a large geographical mixing zone required to meet the cultural water quality objectives for the harvesting of aquatic seafood. Spatially this mixing zone will incorporate numerous other ‘individual mixing zones’, such as for metal toxicants. If an individual mixing zone for a metal toxicant includes a sensitive marine environment (such as the East Point aquatic reserve) then this will not be identified in the regulatory mixing zone and not be captured in a monitoring program designed around such a mixing zone boundary. Furthermore any monitoring on the boundary of the regulatory mixing zone will be valid for the individual contaminant used in its’ definition. This will result in the majority of parameters sampled detecting concentrations below their relevant guideline trigger value. This would represent a significant waste of resources.

If environmental conditions and discharge concentrations remain the same over time, mixing zones will increase in size as growth increases within the catchment of the treatment plants and the volume of discharges increase. As such the size of the mixing zone will also increase.

Most water quality monitoring is by grab samples – representing a single location at a single moment in time. Due to the dynamic nature of the mixing the effluent plume is constantly changing in both size and location. Therefore, application of a single grab sample is limited. Water quality monitoring will need to be planned according to what suits the model application.

The model applies a constant rate of discharge from each outfall over the modelling period. Over the 30-day period the total volume of the effluent discharge from the outfall is accurate. However, the actual discharge rate at one point in time varies significantly. This is due to the nature of the catchment upstream of the treatment plant and the characteristics and operating rules of the plant. This can be modelled, and a future goal for modelling is to form a standard discharge and concentration time series based on a combination of trends and worst case scenarios. The model also applies a constant concentration of water quality of the effluent. If mixing zones are based on atypical plant operating conditions then in reality the average long-term concentrations are much lower than those used to define the mixing zone. This adds to the conservative nature of the model, and should ensure that trigger value exceedances do not occur, but will also result in a sampling program designed around such an approach being inappropriate.

8 FUTURE MODEL DEVELOPMENT

Some new intertidal bathymetric data are available for Darwin harbour and Buffalo Creek which could improve the defined topography in the intertidal zone. These data will be applied to the model in due course, improving the model accuracy at specific effluent outfalls.

When data from operating plants become available a standard effluent discharge time series will be constructed. This will rule out the uncertainty associated with the constant discharge that is currently being applied.

Overflow into a local creek from the Ludmilla Waste Water Treatment plant is likely to occur in some cases. This can be modelled by extending the model mesh to include the local creek and apply water quality and discharge information.

Possible locations for a future extension of the Buffalo Creek outfall to Lee Point will be modelled using the Harbour model. In the meantime, a water quality model for Buffalo Creek will be improved to reflect constituent concentrations in the estuary. Recently there have been problems with the complexity of the hydrodynamics in the area and the water quality has not been represented accurately. This will be explored in greater detail and a more accurate water quality model using water quality data from recent monitoring efforts will be produced.

Biogeochemical models can be developed once foundation research has been carried out in the Darwin Harbour region. General research into chlorophyll a, algae, nutrient cycles and nutrient-sediment cycles are being carried out by NRETAS (Fortune 2009) pp73) to collect baseline data in this area. Following this, laboratory analysis of the samples must be carried out and published before any assumptions are generated and applied to a general model.

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Appendix B Hydrodynamic and Water Quality Modelling

B.2 Hydrodynamic Modelling of Darwin Harbour, Modelling Results

East Point Outfall

Mixing Zone determination using Hydrodynamic and Water Quality Modelling

Report in support of Public Environment Report for Duplication of East Point Effluent Rising Main

Water Services January 2012

Power and Water Corporation

Contents

Tables

Figures

Introduction

This document has been prepared in support of the Public Environment Report for the Duplication of East Point Effluent Rising Main and should be read in conjunction with the report Hydrodynamic Modelling of Darwin Harbour (Valentine et al., 2011) and the PER documentation.

The Darwin Harbour model has been used to investigate the expected fate of a number of constituents of effluent discharged at the existing East Point Outfall. Results of the modelling are presented for a range of scenarios to allow comparison of pre- and post Larrakeyah diversion and Ludmilla WWTP upgrade conditions.

Power and Water Corporation is committed to a major extension of the East Point Outfall, however the diversion of flows from the Larrakeyah catchment will precede these works. Consequently, this assessment has considered the short-term effects of the additional flows discharged via the existing outfall.

1. Modelling Overview

1.1. Model description

Two types of finite element models are used for Darwin Harbour, a hydrodynamic (RMA-10) model and a water quality (RMA-11) model. The model covers a 511km2 surface area, which includes the main harbour water body, mud flats and main tributaries.

Hydrodynamic Model

The RMA-10 hydrodynamic model uses historical and empirical information for the region where possible. The model is developed and run based on surveyed bathymetric and topographic data and measured tidal data. The water velocity and depth calculated by the hydrodynamic model is used as a basis for calculating the advection and dispersion of the effluent water quality constituents, therefore an accurate hydrodynamic model is necessary for the accuracy of the subsequent water quality model.

The model is constructed using a finite element grid, referred to as a 'mesh' to define the bathymetry of the study area. Triangular and quadrilateral elements are used in an unstructured mesh at different resolutions to define the level of detail in areas of interest. Higher grid resolution depicts more bathymetric detail. Bed material types such as sand, rock and mudflats are also defined in the model mesh. These material types have a bed roughness associated with them which are commonly known as Manning's n roughness coefficients. Bathymetry and bed material are represented by 5177 mesh elements.

Control files define options for model parameters such as turbulent closure of momentum (eddy viscosity), water temperature and salinity and boundary conditions.

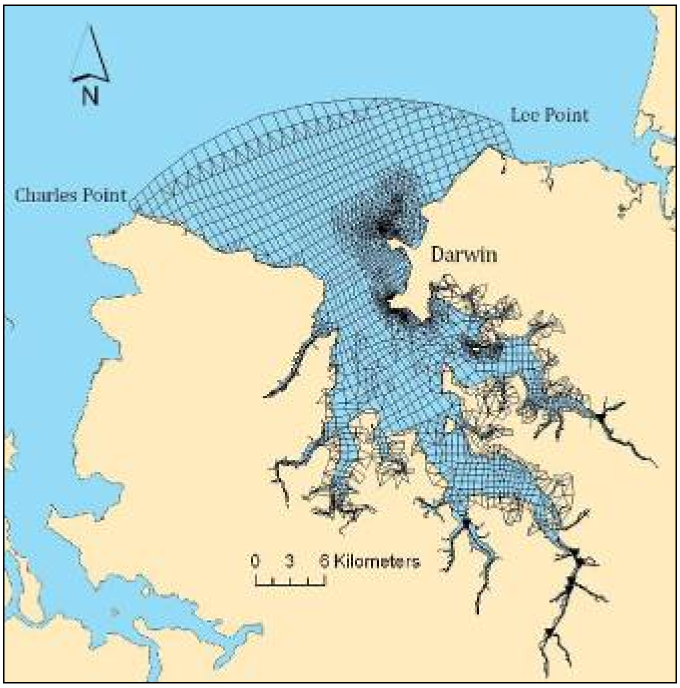


Figure 1: Darwin Harbour Model Mesh

Water Quality Model

The water quality model uses output from the hydrodynamic model and the mesh component to drive the advection and dispersion of introduced constituents. These constituents can take the form of a decaying or non-decaying contaminant and in this case are introduced into the model at a point source location. This is done by allocating a mesh cell in the location of the outfall as the point source. During model simulation, concentrations are calculated by integration across the area of each element in the mesh. A concentration plume diffuses in the x and y Cartesian coordinate directions according to parameters specified in the control file such as the turbulent mixing of mass (eddy diffusivity).

1.2. Model development

Refer to the modelling methodology report for detailed information on model development and calibration (Valentine et al., 2011)

A bathymetric survey of the area around East Point was carried out in 2009 and a Digital Elevation Model (DEM) has been constructed. LiDAR data has more recently become available and will be used to increase the accuracy of bed elevations for the intertidal zone.

Historical tidal data are used to drive the models. A thirty day tide cycle from 1994 has been selected as a standard for all model simulations, which incorporates a full range of spring and neap tidal conditions.

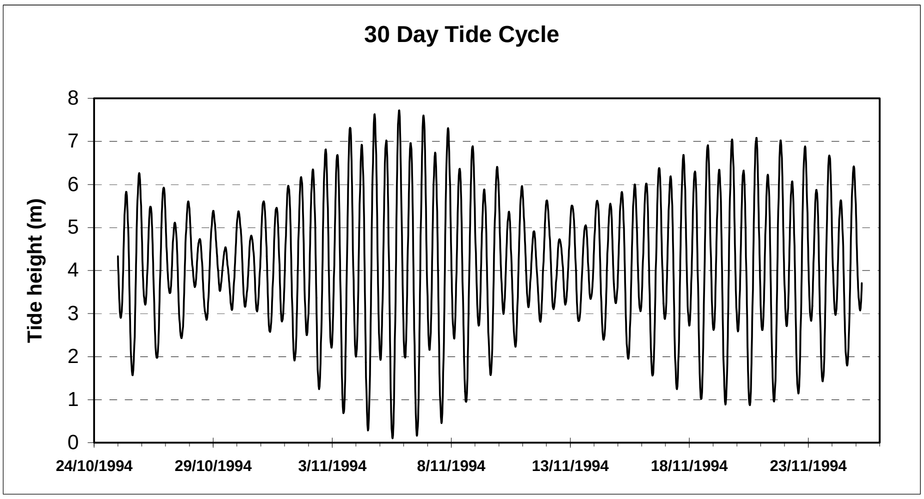


Figure 2: The Fort Hill tide gauge data used to drive the RMA-10 hydrodynamic model.

Meteorological data is applied to the model to incorporate the effects of wind on the water surface and therefore plume movement and dispersion.

Effluent discharge is treated as an inflow to the model and is applied to a mesh element that corresponds to the existing outfall location.

Water quality of the inflow can be adjusted by defining a concentration of a contaminant in the mass of inflow. The contaminant is treated as a parameter which is defined by a set of characteristics in the model, which includes decay or attenuation through biochemical and/or physical processes. This is an area of ongoing research in the wet/dry tropics however some published data exists which complements local field investigations.

1.3. Model calibration

Detailed information on model calibration is presented in Valentine et al. (2011). In 2008 Power and Water undertook an intensive water quality monitoring program in an attempt to provide water quality calibration data for the model at the East Point Outfall and the Larrakeyah Outfall. Water quality monitoring was conducted over two days at seven locations at each outfall site. The parameters monitored included bacteriological indicator organisms (E.Coli, enterococci), nutrients, physico-chemical parameters and a range of metals. The monitoring was conducted at three depths in the water column – bottom, mid and surface. The effluent was also sampled prior to discharge through the outfalls.

This monitoring program provided little benefit to the calibration of the model, primarily due to the extremely low concentrations of contaminants measured. The significant dilution of the effluent from the Larrakeyah Outfall, and the low concentrations in the East Point Outfall effluent resulted in most parameters being below the limit of detection immediately adjacent to the outfall. All of the results from this monitoring investigation have been provided to NRETAS Aquatic Health Unit and Environmental Operations.

In 2010, a tracer study carried out at East Point provided valuable field information which confirmed calibration assumptions and improved the estimation of the mixing zones. Refer to Valentine et al. (2011) for details on the tracer study.

2. Model application

Essentially, the model calculates the concentration of a selected contaminant (parameter) for each mesh element, for a number of time steps over the 30-day tidal cycle.

Some interpretation of the Water Quality Objectives (WQO) for Darwin Harbour (NRETAS 2010) and Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000) is required to describe the model application to Darwin Harbour.

2.1. Water Quality Guidelines

The WQO describe the water quality needed to protect and sustain each of the Beneficial Uses declared for Darwin Harbour under the Water Act (NRETAS 2010). Currently, most of the WQO for physico-chemical water quality indicators are aligned with local guideline or trigger values for estuarine systems in the Darwin Harbour region (NRETAS 2010). For toxicants the guideline values default to the ANZECC guidelines. The guidelines (or trigger values) allow statistical assessment of water quality against the WQO.

WQO and associated guideline trigger values are specified for various water quality indicators for each beneficial use. Three beneficial uses are declared for Darwin Harbour: Aquatic Ecosystems Protection, Cultural and Recreational. Each of these categories has unique water quality indicators and unique methods for assessment of compliance with water quality guideline trigger values.

It is neither feasible nor practical to model all water quality indicators for each beneficial use. However it is possible to model representative water quality indicators for some key contaminants.

NRETAS (2010) defines Darwin Harbour as a slightly to moderately modified system and lists priority water quality indicators for marine waters which comprise conductivity, temperature, pH, dissolved oxygen, nutrients (NOx, FRP, TN and TP), turbidity and chlorophyll-a.

The type of water quality indicator (eg. physico-chem, toxicants and bacteriological), and the beneficial use, determine the procedure and statistical method for assessment against the guideline trigger value. (refer to NRETAS, 2010 for further details)

- **Beneficial Use: Aquatic Ecosystem Protection**

For assessment of physico-chem water quality indicators:

*An exceedance will be deemed to have occurred when the **median concentration** of n independent samples taken at a test site exceeds the derived guideline.*

For assessment of toxicant water quality indicators:

*An exceedance will be deemed to have occurred when the **95th percentile** concentration of n independent samples taken at a test site exceeds the default (guideline) trigger value.*

- **Beneficial Use: Recreation (Primary and secondary contact)**

Water Quality Objectives (NRETAS 2010) generally agree with the water quality assessment criteria specified in the Northern Territory Recreational Microbiological Water Quality Guidelines (DHF 2007), however the latter guidelines provide a number of 'modes' for specifying sampling requirements and actions to be undertaken as a result of sampling results.

As a worst case scenario it has been assumed that:

*An exceedance will be deemed to have occurred when **any single** independent sample taken at a test site exceeds the guideline trigger value.*

- **Beneficial Use: Cultural (Aquatic food collection – shellfish harvest areas)**

NRETAS specify two criteria for assessment of bacteriological contaminants:

*An exceedance will be deemed to have occurred when the **mean probable number (MPN)** exceeds the low guideline trigger value (14 E.Coli / 100mL) or the **10th percentile of samples** exceeds the high guideline trigger value (43 E.Coli / 100mL)*

The concept of an exceedance is generally applied to independent water quality monitoring results, taken periodically over an extended period of time at a single location. However the concept of an exceedance can also be applied to modelling results to assess if guideline trigger values are exceeded. Since the concentration of contaminants can be extracted from the model at any location within the model boundary it allows a theoretical mixing zone to be developed. This approach was approved in discussion with NRETAS Environmental Operations and Aquatic Health Unit.

2.2. Mixing Zones

Where effluent discharge is of poorer quality than the receiving environment and does not meet the specified water quality objectives at "end of pipe", the ANZECC guidelines make allowance for this through the concept of mixing zones. **Mixing zones are defined as explicit areas around effluent discharges where the management goals of the ambient waters do not need to be achieved.**

Generally, mixing zones are determined under worst case environmental conditions (ANZECC & ARMCANZ 2000). In Darwin, during the dry season, there is little freshwater inflow and the possibility of strong onshore winds at stagnant tidal phases provides the worst case conditions in proximity to the outfalls. Standard conditions have been created and applied to the model as discussed in Valentine et al. (2011).

Due to the variation in tidal conditions the instantaneous mixing zones continually change over the tidal cycle. Based on this concept the entire (or “peak”) mixing zone is the spatial accumulation of all the individual mixing zones over a 30-day tidal cycle. **It is important to recognise that, for the purposes of this report, the mixing zone is defined as the spatially accumulated maximum concentrations through the time period of the model run, displayed in one frame, and therefore represents the maximum envelope rather than a single moment in time.**

2.3. Contaminants used for modelling

For each declared beneficial use, a range of contaminants have been shortlisted and grouped according to their category of contaminant (Valentine et al., 2011). These categories include physical and chemical stressors, toxicants and bacteriological indicator organisms.

There are two commonly defined thresholds used in assessment of effluent discharges.

- The median concentration of monitoring data is considered to represent the quality of effluent experienced under typical operating conditions.

- The 90th percentile concentration of monitoring data is considered to represent the quality of effluent experience under atypical operating conditions - that is the small percentage of time where the plant is underperforming and effluent quality is at its worst.

For regulatory purposes, the overall mixing zone will be determined through a process of establishing which contaminant will result in the largest mixing zone (refer Valentine et al., 2011). This process has concluded that Copper and E.Coli are the appropriate parameters for determining the outer limits of regulatory mixing zones.

For the purposes of this assessment, mixing zones have been modelled for a wider range of nutrient and toxicant contaminants and bacteriological indicator organisms. These mixing zones are presented in Section 4.

Metal toxicants are considered non-decaying contaminants; however nutrients (including the toxicant ammonia) and bacteriological indicator organisms undergo decay. It should be noted that Enterococci is the preferred bacteriological indicator for primary recreation, however until a robust Enterococci data base is established in the NT, the use of E.Coli is acceptable (NRETAS 2010).

The trigger values determined to be suitable for use in the model are shown in Table 1.

Beneficial Use WQO		Contaminant Category	Parameter	Statistical Assessment of Compliance	Contaminant Behaviour	Water Quality Guideline Trigger Value*
***Environmental Use** (Aquatic Ecosystem Protection)*						
		Nutrients	Total Nitrogen (mg/L)	Median	Decay	0.44
			Ammonia (mg/L)	Median	Decay	0.02
			Total NOx (mg/L)	Median	Decay	0.01
			Total Phosphorous (mg/L)	Median	Decay	0.020
			FR Phosphorous (mg/L)	Median	Decay	0.010
		Toxicants	Copper (mg/L)	95% ile	Conservative	0.0013
			Zinc (mg/L)	95% ile	Conservative	0.015
			Lead (mg/L)	95% ile	Conservative	0.0044
			Ammonia (un-ionised) (mg/L)^	95% ile	Conservative	0.068
Cultural Use – Recreation						
Primary	Amber Mode	Bacteriological	E.Coli (cfu/100mL)	Maximum	Decay	200
			Enterococci (cfu/100mL)	Maximum	Decay	51
			Pathogenic protozoans (orgs/100mL)	Maximum	N/A	10
	Red Mode		E.Coli (cfu/100mL)	Maximum	Decay	500
			Enterococci (cfu/100mL)	Maximum	Decay	201
Secondary			E.Coli (cfu/100mL)	Maximum	Decay	1000
Cultural Use - Aquatic Food Collection (Shellfish Harvest Areas)						
		Bacteriological	E.Coli (condition 1) (MPN/100mL)	Median	Decay	14
			E.Coli (condition 2) (MPN/100mL)	90% ile	Decay	43

Table 1: Summary of contaminants and their respective attributes and trigger values suitable for model application

Note: *The East Point Outfall is located in the Outer Estuary area as defined in NRETAS (2010 – WQO report)

^ Un-ionised Ammonia is calculated using the transformation formula specified in Appendix 2 of the ANZECC Guidelines (pp161).

The current NHMRC Guidelines for Managing Risks in Recreation Water, do not consider waterborne infections a hazard for incidental (secondary) contact recreational use and therefore have not specified a microbiological indicator for this form of contact. Incidental contact is defined as boating, fishing and wading of adults, but excludes any recreational activities by children, these are always considered as primary contact.

The model is currently developed to establish mixing zones for the following contaminants:

- Nutrients
    - Total Nitrogen
    - Total Phosphorous
- Toxicants
    - Copper
    - Zinc
    - Lead
- Bacteriological
    - E.Coli
    - Enterococci

The model is not yet able to resolve concentrations of other nutrient indicators, such as Ammonia and Filterable Reactive Phosphorous. These constituents are rapidly converted and absorbed in the marine environment and an appropriate conversion factor has to be applied in addition to dilution. Appropriate factors are difficult to determine and have not yet been documented or established for the local conditions.

Copper has been selected as an appropriate constituent for mixing zone modelling as it has the widest gap between the trigger value and contaminant concentration in the effluent.

3. Scenarios

Three operating scenarios, for the existing outfall location, have been modelled using typical (median) and atypical (90%ile) contaminant concentrations:

- Scenario 1 - Pre-Larrakeyah diversion (Ludmilla catchment only);
- Scenario 2 - Combined Larrakeyah and Ludmilla catchment flows – with current (2011) treatment capacity at Ludmilla WWTP
- Scenario 3 - Combined Larrakeyah and Ludmilla catchment flows – with upgraded treatment capacity at Ludmilla WWTP (due for completion Nov 2012)

For each scenario, mixing zones have been generated for the effluent qualities detailed in Table 2. The effluent qualities have been determined based on analysis of up to 6 years of data from the wastewater stream.

Discharge qualities for Scenarios 1 and 2 are based on statistical analysis of monitoring data from the effluent stream. Summary data is presented in Appendix A.

Discharge quality for Scenario 3 (post treatment plant upgrades) is based on historical data for influent wastewater quality and predicted treatment outcomes (Hunter Water, 2011).

Note that these scenarios are only relevant for the period until completion of the East Point outfall extension.

	Scenario 1 current outfall Ludmilla only		Scenario 2 combined effluent, pre upgrade		Scenario 3 combined effluent, post upgrade	
Parameter	**Typical (median)**	**Atypical (90th%ile)**	**Typical (median)**	**Atypical (90th%ile)**	**Typical (median)**	**Atypical (90th%ile)**
Flow rate (ML/day)	9.5	9.5	12.5	12.5	12.5	12.5
E. Coli (cfu/100ml)	80 *	11100 *	80	11100	80	10000
Enterococci (cfu/100ml)	10 *	182.8 *	10	182.8	10	120
Copper (mg/L)	0.139 ^	0.25 ^	0.139	0.25	0.139	0.25
Zinc (mg/L)	0.08 ^	0.1 ^	0.08	0.1	0.08	0.1
Lead (mg/L)	0.003 ^	0.005 ^	0.003	0.005	0.003	0.005
Total Nitrogen (mg/L)	34.2 ^	46.37 ^	34.2	46.37	30	38
Total Phosphorous (mg/L)	4.9 ^	7 ^	4.9	7	2.74	3.92

Table 2: Contaminants used for model application at existing East Point outfall

* Derived from monitoring data 1 July 2010 to 8 November 2011
^ Derived from historical data 2004-2011

4. Results of modelling

It is important to note the following assumptions and limitations:

- As described in Section 2.2, the mixing zones represent the hypothetical area where, at some point in the 30-day tidal cycle, the parameter exceeds the trigger value (ie the Water Quality Objective or the default trigger value defined in ANZECC where no local water quality objective has been determined). It should be noted that if the trigger value concentration is exceeded only once during the thirty day tidal cycle it may still form part of the mixing zone.

- The duration or frequency of exceedence cannot be determined from these plots of peak model output.

- The mixing zones have been contoured to quantify the degree of exceedance, with values representing the parameter concentration above the trigger level, not the absolute concentration. The contour levels (colours) shown do not represent the quantum of exceedence of trigger levels but are used to assist with a comparison of scenarios.

Where no mixing zone is apparent, even at the point of discharge, this may be due to:

- Effluent quality is already below the trigger value; or

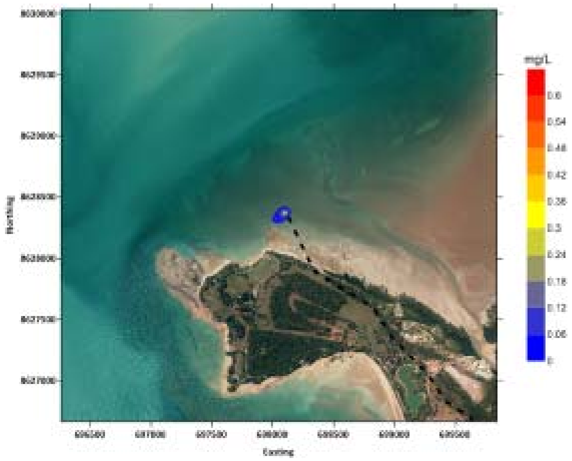
- Near-field effects. The model requires that initial dilution of the effluent is averaged over the mesh element that represents the outfall point. This results in an introductory dilution greater than that observed in the natural environment. This is a common and known limitation of a far field model (Blumberg, 1996). The mesh element representing the current outfall covers an area of $148m^2$.

The following pages provide outputs from the model presented as mixing zones in relation to the established trigger values.

Each page presents a comparison of the three operating scenarios for specific parameters, for both typical (median) and atypical (90%ile) conditions.

Total Nitrogen median

Typical (Median)



CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)

CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

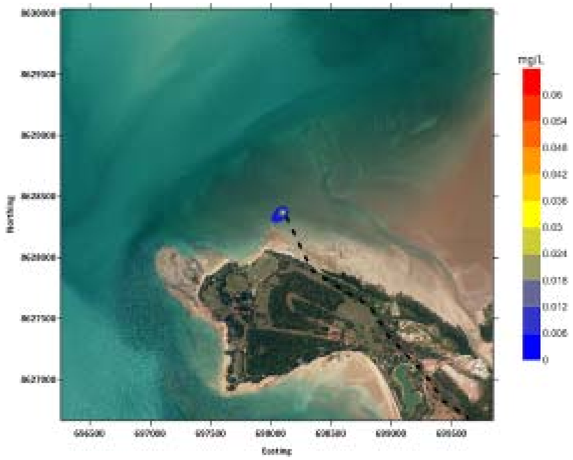
COMBINED EFFLUENT, POST UPGRADE

Total Phosphorous Median

Typical (Median)

CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)

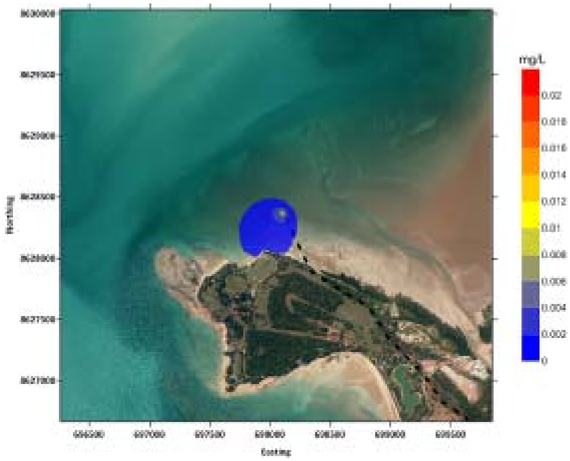
CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

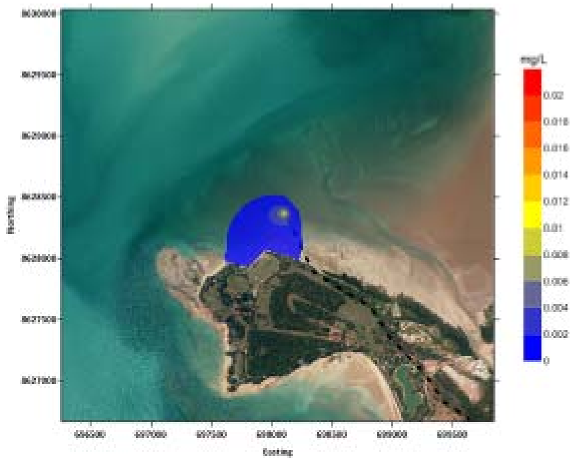
COMBINED EFFLUENT, POST UPGRADE

Copper 95th Percentile

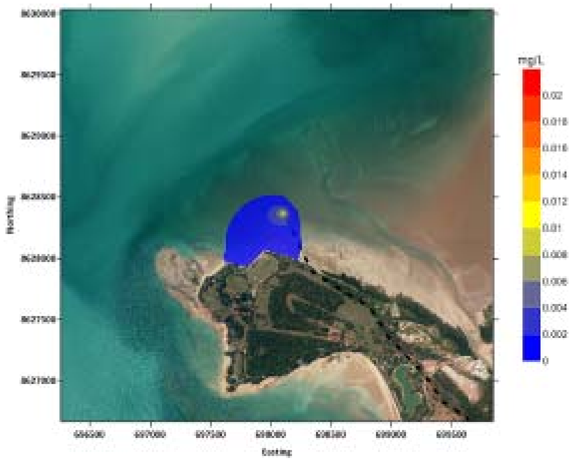
Typical (Median)



CURRENT EFFLUENT, LUDMILLA ONLY

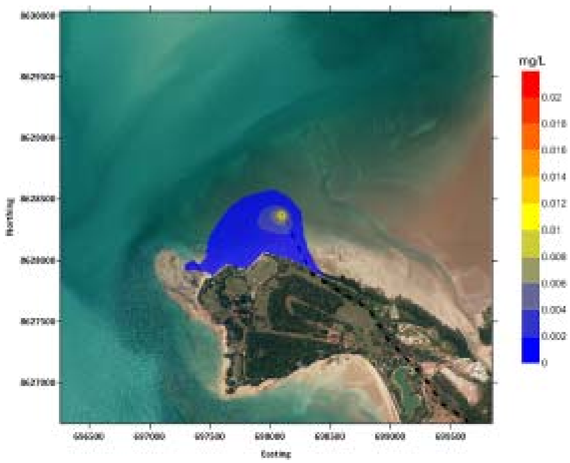


COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)



CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

Lead 95th Percentile

Typical (Median)

CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)

CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

Zinc 95th Percentile

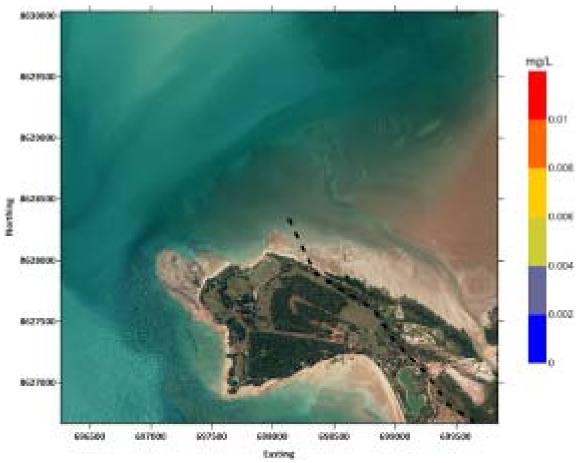
Typical (Median)

CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)



CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

E. Coli. Primary Recreation Amber

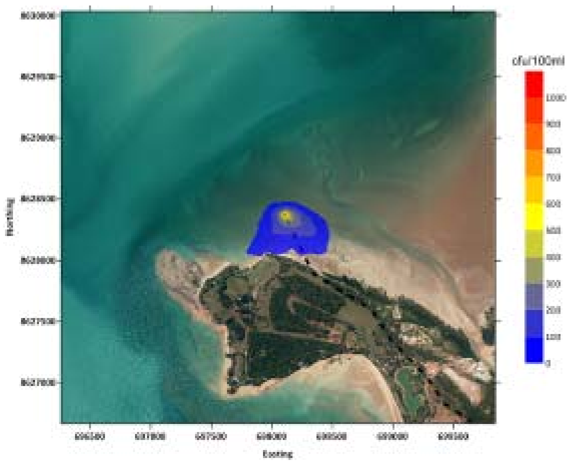
Typical (Median)

CURRENT EFFLUENT, LUDMILLA ONLY

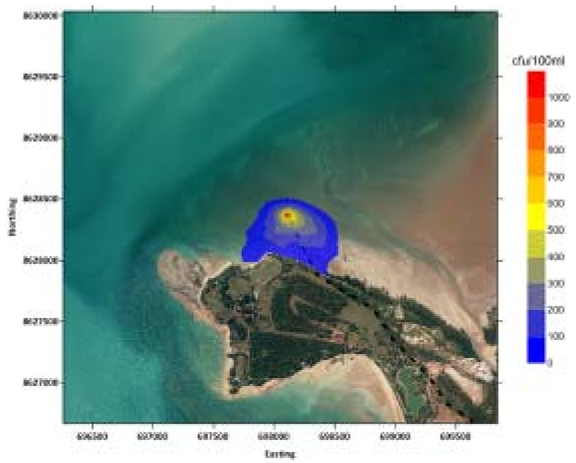
COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

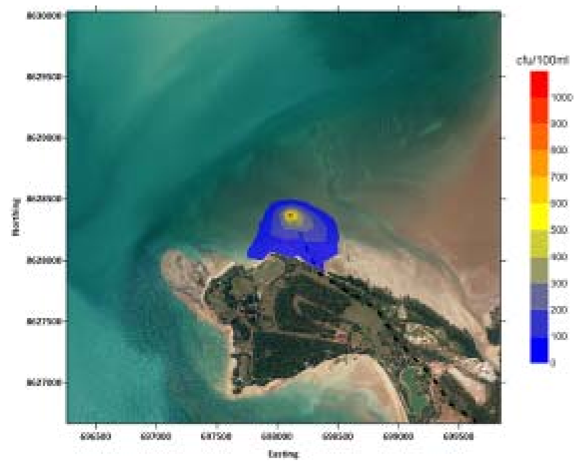
Atypical (90th percentile)



CURRENT EFFLUENT, LUDMILLA ONLY



COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

E. Coli. Primary Recreation Red

Typical (Median)

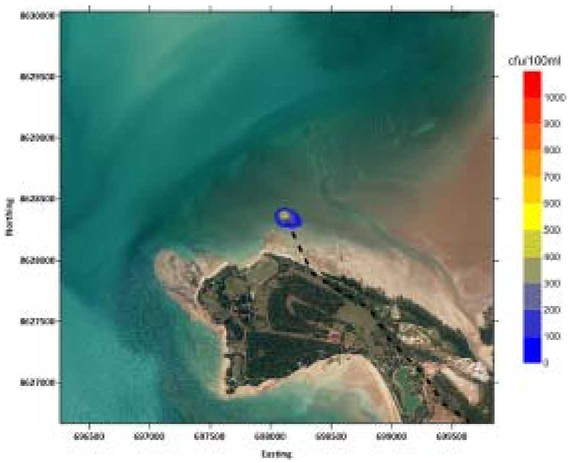
CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

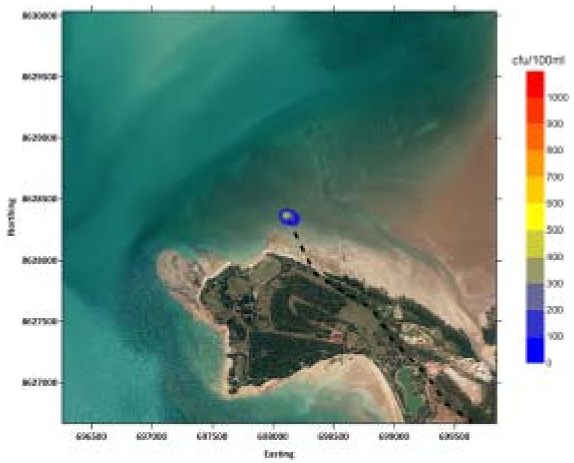
COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)

CURRENT EFFLUENT, LUDMILLA ONLY



COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

Enterococci Primary Recreation Amber

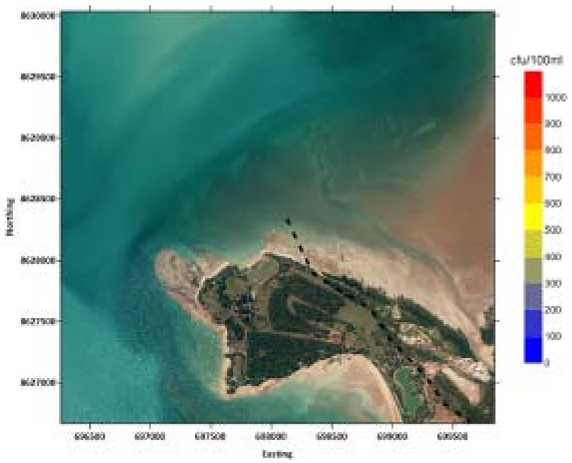
Typical (Median)

CURRENT EFFLUENT, LUDMILLA ONLY

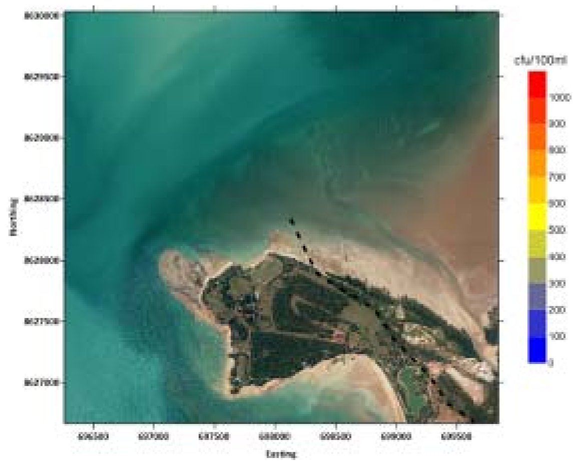
COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

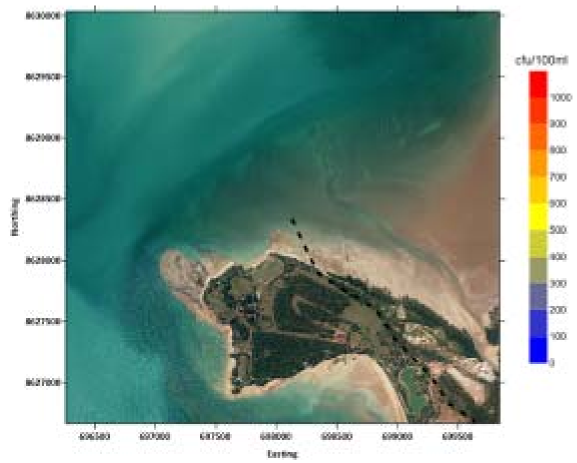
Atypical (90th percentile)



CURRENT EFFLUENT, LUDMILLA ONLY



COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

Enterococci Primary Recreation Red

Typical (Median)

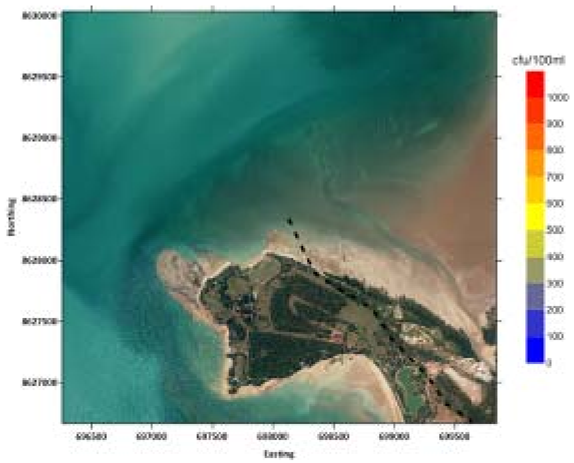
CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

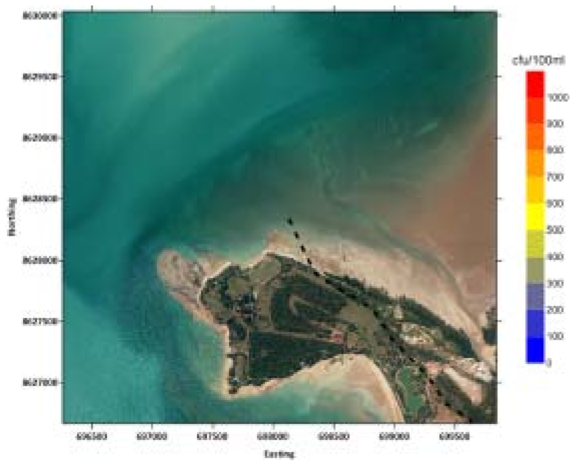
COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)

CURRENT EFFLUENT, LUDMILLA ONLY



COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

E. Coli. Secondary Recreation

Typical (Median)

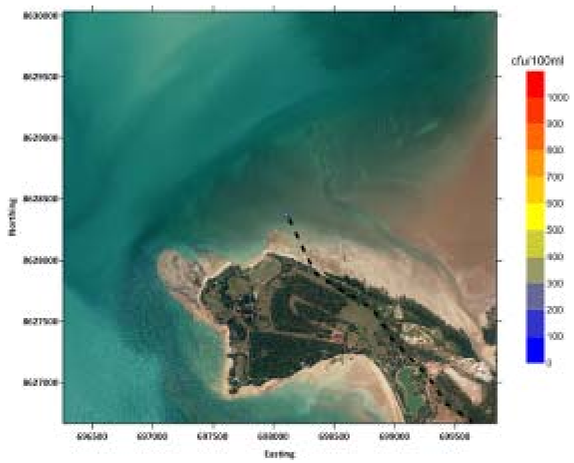
CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE

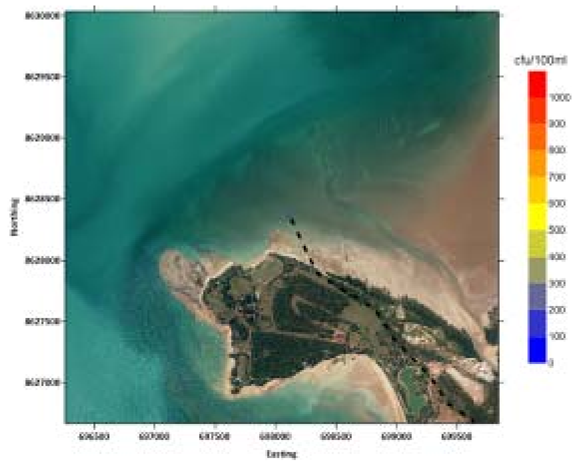
COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)

CURRENT EFFLUENT, LUDMILLA ONLY



COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

E. Coli. Aquatic Foods – Condition 1

Typical (Median)

CURRENT EFFLUENT, LUDMILLA ONLY

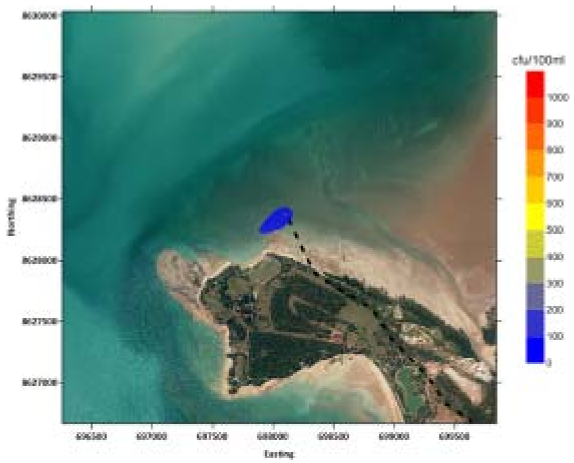
COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

Atypical (90th percentile)

CURRENT EFFLUENT, LUDMILLA ONLY

COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

E. Coli. Aquatic Foods – Condition 2

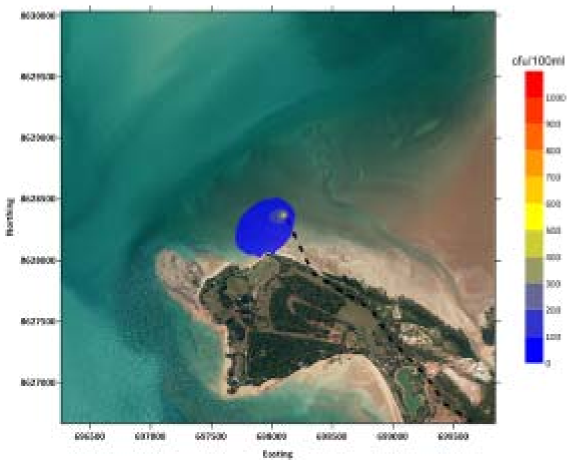
Typical (Median)

CURRENT EFFLUENT, LUDMILLA ONLY

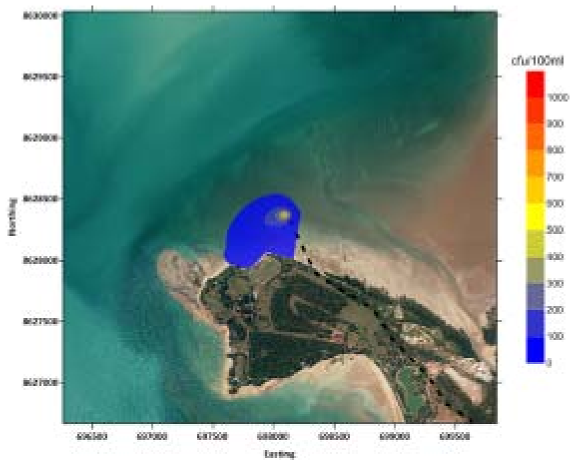
COMBINED EFFLUENT, PRE UPGRADE

COMBINED EFFLUENT, POST UPGRADE

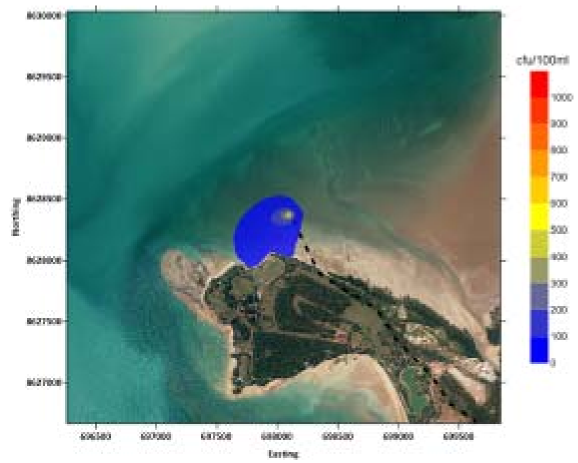
Atypical (90th percentile)



CURRENT EFFLUENT, LUDMILLA ONLY



COMBINED EFFLUENT, PRE UPGRADE



COMBINED EFFLUENT, POST UPGRADE

5. Discussion

Mixing zones have been developed for a number of contaminants for pre- and post-diversion of Larrakeyah outfall and treatment upgrades at Ludmilla WWTP.

Aquatic Ecosystem Protection

Nutrients - The combined effluent discharge results in a slightly increased mixing zone for Total Nitrogen, and a moderately reduced mixing zone for Total Phosphorous for both typical and atypical operating conditions. The mixing zone does generally not reach the coastline and intertidal rock-shelf, with the exception of atypical operations for a combined discharge prior to completion of treatment plant upgrades.

Toxicants – There is no mixing zone identified for Lead or Zinc for all scenarios. Trigger levels are not reached within the initial mesh element. The mixing zone for Copper increases moderately for post-diversion scenarios. The mixing zone does reach the coastline however it does not reach the intertidal rock-shelf for typical operations. The mixing zone reaches the rock-shelf for atypical operations to a limited degree.

Recently surveyed sea-grass beds (NRETAS 2011) have been assessed in relation to proximity to the existing outfall location and modelled interim mixing zones. One map has been presented (Appendix B) which shows that the largest potential mixing zone (Copper, combined effluent, atypical operating conditions) is not expected to reach those seagrass beds.

Cultural Use – Recreation

Primary contact – There is no mixing zone expected for typical operations for all scenarios. There is a mixing zone for E.Coli for atypical operations which increases slightly for combined discharge scenarios. The zone is small for Red Mode conditions (closed for swimming) and does not encroach on the coastline. For Amber Mode (swimming still permissible with increased monitoring) there is a larger mixing zone for E.Coli which does reach the coastline however it is confined to the northern side of East Point where there is limited opportunity for primary contact. Levels of Enterococci are below trigger levels for all scenarios.

Secondary contact – There is no mixing zone for typical operations for all scenarios. There is an extremely small mixing zone for E.Coli for atypical operations which is restricted to the direct vicinity of the outfall.

Cultural Use – Aquatic Foods

There is no mixing zone or impact shown for typical operations. For atypical operations, a mixing zone exists which comes into contact with the coastline. The mixing zone increases slightly for the combined discharge, however the area is restricted to the north side of East Point and does not extend to the rock-shelf area.

6. References

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King, I. P. (1993). A Finite Element Model for Three-Dimensional Density Stratified Flow. Sydney, Resource Management Associates (R.M.A).

NRETAS (2010). Water Quality Objectives for the Darwin Harbour Region - A Background Document, Department of Natural Resources, Environment, the Arts and Sport. Darwin. NT.

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Appendix A – Summary of effluent water quality

		Temp. (oC)	pH	NOx (mg/L)	Ammonia (mg/L) (mg/L)	Total N (mg/L)	Total P (mg/L)	FR P (mg/L)	TSS (mg/L) (mg/L)	Ecoli (cfu/100mL)	Enterococci (cfu/100mL)
All samples	Median	30.3	7.6	0.1	29	34.2	4.9	3.4	84	41	10
	90%ile	31.7	8.3	0.2	36	46.37	7	5.09	153.8	16000	432
	Count	135	135	96	112	123	122	122	147	237	161
WET season (Nov-Apr)	Median	30.9	7.4	0.1	26.2	21	3.1	1.9	62.5	20	10
	90%ile	32.0	8.1	0.2	29.9	35.7	5.49	4.5	118	6488	126.5
	Count	55	54	43	52	57	62	62	76	141	76
DRY season (May-Oct)	Median	30.1	7.7	0.1	33	41.1	5.9	4.1	105	91.5	10
	90%ile	31.3	8.3	0.19	37	47.6	7.9	5.11	157	24196	765
	Count	80	81	53	60	66	60	60	71	96	85

Summary of Effluent water quality – Ludmilla / East Point Outfall – 2004-2011 – Phys / Chem and bacteriological Showing seasonal variation in water quality

		Temp.	pH	NOx	Ammonia	Total N	Total P	FR P	TSS (mg/L)	Ecoli	Enterococci
		(oC)		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(cfu/100mL)	(cfu/100mL)
Jan	Median	30.82	7.38	0.10	10.4	12.3	2.0	1.4	44.5	10	10
	90%ile	31.81	7.87	0.16	19.9	24.8	4.9	3.3	78.6	130	242
Feb	Median	30.13	6.99	0.10	6.5	11.5	1.8	1.2	48.5	20	60
	90%ile	31.22	7.20	0.42	11.5	17.3	2.9	1.8	176.6	595	114
Mar	Median	30.19	7.22	0.10	12.0	14.6	2.8	1.6	86.0	20	10
	90%ile	30.67	7.63	0.15	16.2	23.6	3.6	2.9	250.2	1626	149
Apr	Median	29.99	7.96	0.10	15.5	19.1	2.9	1.8	69.0	135	10
	90%ile	30.79	8.04	0.10	19.8	25.1	3.3	2.6	92.2	44800	28
May	Median	30.27	7.94	0.10	31.0	37.0	5.5	3.7	100.0	64	10
	90%ile	30.65	8.26	0.11	35.0	43.9	6.2	4.0	137.4	1241	14
Jun	Median	28.41	8.18	0.13	30.0	36.0	5.1	4.1	93.0	20	10
	90%ile	29.25	8.46	0.44	35.4	42.9	6.5	5.1	146.8	2490	105
Jul	Median	29.40	7.77	0.10	33.0	41.2	6.7	4.1	120.0	69	10
	90%ile	30.22	8.27	0.34	37.2	47.3	8.9	5.1	168.0	14322	2411
Aug	Median	29.50	7.41	0.10	33.5	43.6	6.0	4.5	90.0	209	36
	90%ile	30.08	8.24	0.11	38.2	48.6	8.4	6.3	151.4	45776	4428
Sep	Median	30.34	7.33	0.10	35.0	43.5	6.4	4.6	104.0	20	10
	90%ile	31.28	7.80	0.18	38.2	49.2	7.3	4.9	204.5	112392	1227
Oct	Median	31.26	7.71	0.12	33.5	42.4	5.7	3.7	105.4	88915	259
	90%ile	31.78	8.13	0.15	37.0	47.8	7.6	5.1	136.8	41000	862
Nov	Median	31.32	7.58	0.11	26.9	33.8	5.1	3.8	72.6	24049	1372
	90%ile	31.80	8.04	0.14	30.0	38.8	7.4	5.5	91.2	26387	120
Dec	Median	32.12	7.73	0.11	25.4	30.9	3.9	2.6	72.0	10343	156
	90%ile	32.26	8.24	0.10	31.0	36.0	5.0	4.2	110.4	20076	189

Summary of Effluent water quality – Ludmilla/East Point Outfall – 2004-2011 – Phys/Chem and bacteriological Monthly summaries

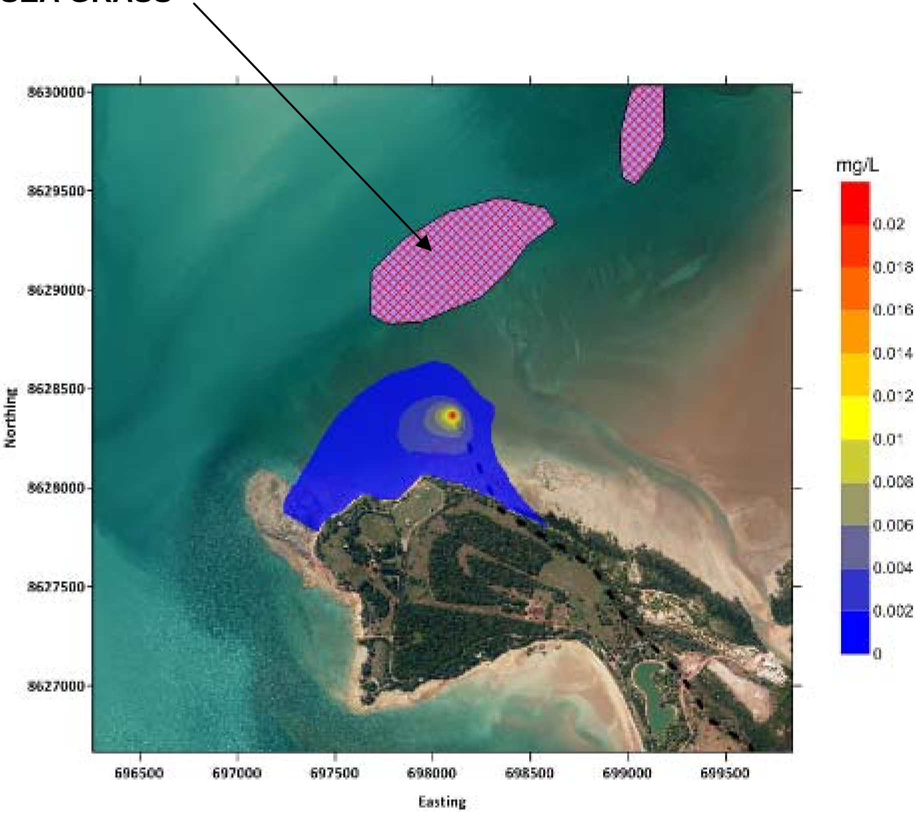
	Ag_T	Al_T	As_T	B_T	Ba_T	Be_T	Br_T	Cd_T	Cr_T	Cu_T	Fe_T	Hg_T	I_T	Mn_T	Mo_T	Ni_T	Pb_T	Sb_T	Se_T	Sn_T	U_T	Zn_T
	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
22/06/2005	<10	400	1.5	120	<50	<1	334	<0.2	<5	150	650	<0.1	20	70	<5	4	9	0.4	2	<10	0.09	80
22/06/2005	<10	420	1.5	120	<50	<1	344	0.2	<5	150	660	<0.1	20	70	<5	6	9	0.4	2	<10	0.1	80
22/06/2005	<10	420	1.5	120	<50	<1	336	0.2	<5	150	670	<0.1	20	70	<5	4	9	0.4	2	<10	0.09	80
04/06/2007	<10	740	2	160	<50	<1	384	0.2	<5	250	1200	<0.1	20	130	<5	6	3	0.6	<1	<10	0.15	100
04/06/2007	<10	520	2	120	<50	<1	272	<0.2	<5	230	880	<0.1	30	115	<5	6	3	0.6	2	<10	0.13	90
05/06/2007	<10	480	1.5	120	<50	<1	262	<0.2	<5	220	840	<0.1	30	125	<5	4	3	0.6	<1	<10	0.12	80
05/06/2007	<10	720	2	140	<50	<1	320	0.2	<5	250	1180	<0.1	30	160	<5	6	4	0.6	<1	<10	0.13	100
29/10/2009	0.9	1520	1.25	103	49.2	<0.5	512	0.56	4.4	246	1340	<0.2	20	112	1	4.44	4.51	<0.5	<2	2.4	0.153	158
19/10/2010	0.6	467	1.3	44.5	38	<0.5	409	<0.2	2.2	139	740	<0.2	15	77.2	0.55	2.24	1.94	<0.5	<2	1.3	0.092	90.2

Summary of Effluent water quality – Ludmilla / East Point Outfall – Metals

Appendix B – Sea-grass beds in relation to current outfall and mixing zones

Copper 95th Percentile Atypical (90th percentile)

SEA GRASS



COMBINED EFFLUENT, PRE UPGRADE