GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELLING OF THE UNCONFINED BROOME AQUIFER: BROOME PENINSULA, WESTERN AUSTRALIA

By

Deirdre Kelly

10013433

This thesis is written in partial fulfilment of the requirements for a Master of Science (MSc) Bachelor of Science (Honours) Thesis and Coursework SCIE5721-5722

FNAS Research Project Thesis
Faculty of Science
The University of Western Australia
(4th December, 2015)

Supervisor: Associate Professor Ryan Vogwill

This thesis is formatted in the style of the Journal of Hydrology

Word Count: 14,774
Declaration

This project contains no material that has been accepted for the award of any other degree or diploma in any University to the best of the author’s knowledge and belief contains no material previously published or written by another person, except where due references is made in the text.

Deirdre Kelly

4th December, 2015
Looking south–east across Roebuck Bay, Broome, Western Australia (photo taken by Nigel Gaunt of Red Dirt Photography)

"We can't solve problems by using the same kind of thinking we used when we created them." – Albert Einstein
Abstract
This study focused on how the Broome aquifer operates hydrogeologically, as a basis for developing best management practices in the surrounding catchment to minimise impacts associated with nutrient pollution from waste water disposal. The importance of these works resides in the need to better understand the environmental triggers for growth of the Cyanobacteria, *Lyngbya Majuscula* (Oscillatoriaceae) on the north shore of Roebuck Bay.

In general the key determinants of the flux of nitrogen through aquifers to coastal waters are: the supply rate of the contaminant from the soil surface medium via deep drainage; redox conditions in subsurface environment; the residence time of groundwater within aquifers, the extent of contact with rich clay sediments; and the availability of dissolved organic carbon (DOC). All of which have either been discussed or evaluated (where possible) during this study. Using finite element modelling in FEFLOW it has been possible to evaluate rudimentary groundwater flow and solute transport processes governing Broome’s unconfined aquifer. The model can successfully simulate observed (regional) flow dynamics, map primary extents of nitrate transport through the aquifer and uncover vital knowledge gaps.

Current information combined and with transient transport modelling suggests that the nutrient migration from the wastewater irrigated sites and the Broome South Wastewater Treatment Plant (BSWWTP) do impact the groundwater beneath these sites. Under varying recharge and nutrient concentration scenarios modelling results show, under best and worst case scenarios, the observed *Lyngbya* blooms in the intertidal zones of Roebuck Bay, can likely be attributed to the migration of nitrogen from the Golf Course and BSWWTP. At this stage initial best estimates extracted from FEFLOW suggest nutrient loads from the BSWWTP and Golf Course into Roebuck Bay are likely to range between 500 kg/year – 1000 kg/year, assuming denitrification is taking place at the source. At the inland irrigated sites (BRAC, St Mary’s and Peter Haynes Oval) nitrogen migration is localised and does not discharge into Roebuck Bay, however infiltration into the Broome aquifer is taking place and will remain for extended periods if wastewater disposal activities are continued unchanged.

Ultimately this study showed the fate of these contaminants is site specific and difficult to measure or predict due to the heterogeneous nature of aquifer sediments (namely the Broome Sandstone), the complex contaminant dynamics within Roebuck Bay’s subterranean estuary and the many factors relating to density-coupled groundwater flow. Nevertheless, the
available evidence does suggest that under a range of point source loads and climatic conditions that significant groundwater fluxes of these contaminants are taking place. The works here also highlight the need for improved waste water holding and disposal practices and monitoring at all wastewater sites across the peninsula.

**Keywords**

Roebuck Bay, marine environment, nitrogen, attenuate, flux, submarine groundwater discharge, flow dynamics, *Lyngbya*
# Contents

Declaration............................................................................................................................................. ii

Abstract................................................................................................................................................. iv

1.0 Introduction.................................................................................................................................... 5

1.2 Study Area ................................................................................................................................... 7

1.3 Research Aims and Objectives....................................................................................................... 9

2.0 Site Information.............................................................................................................................. 9

2.1 Topography and Vegetation.......................................................................................................... 9

2.2 Climate ........................................................................................................................................ 10

2.2.1 Tropical Cyclones.................................................................................................................. 11

2.3 Geology ........................................................................................................................................ 12

2.3.1 Regional Geology................................................................................................................ 12

2.3.2 Project Geology................................................................................................................... 13

*Pindan Sand* ....................................................................................................................................... 14

*Broome Sandstone (BS)* .................................................................................................................... 14

2.4 Hydrogeology............................................................................................................................. 17

2.4.1 Regional .................................................................................................................................. 17

2.4.2 Local ......................................................................................................................................... 17

2.4.3 Hydrochemistry...................................................................................................................... 23

2.4.4 Effect of Tidal Wave Fluctuations on Groundwater.................................................................. 25

2.4.5 Saltwater Intrusion .................................................................................................................. 26

3.0 Materials and Methods................................................................................................................. 27

3.1 Conceptual Hydrogeology ........................................................................................................... 27

3.2 Numerical Modelling.................................................................................................................... 29

3.2.1 Model Development.............................................................................................................. 29

3.2.2 Model Extent and Mesh Generation....................................................................................... 30

3.2.3 Model Geometry.................................................................................................................... 32

3.2.4 Boundary Conditions............................................................................................................... 32

3.2.5 Monitoring Wells.................................................................................................................... 32

3.2.6 Climate Data.......................................................................................................................... 33

3.2.7 Calibration and Sensitivity Analysis ...................................................................................... 34

Steady State Modelling ......................................................................................................................... 35

Transient Nutrient Transport Modelling ............................................................................................... 38

4.0 Results ......................................................................................................................................... 39

4.1 Steady State Model Calibration................................................................................................... 39

4.1.1 Base Case Models.................................................................................................................. 39

4.1.2 Anisotropy............................................................................................................................... 43
4.1.3 Groundwater Residence Time .......................................................................................... 46
4.2 Irrigated Case Modelling Results ...................................................................................... 48
4.3 Transient State Calibration Results .................................................................................. 52

5.0 Discussion .......................................................................................................................... 58
  Numerical Modelling .............................................................................................................. 58
  Steady State Groundwater Flow ............................................................................................. 58
  Solute Transport ....................................................................................................................... 59
  Model Limitations .................................................................................................................... 60

6.0 Conclusions and Future Work Recommendations .............................................................. 61

7.0 References .......................................................................................................................... 64

Appendix 1 .................................................................................................................................. 78
  Transient Transport Modelling Result Figures ......................................................................... 78
    Rainfall Series from 2004 – 2009 – with decay constant/denitrification .................................... 78
    Rainfall Series from 2004 – 2009 – without decay constant/denitrification ................................. 81
    Rainfall Series from 2004 – 2009 (incl. Cyclone Rosita) – without decay constant ..................... 84

Appendix 2 .................................................................................................................................. 85
  Data Reference Tables .............................................................................................................. 85

List of Figures
  Figure 1: Location map .............................................................................................................. 8
  Figure 2: Average monthly rainfall and evaporation from Broome Airport (BOM: 003003) - 1939 - 2014 ................................................................. 11
  Figure 3: Structural Geology of the BROOME sheet (taken from Laws, 1991) ................................. 13
  Figure 4: Plan view of surficial geology for relevant study area (modified from Geological Survey WA, 2015) .............................................................................................................. 16
  Figure 5: Wrights (2013) interpretation of the hydrostratigraphy within the Broome peninsula .... 18
  Figure 6: East-west interpretive cross-section of predicted saltwater wedge position at the Broome peninsula saltwater wedge position at the Broome peninsula ........................................................................ 28
  Figure 7: Conceptual schematic of the Broome Peninsula hydrogeology ........................................ 29
  Figure 8: Model domain, contamination sources, boundary conditions, regional elevation profile and mesh arrangement ................................................................................................................................. 31
  Figure 9: Hydraulic properties and geological layer arrangement ............................................ 31
  Figure 10: Monitoring well distribution across model domain ..................................................... 33
  Figure 11: Various climatic scenarios applied to all steady state and transient models ................. 34
  Figure 12: Dry base case; steady state heads and calibration scatterplot including RMS value (red observation points represent calculated heads outside of confidence interval) .................................................... 41
  Figure 13: Wet base case; steady state heads and calibration scatterplot including RMS value (red observation points represent calculated heads outside of confidence interval) ................................................... 42
  Figure 14 – Scatter plots 1- 5 highlighting groundwater head movement following adjusted anisotropy from 1 – 100 (red observation points represent calculated heads outside of confidence interval) ................................................................. 45
  Figure 15: Mean lifetime expectancy plots based on varying rainfall scenarios (A) average rainfall year (710mm/a) (B) dry year (480 mm/a) (C) cyclonic event (150mm/24hrs) (D) wet year (940mm/yr) ................................................................................................................................. 48
Figure 16: (a) localised plan view of dry irrigated groundwater heads (b) regional view of groundwater heads (dry case) highlighting groundwater mounding at the WWTP; and (c) calibration scatterplot including RMS value.................................................................50
Figure 17: (a) localised plan view of wet irrigated groundwater heads (b) regional view of groundwater heads (wet case) highlighting groundwater mounding at the WWTP; and (c) calibration scatterplot including RMS value.................................................................51
Figure 18: Simulated TN (mg/L) concentrations from centre of plume to Roebuck Bay discharge point– with and without decay applied (measurements extracted from centre of saturated zone within layer 9) ...........................................................(53
Figure 19: Transient scenario 1 scatterplots including RMS values (red observation points represent calculated heads outside of confidence interval) ........................................................................56
Figure 20: Transient scenario 2 scatterplots including RMS values (red observation points represent calculated heads outside of confidence interval) ........................................................................57

List of Tables
Table 1: Broome stratigraphy for study area based on Laws (1991) and Vogwill (2003) ...............15
Table 2: Historical Kh values used in calibration of steady state models .........................................20
Table 3: Summary of layer and aquifer configuration included in all models .................................32
Table 4: Parameters applied to calibration and sensitivity analysis ...............................................35
Table 5: Estimated transport parameters used in the simulation ......................................................37
Table 6: Transient Modelling Scenarios .......................................................................................38
Table 7: Irrigation and Total Nitrogen values applied to contaminated sites .................................39
Table 8: Calibrated parameters ....................................................................................................46
Table 9: TN (mg/L) and SGD results from transient transport modelling at the WWTP and Golf Course with and without Henry’s decay constant ........................................................................53
Table 10: Nitrogen plume details at all irrigated sites following transient modelling with and without the addition of Henry’s decay constant ........................................................................54
Acknowledgements

First I would like to thank Dr Ryan Vogwill; an extremely knowledgeable and interesting person who constantly supported me along the way, thankyou Ryan, I truly hope our paths continue to cross.

To those who provided instrumental technical support and knowledge along the way; these people (in no particular order) are: Alex ‘FEFLOW’ Renz, Keely Mundle, John Mosquira and Ed deSouza. I am extremely grateful for the time you took to help me. I hope I can return the favour one day.

A special mention must go to my dear friend Allan Lundorf (the guru). The funniest Danish water engineer on the planet who also happens to know a lot about hydrogeology. I hope next time the shoe is on the other foot.

Without doubt this testing year would have been a lot less bearable and memorable without these beautiful humans/fur humans by my side: Dr Lana Loxton, Jaffa, Harry, Pluto, Kooks and Baba, Andrea Xanthis, The Walrus, Daisy Pearse, Krista Sanderson, Nigel Andrews and Miecha Bradshaw. Thank you friends, I look forward to seeing you on the other side of this masters.

And lastly to mum and dad, you both, in your own way provided me with the love and support I needed to get through this challenging year. Your patience did not go un-noticed!

This year has been a challenging and truly defining moment in my life and I am so glad I followed it through and emerged a stronger and more insightful person.
1.0 Introduction

With continued residential and agricultural development of coastal areas worldwide groundwater resources in these areas have become increasingly susceptible to the threat of anthropogenic induced contamination. Since the industrial revolution the leaching of reactive nitrogen in terrestrial and aquatic ecosystems from a variety of sources such as landfills, refineries, agricultural practices, petrol stations and wastewater storage sites has increased by an order of a magnitude (Galloway et al., 2008). In coastal environments once contaminants reach the groundwater system, if a positive hydraulic gradient is present, will inevitably discharge into the marine ecosystem as submarine groundwater discharge (SGD). Accurate insight into the magnitude and controls of Nitrogen (N) fluxes associated with SGD is needed if we want to understand how the coastal ocean functions and how it responds to anthropogenic derived nutrient fluxes (Slomp and Van Cappellen, 2004). Therefore hydrogeological investigations are a necessity to enable us to sustain and protect groundwater resources, the ecosystems that they support and to overcome water quality issues such as salinization and pollution. This is often complicated by the fact that coastal aquifers are complex zones influenced by oceanic oscillations and inland groundwater forces (Mao et al., 2006). If, however, the complexities of the groundwater system are intrinsically understood the downstream affects linked to groundwater adjustments (be it contamination or abstraction) can then be properly managed.

This elevated increase of SGD derived nutrients into the marine system can potentially impact the ecosystem in the following ways (MacQuarrie et al., 2000):
1) Increase the frequency of anoxic events and algal blooms
2) Alter fauna composition
3) Reduce aesthetic value; and
4) Reduce reef cover (in some coastal systems)

Although natural systems seem able to withstand certain nutrient inputs there is a certain critical level of nutrient supply where the likelihood of uncontrolled algal blooms increases abruptly in a non-linear way (Ingrid et al., 1996). Hence why the major focus of current scientific coastal research is more often than not focussed on determining the groundwater contribution of wastewater-derived nitrogen to estuaries, bays, and harbours; this is achieved by understanding the underlying mechanisms driving this phenomenon (DeSimone and Howes, 1998).
In many circumstances, complex geochemical reactions, such as sorption, biodegradation, oxidation/reduction and precipitation/dissolution occur when contaminants enter the groundwater system and mix with ambient water (Barry, 1992).

More specifically (in the context of these works) is the practice of wastewater storage and irrigation. In the intertidal zones of Roebuck Bay, Western Australia the downstream affects associated with wastewater storage (containing nitrogen and phosphorus) are triggering eutrophic conditions with sporadic formations of harmful algal blooms of the toxic Cyanobacteria, *Lyngbya Majuscula* (Oscillatoriaceae). For extended periods (15-20 years) the Broome South Waste Water Treatment Plant (BSWWTP) has been leaking treated and un-treated wastewater from evaporation and treatment ponds; known to contain elevated levels of nitrogen (41 mg/L) and phosphorus (7-10 mg/L). Following concerns raised by researchers, community members and organisations on the poor ecological health of Roebuck Bay, a list of essential scientific studies were developed to investigate the issue. Four of these studies were utilised here by providing the rational framework to formulate and integrate knowledge and data inputs for the development of a 3D groundwater model. The relevant studies are:

- Estrella’s (2013) pivotal *Lyngbya* monitoring program which mapped the blooms to nearshore areas of Roebuck Bay.
- Wright’s (2013) investigation into the hydrogeological and hydrochemical parameters of the unconfined Broome aquifer to identify the likelihood of wastewater disposal contributing nutrients into Roebuck Bay; and
- Hearn’s (2014) quantification of groundwater contamination sources (nitrogen and phosphorous) as SGD, the aquifers natural attenuation capacity and the quantity of nutrients being discharged into Roebuck Bay seasonally.
- Gunaratne *et al.,* (2014) assessed the impacts of seasonal flushing of stormwater discharge and nutrient export from Broome Town into Roebuck Bay. This research identified significant nutrient loading into Roebuck Bay following the seasonal first flush event.

With the integration of this knowledge, numerical modelling was carried out to expand upon current understanding of the existing groundwater environment and flow processes occurring within to refine previous estimates of groundwater contributions of wastewater-derived nitrogen.
1.2 Study Area
The study area and closest town, Broome, are located approximately 1,800 km north-north east of Perth and 600 km north-east of Port Hedland, Western Australia in the south-west corner of the Dampier peninsula (see, Figure 1). In close proximity to the town of Broome (200 m south-east) is the ecologically significant Roebuck Bay (see, Figure 1), this is a high value biodiversity asset (Department of Environment and Conservation, 2009) and “the world’s most biodiverse intertidal tropical wetland” (Oldmeadow, 2007)

The study area relevant to this modelling exercise is 41 km$^2$ constrained to the north-east, south-east, south and west by Dampier Creek, Roebuck Bay and the Indian Ocean, respectively with the northern boundary running east-west approximately 3 km north of the Broome airport (see insert demarcated on Figure 1). Also of importance is the proximity of the BSWWTP as it is situated only 200 m directly west of Roebuck Bay.
Figure 1: Location map
1.3 Research Aims and Objectives
Despite Roebuck Bay’s ecological significance the role of hydrogeological mechanisms in the observed algal blooms in the intertidal zones of Roebuck Bay remains a work in progress. Current understanding of the study area is restricted to simplified ‘regional’ hydrogeological studies conducted by Laws, Leech and Vogwill between 1987 and 2003 and the aforementioned studies (Gunaratne et al., 2014; Estrella, 2013; Wright, 2013; Hearn, 2014). Although valuable, data sets from these studies are lacking the spatially and temporally dense information required to capture seasonality including tidal influence of the area. This paucity of information, however, provides an additional driving force for the current study which aims to best use the available information by modelling based on the data which does exist, incorporating uncertainty in unknown parameters where appropriate.

The aim of this study is to conceptualise, then model groundwater flow and solute transport processes in the Broome Peninsula (hereafter the peninsula) as a tool to advance current understanding of the flow of nutrient contaminated groundwater flow through the Broome aquifer and subsequent discharge to Roebuck Bay. With this in mind the specific study objectives were to:

1) Integrate all available historical geological, water quality and water level data to improve on the conceptual hydrogeological understanding of the peninsula and identify key knowledge gaps;
2) Based on the conceptual understanding and all available historical data, develop a 3D groundwater flow and solute transport model;
3) Refine previous estimates of groundwater discharge and total nitrogen loads discharging to the subterranean estuary of Roebuck Bay through model parameterisation incorporating uncertainty in aquifer properties; and
4) Assess the likely range in groundwater flow and nutrient transport processes, including a variety of recharge conditions, to make Roebuck Bay groundwater discharge nitrate load projections in the future.

2.0 Site Information
2.1 Topography and Vegetation
The majority of the peninsula is considered to be a relatively uniform environment of low relief (topography varies from 28 m AHD in the centre to 13 m AHD at the coastline) with undulating aeolian sand dunes, intertidal and supratidal mudflats, platforms of coastal sediments, and narrow sandy beaches (Laws, 1991). The topography slopes radially from the
centre of the peninsula at a maximum height of approximately 28.0 m AHD towards Roebuck Bay and the Indian Ocean. However, localised topographical highs and depressions do exist across the peninsula, the most noteworthy being two dune ridge systems running parallel with the east and west coastlines. These ridges are widely distributed along the regions coastline. Vegetation is predominately Pindan grassland (from which the Pindan Sand takes its name) and scattered trees, particularly Eucalypts with a middle layer of Acacias (Kenneally et al., 1996).

Roebuck Bay is a large, curved, low energy-tide dominated embayment. It presents a macrotidal regime, with spring tides ranging > 10 m, which exposes more than 45% of the tidal flats of the Bay area and approximately 10% of the Bay at neap tide (Pepping et al., 1999). The northern portion of the bay supports two major creeks – Dampier Creek (Jugajun) and Crab Creek (Magalagun). Although hydrologically connected to the bay neither creek are believed to influence the hydrogeological system relevant to this study so were not considered in modelling efforts.

2.2 Climate
The climatic regime of the study area is unique as it resides within three climatic regions: Northern, Dry Interior, and North-western (Laws, 1991); however for the purposes of this study the two key seasons are considered: the wet (November - April) and the dry (May - October). For definition purposes the Broome region resides in the semi-arid monsoonal climatic region. Which means rainfall in the region generally only occurs during the wet season, typically associated with cyclonic activity or tropical lows. Rainfall is highly variable due to the episodic and spatially variable nature of these events. The frequency and volume of these events are an important control on the recharge of the unconfined aquifer (Broome Sandstone). Occasionally the wet season does not deliver significant rain which results in lower than average aquifer recharge (Department of Water (DOW), 2012). Rainfall event frequency, intensity and magnitude are important controls on recharge to the unconfined aquifer. The amount of recharge is an important control over groundwater volumes available for abstraction which, important given that Broome’s entire potable water supply is sourced from the Broome Sandstone (BS). The average annual rainfall for the study area (see Figure 2) acquired from Broome Airport weather station (Bureau of Meteorology Station (BOM): 003003) is 609.5 mm (1939-2014) and 703 mm for the last ten year period (2004-2014); with 90% of rainfall falling between December and April (the wet season) in both instances. However the mean annual rainfall is this region provides little indication of reliability due to
the seasonal and sporadic nature of rainfall events. The annual pan evaporation according to BOM (2014) is 2,700 mm, which exceeds average annual rainfall by a factor of four, suggesting evaporation would have a significant effect on the recharge to the groundwater system.

2.2.1 Tropical Cyclones

As discussed above this region is characterised by extreme short duration rainfall events (often cyclonic in origin) which produce strong winds and heavy rainfall between November and April (Cotching, 2005). An example of such an event is ‘Cyclone Rosita’ which crossed the coast 40 km south of Broome on the 20th April 2000 and resulted in approximately 176 mm rainfall hitting Broome over a 24 hour period. Statistically this was the biggest cyclone to hit the region in the last century. More commonly cyclones tend to occur every four years depositing, on average, in excess of 100 mm of rainfall over a 24 hour period (BOM, 2014). The scale and intensity of both events (average and Cyclone Rosita) produce large volumes of water in a short period resulting in an instantaneous flux of sediment laden water, potentially containing higher levels of nutrients (depending on timing of the event) being discharged into downstream receptors.

Figure 2: Average monthly rainfall and evaporation from Broome Airport (BOM: 003003) - 1939 - 2014

2.2.1 Tropical Cyclones

As discussed above this region is characterised by extreme short duration rainfall events (often cyclonic in origin) which produce strong winds and heavy rainfall between November and April (Cotching, 2005). An example of such an event is ‘Cyclone Rosita’ which crossed the coast 40 km south of Broome on the 20th April 2000 and resulted in approximately 176 mm rainfall hitting Broome over a 24 hour period. Statistically this was the biggest cyclone to hit the region in the last century. More commonly cyclones tend to occur every four years depositing, on average, in excess of 100 mm of rainfall over a 24 hour period (BOM, 2014). The scale and intensity of both events (average and Cyclone Rosita) produce large volumes of water in a short period resulting in an instantaneous flux of sediment laden water, potentially containing higher levels of nutrients (depending on timing of the event) being discharged into downstream receptors.
2.3 Geology

2.3.1 Regional Geology

Regionally all information pertaining to the geological evolution of the Canning Basin has been well summarised by Forman and Wales (1981), Towner and Gibson (1983), and Yeates et al., (1984) and more locally in the vicinity of the study area, the geology has been described by Laws (1991) and later by Vogwill (2003) and Wright (2013).

The peninsula lies resides within the northern edge of an area of sedimentary deposition known as the Canning Basin, the largest sedimentary basin in Western Australia (Laws, 1990) and Australia’s second largest groundwater province after the Great Artesian Basin (DOW, 2008). The geological history of the basin has been dominated by periods of regression and transgression of the sea. In Precambrian times, sediments were laid down, igneous rocks intruded them, and metamorphism took place, these rocks form the basement of the Canning Basin (Cotching, 2005).

This large intracratonic sag basin contains a faulted and folded sequence of Ordovician to Cainozoic sedimentary rocks up to 18 km thick (Yeates et al., 1984). The basin extends over 530,000 km² (DMP, 2011) of which approximately two thirds is onshore. The onshore portion can generally be divided into a northern and southern portion with the study area located in the northern Canning Basin. Structurally this area is located within the Fitzroy Trough, a north trending graben which bound to the south by the Fenton Fault and two major east trending anticlines; the Barlee and Baskerville Anticlines occur within the trough. Depth to basement is some 8km (see Figure 3).

It should be noted that on a local scale the regional structure is expected to have no impact on the hydrogeology of the peninsula.
2.3.2 Project Geology

The geology of the study area is sedimentary and contains a mixture of sediments deposited from aeolian and alluvial processes (Vogwill, 2003; Wright, 2013). This fluvial sedimentary system was deposited between the Quaternary and Early Cretaceous geological periods.

The entire study area is overlain by aeolian and flood derived Quaternary sediments named as the Pindan Sand (Wright, 2013) which overlies Cretaceous Broome Sandstone (BS). This sandstone unit forms the bedrock below the peninsula and only outcrops around the margins of the study area at coastal cliffs. These sediments generally thicken and deepen to the west. Un-conformably underlying the more recent Broome Sandstone is the Jarlemai Siltstone; formed during the Late Jurassic to Cretaceous throughout a period of marine transgression (Holder and Rozlapa, 2009). The Jarlemai is dominated by siltstone and mudstone with minor sandstone inclusions in the lower strata (Laws, 1990). As this highly impermeable unit, located at great depths (~300 m AHD), has no impact on the hydrostratigraphy of the study area it will not be discussed any further within the context of these works. The stratigraphic units most relevant to this study are the Pindan Sand and Broome Sandstone, as such both are...
described in greater detail below. Table 1 lists the stratigraphical succession for the region and Figure 4 shows the Quaternary and Cretaceous sedimentary deposits in the study area.

**Pindan Sand**
Pindan Sand forms the surficial sediment cover for much of the Kimberley region and entire Broome Peninsula (Laws, 1991). Pindan is a Quaternary deposit of largely wind-blown red-brown fine grained sands and silts, with the red coloration attributed to haematite ($\text{Fe}_2\text{O}_3$) staining and clay content (Vogwill, 2003). Within the study area the Pindan ranges in thickness from 8-12m (Wright, 2013) and un-conformably overlies the Cretaceous sedimentary rock unit (Broome Sandstone). Works by Wright (2013) and Vogwill (2003) confirmed the unit to have been formed by fluvial (sheetwash during flooding) and aeolian depositional processes. Careful analysis of Pindan sediments by Vogwill (2003) found these sands to be moderately sorted, non-lithified, quartz-rich, clay-bearing and lacking any lamination or structure. In localised areas the Pindan is known to host shell deposits, associated with anthropogenic and storm surge activity.

**Broome Sandstone (BS)**
The Cretaceous fine to coarse grained quartzose sandstone is partially cemented in its upper surface with glauconitic mudstone and rare conglomerates (Middleton, 1990) and Laws, 1991). It is laterally extensive with a maximum known thickness of 290 m thickening offshore (Vogwill, 2003).

Upon inspection of geological logs Vogwill (2003) found this unit can be broken down into two major facies; the lower fluvial facies and the upper deltaic facies. The lower fluvial facies being a coarse sand grained layer interbedded with minor amounts of silt/claystone whilst the upper deltaic facies is much finer grained containing an abundance of silts often interbedded in complex scour and fill pattern. This was further clarified by DOW (2012) who identified a consolidated and clay rich upper zone highlighted by low resistivity and high gamma counts whilst deeper in the unit were unconsolidated gravels with characteristically lower gamma counts and higher resistivity.
### Table 1: Broome stratigraphy for study area based on Laws (1991) and Vogwill (2003)

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
<th>Maximum Thickness (m)</th>
<th>Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quaternary</strong></td>
<td>Pindan Sand (Qs)</td>
<td>Sand, silt, clay, minor gravel</td>
<td>15</td>
<td>Superficial; fresh</td>
</tr>
<tr>
<td><strong>Early-Cretaceous</strong></td>
<td>Broome Sandstone (Kb)</td>
<td>Fine to coarse grained sandstone, some mudstone and conglomerate</td>
<td>290</td>
<td>Superficial; fresh - brackish</td>
</tr>
<tr>
<td><strong>Late-Jurassic</strong></td>
<td>Jarlemai Siltstone (Jr)</td>
<td>Siltstone and claystone containing thin bands of silt and medium-grained to coarse-grained sand.</td>
<td>259</td>
<td>Aquiclude</td>
</tr>
</tbody>
</table>
Figure 4: Plan view of surficial geology for relevant study area (modified from Geological Survey WA, 2015).
2.4 Hydrogeology

2.4.1 Regional
The hydrogeology of the south-western portion of the Canning Basin has been mapped by The Department of Mines Western Australia at a scale of 1:250,000 (Laws, 1991). The two main aquifers used in the western half of the Dampier Peninsula are the generally confined Wallal Sandstone Aquifer, which principally recharged from inland sources and the generally unconfined Broome Sandstone Aquifer. Regionally groundwater flow is predominantly south and west, south of the Baskerville Anticline (see Figure 3), which is located north-north west of Broome, discharging into the coastal waters of the Indian Ocean. North of the Baskerville Anticline groundwater flow is generally north and west (Vogwill, 2003). The Broome Sandstone Aquifer and has been widely used around Broome for water supply since the 1980's (Laws, 1991). This has resulted in saltwater intrusion beneath the Broome Town Water Supply Wellfield; located 12 km north-east of Broome town and in the Coconut Wells area 10 km north of Broome.

Drainage
The peninsula has no significant permanent watercourses as the majority of rainfall is infiltrated due to the areas low topography and permeable nature of the sand. Surface flows generally only occur as sheet wash after periods of heavy rainfall when the sand becomes saturated. The Pindan Soil form extensive undulating plains with little or no organised surface drainage with seasonal runoff forming sheets of water behind the coastal dune systems (Kenneally et al., 1996). At present the closest surface water features that exist (other than Roebuck Bay) are Lake Eda and the Ungami Lakes, as they are both up-gradient or cross gradient of the site they are not likely to affect the Waste Water Treatment Plant (WWTP) and irrigation areas from a hydrogeological context. The two creeks in the vicinity of the study area, Dampier and Crab Creek, are primarily tidally driven but discharge sheet wash and stormwater.

2.4.2 Local
The vast majority of geological and hydrogeological knowledge held in the area (relevant to this study) was completed by Laws (1991) and Vogwill (2003). More recent studies, in close proximity to the WWTP and Broome town, were conducted by Golder Associates (1997), URS (2012-2013), Wright (2013) and Hearn (2014) in response to algal blooms in Roebuck Bay. Previous works consistently describe the hydrogeology of the study area to be an unconfined aquifer system found within the Pindan Sand and the Broome Sandstone.
Generally the aquifer is unconfined with little vertical difference in hydraulic head (Laws, 1991; Vogwill, 2003).

The Broome Sandstone is a layered aquifer with coarse sandstones and conglomerates producing higher yields and better quality water than the intervening finer-grained sedimentary rocks. The variability of the depositional environment of the sandstone has resulted in an anisotropic nature in which the vertical permeability is smaller than the horizontal permeability (Vogwill, 2003). This is of particular consequence along the eastern margins of the peninsula (specifically near WWTP/Golf Course) where drilling (Golder Associates 1997; URS, 2013; Wright, 2013) suggests the presence of an old deltaic paleo-dune and paleo-drainage system which lends to a more complex heterogeneous and hydrodynamic environment. Comparatively, assessment of Wright’s (2013) lithological logs and cross sections (see Figure 5), suggest the western portion of the peninsula to be characteristic of a more stable fluvial system, having little intervening cementation from finer grained sediments and generally showing greater uniformity.

**Figure 5:** Wrights (2013) interpretation of the hydrostratigraphy within the Broome peninsula
Groundwater flow on the peninsula, based on an assessment of topography and groundwater level data, is from the centre of the peninsula, radially towards the coast (south, east and west) and (under normal conditions) a seaward hydraulic gradient drains groundwater into the sea (pending tidal height) and also Dampier Creek to the north-east. Beneath the WWTP groundwater flow is in a south-easterly directly into Roebuck Bay (Hearn, 2014). Groundwater level gradients within the unconfined superficial unit are flat suggesting slow groundwater movement given the moderate hydraulic conductivity and specific yield (Vogwill, 2003). Relevant studies indicate that groundwater flows to the south and southwest towards Roebuck Bay and Dampier Creek are under an average hydraulic gradient of 0.001 (Laws, 1991; URS, 2013).

Hydrogeological data indicates that groundwater levels across the study area range from RL 1 m AHD to RL 3 m AHD (Laws, 1991; Golder Associates, 1997; Vogwill, 2003; Wright, 2013; Hearn, 2014, URS, 2013). Prior to construction of the treatment plant, groundwater levels were inferred to be about 1 m AHD (with variations due to tidal fluctuations) at the WWTP. However due to long term seepage from the evaporation ponds there is localised groundwater mounding in the proximity of BSWWTP (Golder Associates, 1997; URS 2013; Hearn, 2014). Water levels collected by URS (2013) now indicate groundwater levels at the BSWWTP are between RL 1.6 m AHD and RL 2.7 m AHD (dependent on season). In general groundwater levels are seasonally at their highest in April (end of wet season) and lowest in November/December (end of dry season) which was reported by Hearn (2014) to induce a 0.54 m groundwater level variation. Studies by URS (2013) also noted considerable seasonal groundwater fluctuations of 1 m; however Hearn’s (2014) seasonal groundwater level variation is considered more reliable due the more uniformly distributed nature of his dataset. Groundwater levels are also influenced by the extreme tidal regimes; the degree of influence is currently unknown but expected to increase with proximity to the coast.

**Hydraulic Properties**

Hydraulic conductivity (K) is an important parameter in relation to the flow of groundwater through an aquifer system, it is defined as the capacity of a porous medium to transmit water (Driscoll, 1986). Therefore it is critical to assign accurate K values to hydrostratigraphic units, ideally based on measured field data, when modelling groundwater flow and/or solute transport. The horizontal hydraulic conductivity (Kh) values were obtained from a variety of sources (Table 2) forming the basis for K parameterisation during steady state modelling.
All hydrogeological data utilised in these works which were sourced from previous investigations can be found in Appendix 2.

**Table 2:** Historical Kh values used in calibration of steady state models

<table>
<thead>
<tr>
<th>Lithology</th>
<th>$K_h$ range (m/day)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pindan</td>
<td>0.12 – 1.7</td>
<td>5, 6, 7, 8</td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td>2 - 23</td>
<td>1, 2, 4, 3, 5, 6, 7</td>
</tr>
</tbody>
</table>

1. **Laws (1985)** – pump testing
2. **Golder** – (1997) – pump testing at BSWWTP
5. **Coffee Geotechnics & SKM** (2009) – permeability field testing
6. **URS** (2013) – slug testing of at BSWWTP
7. **Wright** (2013) – grain size distribution
8. **Department of Agriculture** (2013)

**Pindan Sand**

From pump and slug testing data (see **Table 2**) the hydraulic conductivity of the Pindan has been measured to be within the range of 0.3 to 1.9 m/day. Limited drilling at locations AS, DS, ES, GS (see **Figure 5**) to date indicate that higher $K$ values exist within bed load gravels, over a depth of approximately 10 m (5.0 m AHD to -5.0 m AHD) whilst conversely in the older deltaic/low energy environments (i.e. mud flats) $K$ values are much lower ranging between 0.02 m/d and 0.3 m/d (URS, 2013).

**Broome Sandstone**

Based on previous local and regional estimates $K_h$ values within the BS vary from 2 to 23 m/d, which is a high range signalling some degree of heterogeneity within the unit. Regional drilling also indicates that aquifer parameters within the BS vary both laterally and with depth (WAWA, 1994). The variability of $K$ within hydrofacies can range from one to three orders of magnitude (Wright, 2013). It is possible that connected, high-conductivity hydrofacies
form avenues for contaminant movement while connected low-conductivity hydrofacies form barriers to flow that promote channelling of contaminants into the highly-conductivity pathways (Anderson et al., 1999). Once the hydrofacies architecture of the aquifer system, and resulting major K contrasts, are determined (and modelled), then the internal K variability within hydrofacies can be investigated if necessary (Stanford and Ashley, 1998). In the context of contaminated transport, it has previously been demonstrated in unconfined aquifers that aquifer properties (mainly horizontal hydraulic conductivity, saturated aquifer thickness and head gradient) have proven to be influential variables in delineating capture zones for contamination plumes (Mathews et al., 2003). Without proper aquifer characterisation based on the sedimentary geology of an area, the conceptualisation of the aquifer hinges on statistical analysis to calculate a comparable medium.

**Aquifer Recharge**
Groundwater recharge rates are variable across the landscape, and depend on soil type, vegetation, impervious areas and topography as well as rainfall amount and other climatic variables. The complex interplay between these parameters means there is not a simple relationship between the groundwater recharge rates and rainfall amount. The most notable example within the study area is the recent increase in urban development in Broome which has led to significant reductions in groundwater recharge and simultaneous increases in nutrient discharge due to the channelling of storm water runoff into Roebuck Bay (Gunaratne et al., 2014).

Generally speaking the majority of recharge occurs in the wet season (December – March) when rainfall intensity and duration are sufficient (BOM, 2014). During the wet season rainfall replenishes Broome groundwater reserves via direct percolation from the upper porous Pindan horizon, into the unconfined BS then to the confined basal unit via vertical leakage (Jarlemei Siltstone) and then ultimately discharged over a saline interface into the Indian Ocean/Roebuck Bay (Water and Rivers Commission (WRC), 2001). Recharge of the Broome sandstone (via direct rainfall), across all of its aerial extent, has been estimated to be 3 to 6 % of total rainfall; this was determined using chloride ratios and flow net analysis (Laws, 1991). Laws (1991) also found evidence from groundwater flow patterns and chemistry that the coastal dune systems are a significant source of recharge, approximately 30% of rainfall. This is largely due to the layer of more recent, coarser and unconsolidated sand at these dune sites, which assists in water penetration, plant establishment and growth (Kenneally et al., 1996).
Localised aquifer recharge may also occur within low-lying areas where surface water can readily permeate into sediments during and following rainfall events. This is prominent in the area south of the WWTP and Golf Course where flooding occurs following large episodic rainfall events (URS, 2013).

**Aquifer Discharge**
The dominant groundwater discharge processes on the peninsula are evapotranspiration and marine discharge which are highest during the dry season when groundwater levels decline as groundwater is either transpired or discharged to tidal creeks or the ocean. The primary discharge mechanism critical to nutrient transport within the peninsula is SGD. While sources such as precipitation, river discharge, seawater exchange and nitrogen fixation are important to many coastal ecosystems, determining the contribution of nutrients delivered through SGD is essential. SGD from coastal aquifers has long been recognised as an important component of the hydrological cycle as it is the primary mechanism for transporting land derived pollutants to the sea (Burnett et al., 2006).

**Submarine Groundwater Discharge - Roebuck Bay**
SGD is now commonly recognized as a major conveyor of dissolved matter between land and the sea. The main driving forces include the hydraulic gradient of the coastal aquifer as well as tidal forces and wave setup (Weinstein, et al., 2011). Nutrient contributions from small scale tidal and wave pumped SGD can be significant to the nearshore nutrient supply (Shellenberger, et al., 2006). When seawater intrudes into a fresh-water aquifer, an exchange of cations occurs and sodium is taken up by the exchanger (clay), and calcium is released; thus water quality changes from Na-Cl-rich to Ca-Cl-rich water (Appelo and Postma, 2005). In shallow, permeable (sand, limestone) coastal aquifers, (e.g. Broome Sandstone Aquifer) the importance of SGD is even greater due to higher rates of groundwater recharge (Slomp and Van Cappellen, 2004). Without extensive spatially dense data sets it is difficult to quantify SGD and the geochemical processes occurring at discharge zones.

The extent of nutrient contributions to coastal waters via SGD under varying hydrological and marine trophic conditions is an important element in this study. Current understanding of SGD into Roebuck Bay centres around the analytical estimates of Wright (2013), URS (2013) and Hearn (2014), both finding evidence of active groundwater discharge in the area. When attenuation processes (occurring inland) were considered, calculated SGD nitrogen loads from the WWTP (URS, 2013) and Town Beach and Port precinct (Wright, 2013) into Roebuck Bay, respectively, ranged significantly between 470 kg/year and 43,000 kg/year.
This highlights the current degree of uncertainty surrounding contaminated transport across the peninsula.

Evidence suggests there is a diversity of geochemical processes is taking place in the fresh water–seawater contact zone which have the potential to alter the freshwater and seawater mixture away from the theoretical composition. Since these processes are not easily specified, since they vary and are superimposed in both time and space, without extensive water chemistry data understanding the complexities of these processes taking place at the Roebuck Bay freshwater and seawater interface are not possible and as such were not attempted during this investigation. It would be presumptuous at this stage, with the limited information at hand, to draw comprehensive conclusions on the impact of the saltwater interface and SGD on nutrients within the Roebuck Bay intertidal zone. This study will aim to predict nutrient loads discharging to the subterranean estuary, which is the area of variable water quality between the fresh and saline groundwater interfaces.

2.4.3 Hydrochemistry
Since the 1970’s groundwater quality assessments have been undertaken inconsistently and sporadically across the region in the following areas (see Table 1 of Appendix 2, for a complete data set):

- Broome Town and surrounding areas - (Wright, 2013, Hearn, 2014)
- Golf Course [ Water Corp, (2014); URS, (2013) ]

The only long term water quality data for the peninsula has been taken from the WWTP and Golf Course; however this data is not applicable to the rest of the region as it is derived from localised pollutants resultant from leaking ponds at the WWTP. Due to the inconsistency of data collection in the region, hydrochemistry is not understood in detail; however it can be discussed in the context of general trends across the study area and surrounds.

Groundwater collected from the unconfined aquifer shows that it is dominated by Na-Cl type water, which is expected in a coastal environments with Na-Cl rainfall containing cyclic salts (Laws, 1991). Groundwater is fresh to brackish with total dissolved solids (TDS) ranging from 50 to 1,000 mg/L in the upper portion of the unconfined aquifer and increasing to a maximum of 14,000 mg/L at depth, due to proximity to the saltwater-interface (Wright, 2013; URS, 2013). Laws (1991) also reports groundwater TDS ranging from 100 to 30,000 mg/L, with the lower levels in inland areas increasing towards discharge zones along the coast,
hence the vulnerability to seawater encroachment as most abstraction is near the coast. Seasonally groundwater salinity and nutrients levels show a marked increase at the end of the dry season. Seasonal data from Wright (2013) and Hearn (2014) show a 10 fold increase in TDS levels between wet and dry seasons with the exception being location C where TDS did not change seasonally. This is likely due the groundwater dynamics being controlled by saltwater intrusion and tidal fluctuations rather than rainfall recharge at that location.

As with TDS the distribution of nitrogen and nitrates varies the wet and dry seasons; with the highest concentration of nitrates and nitrogen occurring at the end of the dry season in wells positioned down-gradient and proximal to wastewater irrigated areas or the WWTP (Hearn, 2014). With all baseline observation wells (i.e. not in the vicinity of the contaminated zones) having Total Nitrogen (TN) and nitrate levels 1 to 2 orders of a magnitude lower than all other wells. In general however, groundwater exceeds the recommended maximum concentration of TN and nitrate for tropical wetlands and marine ecosystems, by several orders of a magnitude, throughout the Broome peninsula (ANZECC, 2000). All historical pH readings from shallow and deep bores suggest little variation between stratigraphic units (on average 6.2 – 7.4) both are generally neutral with some locations (B, 6_13D) exhibiting slightly higher alkalinities (8.2-9.2); suggestions are that these locations are linked to historical anthropogenic influences (Wright, 2013).

**Nutrient Attenuation (Nitrogen)**

When recharge water containing nitrogen compounds enters the subsurface environment two main chemical transformations can potentially remove nitrogen from groundwater: nitrification and denitrification. Nitrification transform ammonia (NH$_4^+$) and ammonium (NH$_3^+$) to nitrate (NO$_3^-$) whilst denitrification converts NO$_3^-$ to several gaseous species (primarily N$_2$O and N$_2$) when soil water content is high and a source of organic carbon is present under anaerobic conditions (Loehr, 2012). Furthermore Rivett *et al.*, (2008) found the limiting factors in the attenuation process are oxygen and electron donor concentration with all other environmental factors being secondary, such as pH, temperature, nutrient availability and microbial acclimation.

In the context of the peninsula observed drilling and mapping has shown carbonaceous horizons within areas of older drainage networks where mangroves and lower energy systems may provide ideal conditions for carbon decomposition. It’s these areas where the nitrogen attenuation capacity is likely to be at its highest. However current geology information suggests these areas to be restricted to the eastern and north-eastern margins of the peninsula.
nearing Dampier Creek, outside of irrigated areas. Comparatively the remainder of the peninsula hosts medium to coarse grained sands with little known capacity to attenuate or denitrify nitrogen. At a localised scale silty horizons within Pindan and BS may present opportunities for attenuation; however where these reside above the water table the opportunities for this will be limited. The loss of nitrogen by denitrification may take place as long as there is sufficient organic matter within the plume to sustain denitrifier activity; beyond that, nitrogen concentrations may continue unchanged downgradient (Valiela et al., 1997). To date there have been no studies focussed on the geochemical and biological strata beneath the irrigation sites and their natural attenuation capacity so any statement on this topic would be an assumption at best. Current information rest in estimates made by Hearn (2014) and URS (2013) who both assigned a denitrification value based on Tesoriero and Puckett (2011) estimates from 12 USGS study areas across the US. Evidently no site specific attenuation estimates currently exist for the peninsula.

Additionally chemical reactions involving dissolution or precipitation of minerals commonly do not have a significant effect on groundwater chemistry in sand and gravel alluvial aquifers (such as Broome Sandstone) because the rate of water movement is relatively fast compared to weathering rates (Ezzy, 2005). Instead, sorption and desorption reactions and oxidation/reduction reactions related to the activity of microorganisms probably have a greater effect on the chemistry of groundwater in these systems (Winter et al., 1998).

2.4.4 Effect of Tidal Wave Fluctuations on Groundwater
In coastal areas the periodic rise and fall of tide-water stage in the ocean produces progressive pressure waves inland resulting in fluctuating groundwater levels and hydraulic gradients. This creates a situation where a single set of water level measurements cannot be used to accurately characterise ground-water flow (Serfes, 1991). Ultimately this may result in significant misinterpretation and future un-predictability.

The prominence of large tidal fluctuation is high in the north-west region of Western Australia, with a maximum reported tidal range in Broome of 9.83 m and an average of 8 m. This fluctuation in water levels has been noted in all previous field investigations at the peninsula. Whilst conducting test pumping on a number of monitoring wells positioned around the WWTP, Golder Associates (1997) noted water level fluctuations up to 0.36 m (peak to trough). Conversely URS (2013) recorded a high and low tide groundwater level height difference between 0.27-0.65 m in four bores (installed with data loggers) positioned in close proximity to Roebuck Bay. Such a transient water level environment is likely to have
dramatic impacts on the cyclic fluctuation and discharge rates at the Roebuck Bay/WWTP freshwater-seawater interface; the spatial and temporal patterns of which are not yet understood.

Typically, in a broader context, groundwater discharge is inversely correlated with tidal activity (Robinson and Gallagher 1999) such that discharge is at its lowest during high tides and highest during low tides. Furthermore Mao et al., (2006) found tides tend to intensify vertical mass exchange and generate more complex hydrodynamic patterns in mildly sloping beaches when compared against vertical beaches, this may have relevance at Roebuck Bay where beach faces are generally considered to be ‘mildly’ sloping. Due to the lack of diurnal groundwater level and quality across the peninsula, tidal influence on groundwater hydrodynamics, saltwater intrusion and SGD is poorly quantified in this system.

2.4.5 Saltwater Intrusion
As with any landmass surrounded by saline water there are many influences on the hydraulics of the groundwater. The proximity to the ocean will likely result in some degree of tidal influence, as well as a buoyancy influence due to the likely existence of a salt water wedge underlying the coastal fringes. Any actions that change the volume of groundwater discharge or lower the water table or potentiometric surface below sea level will result in a consequent change in saline water-freshwater interface (Driscoll, 1986).

Due to the preliminary nature of this study and the lack of water quality and level information at the saltwater-freshwater interface, the Ghyben-Herzberg relation was used to facilitate discussion around likely impacts of the interface on the groundwater environment in the vicinity of the WWTP. This method generally overestimates the thickness of the freshwater layer as it assumes no vertical head gradients or vertical flow (Izuka and Gingerich, 1998). In practice the interface between fresh water and saline water is not sharp and the seawater merges gradually with the freshwater by the process of mechanical dispersion (Javadi et al., 2011).

This zone has been termed a subterranean estuary (Moore, 1999) and is the result of dispersion during flow along the freshwater-saltwater interface (Slomp and Van Cappellen, 2004). In this dynamic zone topography driven flow of freshwater drags saline water from the underlying saline groundwater body and the resulting brackish water is discharged to sea (Slomp and Van Cappellen, 2004). This is a likely explanation for the groundwater at location C which is similarly saline all year round, more so than most sites on the peninsula.
In mixing zones which undergo only minor changes with respect to location and width, transformations and removal of nitrogen and phosphorus are strongly influenced by the flow rates and redox characteristics of the freshwater and seawater (Slomp and Van Cappellen, 2004).

Limited water chemistry from the aquifer beneath the WWTP suggests dissolved oxygen content to range between 1.0 and 4.9 mg/L, which, according to Slomp and Van Cappellen (2004) indicates oxic groundwater conditions. Where groundwater is in contact with oxic seawater denitrification (removal of NO$_3^-$) prior to SGD is likely to be limited. However as stated previously groundwater chemistry data is extremely limited across the peninsula, especially in nearshore and intertidal locations, as such estimates of dissolved oxygen should be considered accordingly.

### 3.0 Materials and Methods

#### 3.1 Conceptual Hydrogeology

Conceptual hydrogeological models represent a simplified form of reality to assist with developing an understanding of the groundwater resource and/or development of numerical models. A conceptual model involves the collation of all known geology and hydrology of a groundwater system. In this instance the following factors have been considered; geology, topography, climate (recharge and evapotranspiration), land types, aquifer types, groundwater flow and gradients. A sound grasp of the conceptual hydrogeology often uncovers uncertainties within the data set prior to the commencement of numerical modelling.

As discussed in Section 2.1.2, the peninsula is composed of bands of aeolian dune sand running parallel to the coastal margins above Quaternary Pindan and coastal dune deposits that overlie the Broome Sandstone. Also of significance is a highly variable gravel lag layer which sits low in the Pindan sand, the lateral and horizontal extent of this layer is presently unknown and worth investigating in future field studies (Wright, 2013).

The unconfined Broome Aquifer is made up of two different units; the Pindan and Broome Sandstone. The Broome Sandstone is saturated over its entire depth. Previously the freshwater lens/freshwater-saltwater interface has been estimated to be between 30 m and 50 m thick (Wright, 2013). Utilising 2013/2014 dry and wet season water levels and the Ghyben-Herzberg it was possible to verify the position of the saltwater-freshwater interface beneath the eastern portion of the peninsula, see Figure 6. Using well C as a marker (closest
piezometer to the WWTP) the aquifer underlying the WWTP and Golf Course are likely to be positioned within the diffusion/mixing zone.

![Figure 6: East-west interpretive cross-section of predicted saltwater wedge position at the Broome peninsula](image)

Hydraulic conductivity results from sporadic field testing range from 0.1 – 3.5 m/day for the Pindan Sand and 2 – 23 m/day for the unconfined Broome Sandstone. Based on Vogwill (2003) and Wright’s (2013) lithological interpretations the vertical hydraulic conductivity is expected to be low. The nature of the unconfined aquifer means that on a local scale groundwater flow is in some areas via preferential pathways, however, on a basin wide scale the aquifers are considered to behave as an equivalent porous media with high transmissivities and low storage capacity. Hydraulic gradients are expected to be extremely low (0.0001 – 0.0002). The aquifer’s storage characteristics largely depend on the hydraulic properties of the Broome Sandstone/Pindan Sand, estimates from previous studies were consistently between 0.2 (Vogwill, 2003; URS, 2013; Hearn, 2014).

Evapotranspiration and groundwater discharge to the ocean dominate groundwater discharge processes. The impact of abstraction of groundwater from privately owned bores to groundwater levels, depends on the abstraction rate and the hydraulic properties of the aquifer of which transmissivity is the most important. Based on the lack of information on volumes, and a lack of widespread use, groundwater abstraction was not included in modelling efforts. The conceptual hydrogeological model is shown in Figure 7.
3.2 Numerical Modelling
3.2.1 Model Development
The finite element package FEFLOW v6.2 from DHI-WASY (Diersch, 2014) was utilised under both steady and transient state conditions. The resultant groundwater heads and nitrogen concentrations were then qualitatively compared to field observations. Data used in the development of the model included all available drill hole data for model domain, geological mapping (surficial sediments), Digital Elevation Model (DEM), water level and
quality data from largely from 33 monitoring wells (see Tables 1 and 2, Appendix 2) and available aquifer testing data. All utilising the same hydrogeological stratigraphy with varying hydrogeological parameters based on field data where available. The finite element grid design was based on the conceptualisation referred to in Section 3.1. The following assumptions were made: (i) the BS is homogenous; and (ii) boundary conditions on the ocean side (south, east, west) are constant. The saltwater-freshwater interface is not modelled as the numerical model did not incorporate density coupled flow. It was developed to simulate groundwater flow within the context of nutrient transport and does not attempt to specifically map the freshwater-saltwater boundary or make any evaluations on the impacts that may be associated with this saltwater interface within the study area (see Section 2.3.2).

3.2.2 Model Extent and Mesh Generation
The model area comprises a surface area of 41 km² with a maximum width (east-west) of 4.6 km, a length (north-south) of 10 km and a depth of 65 m. The study domain and contaminations sources are shown in Figure 8 whilst the geological layers and parameters are shown in Figure 9.

The model mesh was developed using the Triangle generator firstly at a regional scale to encompass the extent of the Broome aquifer with a greater level of detail around the irrigation areas and the eastern coastal margins where the aquifer system is more dynamic. The resultant model mesh was 231,042 elements and 136,710 nodes with cell size 100 m regionally and 10 m near contaminated zones. The mesh refinement scale is illustrated in Figure 8.
Figure 8: Model domain, contamination sources, boundary conditions, regional elevation profile and mesh arrangement

Figure 9: Hydraulic properties and geological layer arrangement
3.2.3 Model Geometry
The 3D model geometry configuration was generated based on the conceptualisation of the study area discussed in Section 3.1 and was then developed using point shape files extracted from a SRTM raster grid in ArcGIS. All slice and layer levels were then set within FEFLOW relative to topographical elevations extracted from ArcGIS. A summary of resulting layer configuration and is provided in Table 3.

<table>
<thead>
<tr>
<th>Geological Unit</th>
<th>Layer Number</th>
<th>Aquifer Type</th>
<th>Model Thickness (m)</th>
<th>Layer Elevations (m AHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pindan Sand</td>
<td>1-4</td>
<td>Unconfined</td>
<td>0 – 15m</td>
<td>36 - 10</td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td>5-14</td>
<td>Unconfined</td>
<td>15 – 65m (10 layers at 5m)</td>
<td>10 to -40</td>
</tr>
</tbody>
</table>

3.2.4 Boundary Conditions
Constant head boundaries, termed a 1st-kind (Dirichlet) flow boundary conditions (BC) in FEFLOW, were applied along the western, eastern, southern model boundaries to represent the Indian Ocean, Dampier Creek/Roebuck Bay and Roebuck Bay/Indian, respectively (see Figure 8, above). A constant head boundary (Dirichlet) of 2.5 m was assigned to the northern model boundary based on groundwater level contours obtained from Laws (1991), DOW (2008) and Rockwater (2008). This boundary condition allowed for groundwater inflow from the Broome Sandstone across the northern model boundary. An average salinity (TDS) value of 0 mg/L was applied as a 1st-kind (Dirichlet) mass transport BC to all layers at the northern boundary to represent freshwater concentrations at the inland side. The base of the aquifer was considered a no flow boundary and the upper layers leaky.

3.2.5 Monitoring Wells
Monitoring wells across the study area comprise firstly the Water Corporations wells installed around the perimeter of the BSWWTP and within the golf course (monitored by Water Corp/URS). Secondly eight nested wells installed by Wright (2013), which are sparsely distributed across the southern portion of the peninsula. The 33 monitoring wells (see Table 1, Appendix 2) were represented in the model as observation points, with their respective wet and dry season water levels compared against computed water levels to achieve calibration in steady state. Not all wells had water level and TN information for both wet and dry seasons.
Within the model, layers 1-4, (shallow, Pindan Sand) contained 15 wells whilst layers 4 – 14 (deep, unconfined Broome Sandstone) contained 18 wells. The observation well distribution is displayed below in Figure 10.

**Figure 10: Monitoring well distribution across model domain**

**3.2.6 Climate Data**
All rainfall data used was sourced from BOM (2014) for the Broome Airport Station (see Section 2.1). Analysis of historical rainfall data revealed average rainfall for the last 10 years (2004/2014) to be approximately 100 mm greater than the long term rainfall average of 610 mm/a. To ensure modelling efforts reflect current rainfall patterns the average rainfall (703 mm/a) from 2004-2009 were applied to all irrigated steady state models at the calibrated recharge rate of 12%. Subsequent transient simulations, following calibration, applied varying climatic scenarios; see Figure 11 and relevant sections below for greater detail.

As this region is characterised by extreme short duration cyclonic rainfall events rainfall recharge estimates typically experienced during a cyclonic event such as ‘Cyclone Rosita’ were considered by applying 176 mm/24 hours in transient nutrient transport modelling. The effects of such an event were modelled to ascertain the impacts to downstream contaminant distribution.
3.2.7 Calibration and Sensitivity Analysis

Initially the models were run in steady-state and then a manual adjustment of the parameters listed in Table 4 was conducted. This is required to ensure precise model calibration to ideally resemble observed site conditions (groundwater level and total nitrogen). Sensitivity analysis in steady state was then carried out to find the most sensitive parameters affecting the system. The value of all parameters were adjusted within the range limits reported in Table 4 whilst keeping all other parameters and conditions constant. Scaled Root Mean Square (SRMS) (Barnett et al., 2012) a value that represents the collective error in the model output, was utilised for statistical comparison of the calibrations for each of the steady state numerical models.

Unfortunately three-dimensional distribution of groundwater salinity was not included in the calibration. Although salinity data has been collected previously from wells A-H and those positioned around the WWTP/Golf Course, there are no monitoring wells screened within the transition zone of the saltwater interface that can be used for comparative purposes. The residual water depth for dry (phreatic) elements was set for all modelling cases to 1.4 m as this setting was found to produce the most stable readings during steady state calibrations.
Table 4: Parameters applied to calibration and sensitivity analysis

<table>
<thead>
<tr>
<th></th>
<th>Lower Limit</th>
<th>Mid Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pindan Sands</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kh (m/d)</td>
<td>0.5</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>Kv (m/d)</td>
<td>0.05</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Specific Yield (Sy)</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Broome Sandstone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kh (m/d)</td>
<td>0.5</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Kv (m/d)</td>
<td>5:1</td>
<td>7.5:1</td>
<td>20:1</td>
</tr>
<tr>
<td>Specific Yield (Sy)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Recharge (%) - assuming 703 mm/a</td>
<td>3</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

Steady State Modelling
Steady-state groundwater flow models were developed and calibrated against existing dry and wet groundwater level data collected during the October 2013 and March 2014 field programs by Wright (2013) and Hearn (2014); respectively. Two scenarios were established to ensure accurate calibration of groundwater heads:

1) **Base Case** – included all observation wells seemingly not impacted by irrigation activity due to their position up-gradient of irrigated sites; this included well locations A, C, D, E and H.

2) **Irrigated Case** – included all base case observation wells plus those impacted by irrigation activity (A-H) and 16 wells positioned around the WWTP and Golf Course.

The following parameters were modified manually to assess their effect on the model output: hydraulic conductivity, recharge, anisotropy and boundary conditions.

Following application of initial conditions a manual sensitivity analysis was performed by making adjustments to recharge volumes, boundary conditions, hydraulic conductivity and anisotropy to determine the sensitivity of the system within the irrigation sites and WWTP. Both wet and dry scenarios were modelled to achieve calibration of irrigated sites against both wet (2014) and dry (2013) data sets. Root Mean Square (RMS) and head contours were used to compare results during the sensitivity analysis. Results from this comparison are discussed in Section 4.0.
**Hydraulic Conductivity**
Variations of hydraulic parameters within all layers were used for each numerical model. A range of hydraulic conductivities (K\text{h} and K\text{v}) established from a number of field programmes across the area were refined both vertically and horizontally within the Pindan and Broome Sandstone units (see Section 2.2.2.1). The original anisotropy ratio of 1:1 (horizontal: vertical) was altered to 1:5, 1:10, 1:20:1:50 and 1:100 in both the Pindan and Broome Sandstone units. The model assumes averages across large areas with limited data to validate against. Whilst this may not affect average water budgets, it may affect the localised flow directions and flow rates. However there would be merit (in future studies) in splitting the Broome Sandstone into two layers, the upper having a lower hydraulic conductivity (K) and the lower a higher K, to reflect stratigraphic findings. With the focus being the WWTP, Golf Course and shallow aquifer groundwater discharge it is likely that all of the significant groundwater and nutrient flow occurs within the Pindan and upper deltaic facies of the BS so would not represent a significant limitation of the modelling.

**Quantification of Recharge**
As discussed in Section 2.2.2 the two forms of recharge ‘diffuse’ (entire model domain) and ‘localised’ (at the WWTP and irrigation sites) were considered and applied to the respective areas in all steady state irrigation case models.

The ‘diffuse’ rate of groundwater recharge rates across the peninsula is largely dependent upon soil type, vegetation, urbanisation/hardstand percentage and topography (see Section 2.2.2) as well as rainfall intensity, volumes and other climatic variables (e.g. seasonality). However given the lack of data and the regional scale these factors were not considered individually, instead a known recharge range of 3-6% as defined by Laws (1991) was used initially and then amended during sensitivity analysis to achieve calibration to observed water levels. Water level response using this recharge range drastically under estimated observed water levels suggesting recharge for the region to be higher. It was then found during the sensitivity analysis on the dry and wet season base case that diffuse recharge for the study area is closer to 12%.

To estimate ‘localised’ rates of recharge at the irrigated sites and WWTP, the Water Corp 2013-2014 metered volumes were referenced. Water Corp reported these areas received 699,537 kL of treated effluent annually and losses from the WWTP (evaporation and leakage) were estimated to be 193,962 kL/annum. As there is a degree of uncertainty surrounding these numbers they were applied with caution as a benchmark whilst trying to
achieve calibration and adjusted accordingly to reflect observed water levels. Calibration in the irrigation sites determined the recharge estimates.

Observations have shown that the water table fluctuates seasonally, rising after sustained rainfall events in the wet season and declining during periods of reduced rainfall by up to 0.60m in some areas (URS, 2013). To account for seasonality a number of time series data sets were applied as recharge (termed In/Outflow on Top/Bottom in FEFLOW) to all transient transport models. Rainfall data from the Broome airport station for the relevant period (2004-2009) was used to develop the time series data.

As recharge to the Broome Sandstone is by direct percolation of rainfall (or indirectly through overlying sediments) in each modelling scenario the distribution of recharge was applied directly to the Pindan Sand.

*Average Lifetime Expectancy*

To facilitate practical management decisions at the WWTP it’s important to understand the residence times of contaminants in the aquifer. This may aid predictions as to how long the nitrogen is likely to contaminate groundwater following closure.

Within FEFLOW this was achieved in steady state by basing calibrated attenuation times and mass transport parameters on approximate nutrient migration time from source to sink. This was based on the first sightings of the Roebuck Bay algal blooms (in 2005) to the opening the WWTP in the early 1991 (approximately 14-15 years). Since information pertaining to the natural attenuation capacity of the subsurface formations within the study area is limited (see Section 3.2.7), principal representative parameter values were sought from relevant literature sources, see Table 5.

**Table 5:** Estimated transport parameters used in the simulation

<table>
<thead>
<tr>
<th>Transport Parameters</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Porosity</td>
<td>0.25</td>
<td>Vogwill, 2003</td>
</tr>
<tr>
<td>Sorption Coefficient (Henry constant-K)</td>
<td>0.03</td>
<td>Charbeneau, 2000</td>
</tr>
<tr>
<td>Molecular Diffusion (m²/s)</td>
<td>0.0002</td>
<td>Boudreau, 1997</td>
</tr>
<tr>
<td>Longitudinal Dispersivity</td>
<td>7.5</td>
<td>Gelhar et al, 1992</td>
</tr>
<tr>
<td>Transverse Dispersivity</td>
<td>0.75</td>
<td>Gelhar et al, 1992</td>
</tr>
<tr>
<td>First Order decay rate (1/d)</td>
<td>0.03-0.05</td>
<td>Slomp, 2004</td>
</tr>
</tbody>
</table>
**Transient Nutrient Transport Modelling**

Transient transport modelling of nitrogen was carried out with the parameters derived from the aforementioned steady state calibrations. Rainfall recharge values (of the time period 2004-2009) were converted into monthly values (with and without a cyclonic event), leading to time-dependent functions for recharge and subsequent subsurface flow. As there is uncertainty surrounding nutrient application loads and leakage rates at the irrigated sites and WWTP a number of transient scenarios (see Table 6) were developed.

**Nitrogen and Irrigated Recharge Loading**

In accordance with license conditions the Water Corporation reports on metered irrigation volumes and nutrient contributions for all wastewater irrigation sites at the completion of every reporting year. This data was used to define initial nutrient loads at the irrigation sites (28 ha) and WWTP (13 ha). The metered TN loads for the 2013/2014 year were applied as 1st Order Mass Transport BC’s to all irrigation sites over a maximum period of 5 years. The extent of the contamination plumes at each irrigation site were then assessed under the varying recharge rates and nitrogen concentrations presented in Table 7. The denitrification (decay) values applied here was based on the calibrated best fit during the ‘average lifetime expectancy’ modelling discussed above. The methodology applied here is considered appropriate given previous subsurface attenuation estimates for the area have been hypothesised.

**Table 6: Transient Modelling Scenarios**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Rainfall Record Used in Model</th>
<th>Decay Constant</th>
<th>% of TN Load (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>2004-2009</td>
<td>0.04</td>
<td>25</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>2004-2009</td>
<td>0.04</td>
<td>50</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>2004-2009</td>
<td>0.04</td>
<td>100</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>2004-2009</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>2004-2009</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>2004-2009</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Scenario 7</td>
<td>2004-2009 (incl. ‘Cyclone Rosita’)</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>
The TN contamination at each site (where possible) was then compared to field data collected by Wright (2013), Hearn (2014) and the Water Corporation (2014); URS (2013) for both wet and dry seasons. As there are no boreholes positioned within the bounds of the TN plumes at either St Mary’s or Peter Haynes Ovals this comparative analysis was not possible at these sites. Although preliminary in nature the movement of TN in the model is a useful guide to contamination behaviour.

**Table 7:** Irrigation and Total Nitrogen values applied to contaminated sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Area (m²)</th>
<th>Infiltration/Recharge to Site (m/d) or</th>
<th>Scenario 1 - 25% of MTNL (mg/L)</th>
<th>Scenario 2 - 50% of MTNL (mg/L)</th>
<th>Scenario 3 - 100% of MTNL (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRAC</td>
<td>80,000</td>
<td>0.0006</td>
<td>6.25</td>
<td>12.5</td>
<td>25</td>
</tr>
<tr>
<td>St Mary’s Oval</td>
<td>29,700</td>
<td>0.0009</td>
<td>10</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Peter Haynes</td>
<td>36,400</td>
<td>0.0013</td>
<td>6.25</td>
<td>12.5</td>
<td>25</td>
</tr>
<tr>
<td>BSWWTP</td>
<td>13,000</td>
<td>0.0137</td>
<td>10</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Golf Course</td>
<td>288,000</td>
<td>0.0006</td>
<td>7.5</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

MTNL = Maximum Total Nitrogen Load (mg/L); as reported by the Water Corp (2014)

**4.0 Results**

**4.1 Steady State Model Calibration**

4.1.1 Base Case Models

Steady state hydraulic head maps and scatterplots of observed heads verses modelled heads simulated by the steady state modelling for dry and wet season data are presented in Figure 12 and Figure 13. From the optimised steady state both wet and dry models were able to achieve a root mean square (RMS) value of 0.44, a value that represents the collective error in the model outputs.

The results from steady state base case modelling in both wet and dry scenarios suggests the horizontal groundwater flow direction in the model to be dominated by east-west flow from the topographically high central ridge line to the low lying coastal areas. Simulated groundwater level contours suggest that there is distinct correlation between distance from
the coast and groundwater level. Modelling suggests the highest degree of tidal influence to be in wells positioned between 0 and 900 m from the coast, here adjustments to recharge and hydraulic conductivity have little impact on heads when compared to adjustments in constant head boundaries. Given the width of peninsula is only 2 km modelling results suggest all groundwater heads across the peninsula are, to some degree, influenced by the periodic rise and fall of tidal-water fluctuations. Conversely the greatest impact on hydraulic heads of all inland wells (E, F, and G) occurred when recharge and vertical hydraulic conductivity within the Broome Sandstone were varied. The model was therefore found to be non-unique in that it could be calibrated if both recharge and hydraulic conductivity of the Broome Sandstone were increased or decreased concurrently.

In general the results from these wet and dry base case models reflect the conceptualisation presented in Section 3.1. Both wet and dry cases are considered calibrated by current Australia Modelling Guidelines (Barnett et al., 2012).
Figure 12: Dry base case; steady state heads and calibration scatterplot including RMS value (red observation points represent calculated heads outside of confidence interval)
Figure 13: Wet base case; steady state heads and calibration scatterplot including RMS value (red observation points represent calculated heads outside of confidence interval)
4.1.2 Anisotropy
When the original anisotropy ratio of 1:1 (horizontal: vertical) was adjusted (between 1:5 - 1:100) within the Pindan Sand and Broome Sandstone, a significant change in heads was observed. The largest head adjustment was noted to occur in wells positioned along in the peninsula central ridgeline; namely A, F, G, 1_13D (see Appendix A), comparatively little to no movement was noted in HS and HD. The greatest sensitivity was noted to occur in wells screened within the Broome Sandstone, which is expected given saturation extends across the entire unit. Figure 14 – Scatter plots 1- 5 highlighting groundwater head movement following adjusted anisotropy from 1 – 100 shows the groundwater head difference with the increasing anisotropy. The model did not precisely predict heads, suggesting other factors, such as spatially varying recharge, preferential flow paths and tidal fluctuation are involved. Based on the sensitivity results, anisotropy of 1:50 was used in all later models, irrigated and transient transport, as this ratio ensued the most stable and uniform head adjustments across the spread of data.

Results from the manual sensitivity analysis (performed during steady state simulations) produced a set of calibrated parameters, see Table 8 for a complete list. These calibrated parameters that were later used in transient transport modelling to improve accuracy of contaminant transport calculations.

Anisotropy-1:5

![Anisotropy-1:5](image-url)
Anisotropy-1:10

Anisotropy-1:20
Figure 14 – Scatter plots 1-5 highlighting groundwater head movement following adjusted anisotropy from 1-100 (red observation points represent calculated heads outside of confidence interval)
**Table 8:** Calibrated parameters

<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Kh</th>
<th>Kv</th>
<th>Sy</th>
<th>Porosity</th>
<th>Recharge (%)</th>
<th>Anisotropy</th>
<th>Constant Head Boundary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pindan Sand</td>
<td>1.5</td>
<td>0.03</td>
<td>0.1</td>
<td>0.25</td>
<td>12</td>
<td>50:1</td>
<td>2.5 m at northern boundary &amp; 0.7 m at east, west and southern boundaries.</td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td>7.5</td>
<td>0.15</td>
<td>0.1</td>
<td>0.25</td>
<td>12</td>
<td>50:1</td>
<td></td>
</tr>
</tbody>
</table>

Note: As specific yield does not impact hydraulic heads during steady state simulations it was not considered during the sensitivity analysis but is included here for information purposes only.

### 4.1.3 Groundwater Residence Time

To ascertain indicative groundwater residence times of nitrogen from contaminated source to sink (i.e. Roebuck Bay) the mean lifetime expectancy function within FEFLOW was utilised under steady state. Prior to simulation the residence times of nitrogen were estimated to be between 10-15 years, based on algal blooms occurrence in 2005 (see Section 3.2.7). Back-calculations resulted in the calibration of transport parameters, see **Table 8**. Results from this numerical analysis were successful in replicating estimated travel time within 1-2 years; pending applied climatic conditions. These initial estimates suggest short travel times under conditions of high rainfall recharge (C and D, see **Figure 15**) in low lying areas proximal to the coast.

In general these plots indicate significantly lower residence times along the low lying coastal margins (0 – 160 years) of the peninsula when compared with the topographically high areas (16-800 years). Groundwater residence times in these higher zones tends to increase from south to north. These results reflect expectations given the lower groundwater gradients associated with higher elevations in inland areas compared to the steeper groundwater gradients and higher groundwater flux conditions characteristic of lower elevations.
Groundwater in the higher areas are therefore expected to be more ‘stagnant’ suggesting groundwater contaminants will remain within the aquifer for sustained periods; 400 to 800 years pending climatic conditions. As these times are based on homogenous groundwater conditions, there is potential for higher permeability zones to substantially increase groundwater flux. In the event hydrostratigraphy beneath irrigated areas is consistent with the stratigraphy modelled here, nitrogen contamination is expected to remain within localised areas and not move downgradient towards Roebuck Bay. Likewise it would be reasonable to assume that under the climatic conditions induced here (wet, dry, cyclonic, average) any contamination of the groundwater near the WWTP will discharge to Roebuck Bay within a 8 to 15 year time period. However if additional factors such as diffusion are considered travel times may be longer.
Figure 15: Mean lifetime expectancy plots based on varying rainfall scenarios (A) average rainfall year (710mm/a) (B) dry year (480 mm/a) (C) cyclonic event (150mm/24hrs) (D) wet year (940mm/yr)

4.2 Irrigated Case Modelling Results
In this steady state case irrigated sites and the WWTP were initially applied recharge at the 2013/2014 rates supplied by Water Corp and then adjusted to best fit observed wet and dry season water level data. Multiple manual adjustments of recharge at these sites could not, well match the observed data (see scatter plots Figure 16c and Figure 17e). However the results to date do reflect current groundwater mounding at the WWTP when compared against both wet and dry data sets. When recharge was increased significantly to raise
groundwater levels in wells positioned around the WWTP it had little effect on heads suggesting groundwater hydraulics are in the area allow the extra water to discharge to the constant head boundary hence factors other than recharge, such as tidal fluctuations would need to be incorporated for the model to well match the observed data.

The recorded groundwater level data also show a large degree of variability, this is likely due to the heterogeneity of the upper deltaic and lower fluvial sediments within the Broome Sandstone unit.
Figure 16: (a) localised plan view of dry irrigated groundwater heads (b) regional view of groundwater heads (dry case) highlighting groundwater mounding at the WWTP; and (c) calibration scatterplot including RMS value
Figure 17: (a) localised plan view of wet irrigated groundwater heads (b) regional view of groundwater heads (wet case) highlighting groundwater mounding at the WWTP; and (c) calibration scatterplot including RMS value.
4.3 Transient State Calibration Results

The transient state model runs were effective in simulating contamination plume migration horizontally into Roebuck Bay via SGD and laterally through the Broome aquifer; see Appendix 1 for all indicative nutrient migration plumes, scatter plots and nutrient loads for all sites under all modelling scenarios presented in Table 9 and Table 10.

The modelling results taken from all modelling scenarios across all sites clearly display a strong correlation (see Figure 18) between nutrient loading, decay/denitrification rate and subsequent TN contamination plume concentration. In general either a reduction or increase in TN load at the contamination source results in a proportional decrease or increase in downstream contamination (see Table 9). Similarly with the inclusion of a decay constant, consistently, across all scenarios, results show a 6 fold reduction in TN concentration at all distances within the contamination plume. This would suggest the overall TN concentration and subsequent nutrient loading into Roebuck Bay to be sensitive to denitrification, this is to be expected.

The introduction of ‘Cyclone Rosita’ (Appendix 1, Scenario 7) had little effect on TN concentrations within the plume, however, a marginal increase in overall TN load into Roebuck Bay was noted (see Table 9). This may be attributed to an error in modelling prior to simulation. Principally, however, modelling shows an increase in the distance or ‘spread’ of the plume, at all sites, when ‘Cyclone Rosita’ was considered which is likely due to increases in dispersion (longitudinal and transverse) proportionally to intensified rainfall recharge. This is particularly evident at the irrigation sites where plume distance increased by 50-100m (see Table 10).

In general the response from observation wells to adjustments of TN loads were consistent, with TN levels either rising or falling relative to changes at the source location. The only marked outliers were the significant high TN values of 30 mg/L and 69 mg/L found in wells C and 8_17s, respectively. At location C, this has previously been attributed to historical contamination from an old landfill sight which is likely considering C’s position up-gradient of the WWTP. However 8_17s situated on the eastern margins of the Golf Course boundary, directly downgradient of the leaking WWTP, may be screened in a high permeability zone directing up-gradient contaminants into this lower lying region of the landscape. Since TN values from wells positioned 100m away have recorded TN readings 5 – 17 times less than
8_17s it likely this is a localised occurrence. Only short term water quality data is available so at this stage it is difficult to verify the potential cause of the unusually high TN levels in C and 8_17s.

**Table 9:** TN (mg/L) and SGD results from transient transport modelling at the WWTP and Golf Course with and without Henry’s decay constant

<table>
<thead>
<tr>
<th>Distance from WWTP/Golf Course (m)</th>
<th>Nitrogen concentration with decay constant (mg/L) - rainfall period 2004-2009</th>
<th>Nitrogen concentration without decay constant (mg/L) - rainfall period 2004-2009</th>
<th>Nitrogen concentration without decay constant (mg/L) - rainfall period 2004-2009 (incl. cyclone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Scenario 1 1.5 2.0 3.9</td>
<td>Scenario 2 2.0 3.9</td>
<td>Scenario 3 1.5 2.0 3.9</td>
</tr>
<tr>
<td>100</td>
<td>Scenario 1 1.5 2.0 3.9</td>
<td>Scenario 2 2.0 3.9</td>
<td>Scenario 3 1.5 2.0 3.9</td>
</tr>
<tr>
<td>200</td>
<td>Scenario 1 1.5 2.0 3.9</td>
<td>Scenario 2 2.0 3.9</td>
<td>Scenario 3 1.5 2.0 3.9</td>
</tr>
<tr>
<td>300</td>
<td>Scenario 1 1.5 2.0 3.9</td>
<td>Scenario 2 2.0 3.9</td>
<td>Scenario 3 1.5 2.0 3.9</td>
</tr>
<tr>
<td>400</td>
<td>Scenario 1 1.5 2.0 3.9</td>
<td>Scenario 2 2.0 3.9</td>
<td>Scenario 3 1.5 2.0 3.9</td>
</tr>
<tr>
<td><strong>Total Nitrogen Load to RB (kg/year at 5yrs)</strong></td>
<td>500 985 2000</td>
<td>2300 4600 11000</td>
<td>118000</td>
</tr>
<tr>
<td><strong>SGD from GC and WWTP (m3/d at 5yrs)</strong></td>
<td>1850 1834 1830</td>
<td>1800 1700 2000</td>
<td>2140</td>
</tr>
<tr>
<td><strong>Average Darcy Flux Range (m/d)</strong></td>
<td>0.01-0.02 0.01-0.02 0.01-0.02</td>
<td>0.01-0.02 0.01-0.02 0.01-0.02</td>
<td>0.01-0.02 0.01-0.02 0.01-0.02</td>
</tr>
</tbody>
</table>

**Figure 18:** Simulated TN (mg/L) concentrations from centre of plume to Roebuck Bay discharge point– with and without decay applied (measurements extracted from centre of saturated zone within layer 9)
When only irrigated sites are considered the resultant contaminated plumes suggest TN spatial distribution to be localised between 325 m and 700 m from all point source locations; this is dependent upon recharge and nitrogen loading. As there are little to no monitoring wells in the vicinity of irrigated sites it is a difficult to compare and verify observed nutrient values against calculated modelling results. Utilising the scatterplot results from the only monitoring wells positioned within a contaminated plume, location B, scenario 3 shows the strongest correlation when compared against observed TN values (see Appendix 1 for compilation of all scatterplots). However in this instance TN values are drastically underestimated which suggests current nutrient loading at these sites to be greater than those applied in this study. Assuming groundwater hydraulics and stratigraphy are consistent across all irrigated sites the results discussed here at location B (BRAC) can theoretically be applied to St Mary’s and Peter Haynes Ovals.

Table 10: Nitrogen plume details at all irrigated sites following transient modelling with and without the addition of Henry’s decay constant

<table>
<thead>
<tr>
<th>Irrigation Site</th>
<th>BRAC</th>
<th>Peter</th>
<th>St Marys</th>
<th>Golf Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Decay Constant</td>
<td>BRAC</td>
<td>Peter Haynes</td>
<td>St Marys</td>
<td>Golf Course</td>
</tr>
<tr>
<td>Max Plume Distance (m)</td>
<td>450</td>
<td>325</td>
<td>400</td>
<td>550</td>
</tr>
<tr>
<td>Plume Depth (m)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>TN Conc. at Max Depth (mg/L)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Scenario 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plume Distance (m)</td>
<td>450</td>
<td>325</td>
<td>400</td>
<td>550</td>
</tr>
<tr>
<td>Plume Depth (m)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>TN Conc. at Max Depth (mg/L)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Scenario 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plume Distance (m)</td>
<td>450</td>
<td>325</td>
<td>400</td>
<td>550</td>
</tr>
<tr>
<td>Plume Depth (m)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>TN Conc. at Max Depth (mg/L)</td>
<td>1.1</td>
<td>1</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Scenario 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plume Distance (m)</td>
<td>450</td>
<td>350</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>Plume Depth (m)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>TN Conc. at Max Depth (mg/L)</td>
<td>5.6</td>
<td>4.5</td>
<td>6.4</td>
<td>7.5</td>
</tr>
<tr>
<td>Scenario 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plume Distance (m)</td>
<td>450</td>
<td>350</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>Plume Depth (m)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>TN Conc. at Max Depth (mg/L)</td>
<td>11.2</td>
<td>9</td>
<td>12.7</td>
<td>15</td>
</tr>
<tr>
<td>Scenario 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plume Distance (m)</td>
<td>450</td>
<td>350</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>Plume Depth (m)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>TN Conc. at Max Depth (mg/L)</td>
<td>11.2</td>
<td>9</td>
<td>12.7</td>
<td>15</td>
</tr>
<tr>
<td>Scenario 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
When observed TN values are compared against calculated TN values using RMS values from FEFLOW scatterplots (for all modelled scenarios; see Appendix 1) little to no correlation is found. Nevertheless a closer inspection of the above mentioned scatterplots suggests a stronger correlation under scenarios 1 (see Figure 19) and 2 (see Figure 20) when only WWTP wells are included. This can be attributed to the exclusion of baseline wells positioned outside of contaminated zones influencing results. It is therefore plausible to assume that under low nutrient loading scenarios, where denitrification is considered, observed conditions are more closely resembled.
Figure 19: Transient scenario 1 scatterplots including RMS values (red observation points represent calculated heads outside of confidence interval)
Figure 20: Transient scenario 2 scatterplots including RMS values (red observation points represent calculated heads outside of confidence interval)
5.0 Discussion  
Numerical Modelling  
Steady State Groundwater Flow

At the Broome peninsula the interaction between the groundwater and nutrient flow was initially investigated by using wet and dry season groundwater level data to develop a number of steady state numerical models in FEFLOW. The groundwater flow models returned reasonable estimates of groundwater levels regionally and in the vicinity of the WWTP. However, the conditions observed from field data could not be replicated entirely using numerical modelling techniques due to a number of modelling limitations (see below for greater detail).

Modelling successfully reiterated pre-modelling conceptualisation of horizontal groundwater flow direction along an east-west axis from the central ridge in all directions towards the coastline. Additionally the steady state models enabled conceptualisation in data poor areas, particularly those which carry the highest degree of uncertainty along the coastal margins of the peninsula near the WWTP. It is these areas where groundwater hydraulics controlled by heterogeneity, large tidal fluctuations and density driven flow cause sporadic and at times, an uneven distribution of groundwater levels. Although generalised the conceptualised flow model of the peninsula can be used as a useful numerical evaluation tool in subsequent recalibration efforts. In the event more groundwater data becomes available this may improve accuracy and reduce uncertainty surrounding estimates of nitrogen discharge in Roebuck Bay via SGD.

Sensitivity analysis of all parameters resulted in the determination of key hydraulic parameters and the refinement of old estimates (see Table 8). Numerical modelling also highlighted a distinction between the subsurface conditions in central areas of the peninsula compared to the coastal margins. The distinction being two geological environments; an old deltaic paleodunes & paleo drainage system resides along the eastern costal margins and a more stable fluvial system with greater uniformity occurring in the central and western portion of the peninsula. Although distribution and extent of these two geological systems is currently unknown the contrasting groundwater level response in these two regions following parameter adjustment confirmed this geological variability. These modelling results echo the importance of the heterogeneity and preferential flow pathways in this coastal environment. Many hydrogeological investigations recognise that detailed field measurements of heterogeneity are needed in order to establish the occurrence of interconnected paths in
different types of aquifer materials (Anderson, 1995; Webb and Davis, 1998). Although this holds true this regional model was not designed to examine localised solute transport problems where travel times and distribution of the solute are influenced by preferential pathways so is considered appropriate in this instance. However in the event that more field data is collected this should be consideration for future modelling efforts, particularly in the vicinity of the Golf Course and WWTP.

Steady state modelling refined diffuse recharge estimates across the peninsula to 12% suggesting previous estimates of 3-6% have drastically under estimated recharge contributions in the area. This may be attributed to the regional nature of previous rainfall recharge studies. Often recharge modelling is undertaken in isolation to groundwater modelling (Barnett et al., 2012). In this instance the use of numerical recharge modelling (e.g. SWIM, Hydrus 1D) was not deemed appropriate due to the scarcity of information. At this premature stage of the investigation the methodology applied here for estimating recharge appears to be adequate. However process based and fully distributed estimation of recharge would be preferred and further work is warranted.

**Solute Transport**

In this study numerical transport modelling was used to describe and illustrate the transport of nitrogen in the unconfined Broome aquifer at four wastewater irrigated sites and the leaking BSWWTP. The model was verified, where possible against measured 2013 dry season TN values. Several scenarios were run to ensure seasonality impacts and uncertainty surrounding nitrogen loads were evaluated appropriately to resemble realistic results. The results do not show a close agreement between simulated and measured concentrations for total nitrogen. This is expected given the limitations discussed below.

Given the rudimentary nature of these works the results here are still considered useful when discussing generalised solute transport and migration across the peninsula. With this in mind, evaluation of numerical modelling results show that when best (scenario 1) and worst case (scenario 7) scenarios are considered the observed *Lyngbya* blooms in the intertidal zones of Roebuck Bay, can likely be attributed to the migration of nitrogen from the Golf Course and BSWWTP. At this stage initial best estimates extracted from FEFLOW suggest nutrient loads from the WWTP and Golf Course into Roebuck Bay are likely to range between 500 kg/year – 1000 kg/year, assuming denitrification is taking place at the source. At the inland irrigated sites (BRAC, St Mary’s and Peter Haynes Oval) nitrogen migration is localised and does not
discharge into Roebuck Bay, however infiltration into the potable Broome aquifer is taking place and will remain for extended periods (see Section 4.1.3) if wastewater disposal activities are continued unchanged. Furthermore adjustments to recharge by incorporating ‘Cyclone Rosita’ (150 mm/24hours) revealed the distribution of groundwater contamination was altered slightly due to the mechanics of dispersion and diffusion. This supports previous findings that these transport solute mechanisms reduce groundwater contaminant concentrations at plume margins however they are not reducing net concentrations at discharge/outlet locations.

Model Limitations
As with all numerical groundwater flow models there are limitations associated with the quality and quantity of data. In this case the limitations in the numerical modelling have been narrowed down to the following:

- Heterogeneity and preferential flow pathways were not considered in the Broome Sandstone stratigraphy. This could potentially play an important role in groundwater flux.

- Analysis was limited to either a small cluster of wells (BSWWTP) or a non-uniform spread across the model domain (A-H); consequently uncertainty in the model accuracy is limited by the accuracy of measured field parameters.

- A lack of tidal data to adjust measured data. This creates a situation where a single set of water level measurements cannot be used to accurately characterise ground-water flow which may result in significant misinterpretation (Serfes, 1991).

- Modelling did not account for the nitrogen loads derived from other contamination sources, namely landfill sites, agriculture and stormwater runoff from Broome town. These nutrient sources have the potential to increase current estimates of nitrogen loads discharging into Roebuck Bay.

- Modelling of the freshwater-saltwater interface using density-coupled flow was not incorporated into the model; therefore it is likely the model does not accurately predict groundwater levels near the coast.

This is expected given the numerous natural and anthropogenic processes affecting the interaction between groundwater and solute transport within this coastal setting and spatially limited data sets. Given the majority of available data was located within a small 1.5 km² area
(BSWWTP/Golf Course), applying the results from this concentrated data set to a regional setting is not considered reliable and may ensue incorrect parameter assumptions in the future. This should be considered when applying the aforementioned parameters discussed here to any regional context.

Due to the heterogeneous and anisotropic nature of the Broome Sandstone, it is anticipated that the model represents the overall flow regime in the area but it is unlikely to reflect local, microscale flows and nutrient contamination accurately. This has particular pertinence in the vicinity of the BSWWTP where the hydro dynamics are complicated by tidal variations and the depositional environment.

6.0 Conclusions and Future Work Recommendations
This work represents a preliminary modelling study of nitrogen migration from wastewater irrigated sites by means of a simplified solute mass transport approach in an ecologically significant coastal environment. Numerical analysis using FEFLOW was carried out to study the impacts associated with wastewater storage activities by validating previous estimates of nitrogen loads into Roebuck Bay by the complex process of SGD. Previous studies were conducted using conventional analytical methods which did not consider nutrient attenuation under varying recharge and TN conditions. Thereby, in comparison to these studies, this model provides a much more accurate prediction of SGD derived nitrogen into Roebuck Bay.

For the Broome aquifer the evaluation of the relative impact of nitrogen migration has led to a general estimation of nutrient loads into Roebuck Bay between 500 – 12,000 kg/year (pending realised scenario). However when denitrification is considered in scenarios 1 and 2 (which is likely given the subsurface environment) best estimates of nitrogen loads into Roebuck Bay are considerably less ranging between 500 kg/year and 1,000 kg/year. This is consistent with the URS nutrient load estimate of 470 kg/year. Albeit the assumptions in the model relating to the fates of wastewater derived nitrogen in plumes and aquifers certainly needs verification. If data was available to measure the attenuation of nitrogen within plumes and in diffuse travel in the aquifer it would be possible to define how in situ wastewater disposal at different distances from Roebuck Bay is likely to affect loading to the bay. This is especially holds true when considering the complex distribution of alluvial, fluvial and tidal architecture elements in this coastal setting.

In conclusion the numerical simulations performed here provided both steady-state and transient system estimates of water and contaminant behaviour and were used to further
refine the range of conditions currently being observed. This research project has also confirmed the substantial influence the Golf Course and largely BSWWTP is having on the Roebuck Bay environment by contributing TN loads 25 times the MITA limit. It has also assessed and defined likely horizontal and vertical distributions of nitrogen plumes at irrigated sites. Furthermore the results also emphasise the data gaps which require attention in future studies to refine the work discussed here. Such knowledge would help to define how to best, and most fairly, implement management for control of nitrogen loading from the BSWWTP and Golf Course.

Although there is a considerable body of knowledge on the hydrogeology of the peninsula, most of which has become available recently, there are still significant data gaps which require attention:

- A more comprehensive dataset capturing long term water levels and water chemistry data from the Broome Sandstone at coastal margins is required to enable transient calibration at coastal boundaries. Additional monitoring points along the Roebuck Bay intertidal zone are recommended to improve understanding of tidal impacts on hydrodynamics across the peninsula. This would be needed for a number of years to encompass seasonality and cyclonic events. Ultimately this would improve SGD and contaminated transport assessments.

- Installation of additional monitoring wells (shallow and deep) at irrigated sites and across the peninsula in a more uniform manner. Carry out a comprehensive quarterly monitoring programme at these additional sites which is the synchronised with existing monitoring wells to allow later compatibility of results.

- Continued sampling and groundwater level monitoring in existing monitoring bores, with the inclusion of high resolution data loggers to assess seasonality and groundwater level fluctuation resultant from tidal movement.

- Incorporate the aforementioned dataset into a transient density dependent coupled flow FEFLOW model to simulate seawater intrusion beneath the WWTP and Golf Course. This would improve understanding around the hydrodynamics at the saltwater-freshwater mixing zone which may aid in refinement of nutrient discharge estimates.

- Further research into the biogeochemical processes at the saltwater-freshwater mixing zone and subterranean estuary with a direct focus on the redox conditions in this
dynamic zone as it has a large influence on the transformation and mobility of nutrients in this zone (Slomp and Cappellen, 2004).

- Quantify attenuation of groundwater-transported nitrogen by way of field-scale measurement of biological and redox conditions at all waste water disposal sites and background locations (for comparison purposes). This will refine denitrification/decay values applied during this study and in turn improve upon current projected nitrogen concentrations.

- Results from this study suggest that sub-surface permeability distributions as well as seasonal fluctuations in rainfall may strongly influence groundwater flowpaths and recharge processes. Accordingly further studies into hydrochemical and isotopic indicators should be carried out to ensure proper examination of recharge processes and groundwater flowpaths across the entire study area.

- Refinement of hydraulic conductivity within the sandstone, both vertically and horizontally across the entire peninsula with a greater focus at irrigated sites and beneath the WWTP. Current modelling assumes averages across large areas with only anisotropy considered.
7.0 References


Department of Agriculture and Food, Department of Regional Development and Lands, 2013. A review of the Broome Sandstone aquifer in the La Grange area, Department of Agriculture and Food (Ed.), Perth.


Sophiya, M.S., Syed, T.H., 2013. Assessment of vulnerability to seawater intrusion and potential remediation measures for coastal aquifers: a case study from eastern India.


URS., 2013. Hydrogeological assessment of Nutrient Flux from Broome South Wastewater Treatment Plant. Prepared for Water Corporation Pty Ltd.

Method and Application. Ecological Society of America, 7 (2) 358-380.


Appendix 1

Transient Transport Modelling Result Figures

Rainfall Series from 2004 – 2009 – with decay constant/denitrification

SCENARIO 1
SCENARIO 2
SCENARIO 3
Rainfall Series from 2004 – 2009 – without decay constant/denitrification

SCENARIO 4

Scatter containing all observation wells

Nitrogen Load/Scenario - 4
Simulation Time - 5 years
Estimated TN Load into RoshellBay - 2,100 lb/year
Average Decay Flux at WWTP (m/d) - 0.34 - 0.52

Scatter containing only WWTP observation wells
SCENARIO 5

- Nitrogen Load: Scenario 5
- Simulated Time: 5 years
- Estimated TN Load into Reservoir (Dry): 4,000 kg/year
- Average TN Flux to WWTP (mol): 0.016 ± 0.002

Calculated parameters and data are visualized in the diagrams, showing concentration distributions and trend lines.
SCENARIO 6

Nitrogen Load Scenario: 6
Simulation Time: 5 years
Estimated TN Load into Roebuck Bay: 10,000 kg/year
Average Bassey Flux at WWTP (m/d): 0.01 - 0.02

Scatter containing all observation wells
Scatter containing only WWTP observation wells
Rainfall Series from 2004 – 2009 (incl. Cyclone Rosita) – without decay constant

SCENARIO 7
Appendix 2
Data Reference Tables

Table 1: Master table of all relevant data used/referred to during this study

<table>
<thead>
<tr>
<th>Bore Name</th>
<th>Owner (As called by)</th>
<th>Location</th>
<th>Easting</th>
<th>Northing</th>
<th>Borehole Depth (m NG)</th>
<th>Ground Surface Elevation (m AHD)</th>
<th>Screened Geology</th>
<th>Wet Season (Weight’s Date: 03/2014) Water Level (m AHD)</th>
<th>Wet Season (Weight’s Date: 03/2014) Water Level (m AHD)</th>
<th>Dry Season (Weight’s Date: 03/2013) Water Level (m AHD)</th>
<th>Daily GWL Fluctuation (m)</th>
<th>Wet Season (Weight’s Date: 03/2014) TN Conc (mg/L)</th>
<th>Wet Season (Weight’s Date: 03/2014) Nitrate Conc (mg/L)</th>
<th>Dry Season (Weight’s Date: 03/2013) TN Conc (mg/L)</th>
<th>Dry Season (Weight’s Date: 03/2013) Nitrate Conc (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_shallow</td>
<td>UWA - N. Wright</td>
<td>North - BRAC</td>
<td>410212.7</td>
<td>80153047</td>
<td>8015687.7</td>
<td>18.09</td>
<td>13.42</td>
<td>Pindan, gravel &amp; BS</td>
<td>2.77</td>
<td>2.3</td>
<td>4.05</td>
<td>11.33</td>
<td>3.28</td>
<td>10.87</td>
<td></td>
</tr>
<tr>
<td>A_deep</td>
<td>UWA - N. Wright</td>
<td>North - BRAC</td>
<td>410214.7</td>
<td>80153047</td>
<td>35.18</td>
<td>13.42</td>
<td>Brome Sandstone</td>
<td>2.57</td>
<td>2.1</td>
<td>27.88</td>
<td>18.75</td>
<td>2.14</td>
<td>20.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B_shallow</td>
<td>UWA - N. Wright</td>
<td>South - BRAC</td>
<td>410003.7</td>
<td>8014486.4</td>
<td>18.07</td>
<td>14.08</td>
<td>Brome Sandstone</td>
<td>2.7</td>
<td>2.25</td>
<td>8.11</td>
<td>10.46</td>
<td>6.13</td>
<td>10.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B_deep</td>
<td>UWA - N. Wright</td>
<td>South - BRAC</td>
<td>410004.2</td>
<td>8014486.6</td>
<td>35.83</td>
<td>14.8</td>
<td>Brome Sandstone</td>
<td>2.62</td>
<td>2.16</td>
<td>6.7</td>
<td>8.85</td>
<td>0.26</td>
<td>8.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_shallow</td>
<td>UWA - N. Wright</td>
<td>N-East of WWTP</td>
<td>410360.3</td>
<td>8016203</td>
<td>17.99</td>
<td>13.88</td>
<td>Pindan, OM &amp; BS</td>
<td>1.51</td>
<td>1.63</td>
<td>0.85</td>
<td>0.85</td>
<td>0.88</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_deep</td>
<td>UWA - N. Wright</td>
<td>N-East of WWTP</td>
<td>410360.9</td>
<td>8012462.3</td>
<td>29.83</td>
<td>13.88</td>
<td>Pindan &amp; BS</td>
<td>1.47</td>
<td>1.81</td>
<td>1.05</td>
<td>3.43</td>
<td>13.95</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D_shallow</td>
<td>UWA - N. Wright</td>
<td>West Peninsula</td>
<td>410140.1</td>
<td>8014183.6</td>
<td>18.08</td>
<td>13.1</td>
<td>Pindan and Gravel</td>
<td>2.72</td>
<td>2.07</td>
<td>0.21</td>
<td>0.98</td>
<td>0.24</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bore Name</td>
<td>Owner/Installer</td>
<td>Location</td>
<td>Drilling</td>
<td>Borehole Depth (m below)</td>
<td>Ground Surface Elevation (m AHD)</td>
<td>Sealed Geology</td>
<td>Wet Season (Heard's Data 05/2014) Water Level (m AHD)</td>
<td>Wet Season (WattarCarp Data 05/2014) Water Level (m AHD)</td>
<td>Dry Season (Heard's Data 05/2014) Water Level (m AHD)</td>
<td>Daily GWTS Fluctuation (m)</td>
<td>Wet Season (WattarCarp Data 05/2014) TN Conc. (mg/L)</td>
<td>Dry Season (Heard's Data 05/2014) TN Conc. (mg/L)</td>
<td>Dry Season (WattarCarp Data 05/2014) Nitrate Conc. (mg/L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
<td>---------------</td>
<td>----------</td>
<td>--------------------------</td>
<td>----------------------------------</td>
<td>---------------</td>
<td>------------------------------------------------------</td>
<td>------------------------------------------------------</td>
<td>------------------------------------------------------</td>
<td>-----------------------------------</td>
<td>------------------------------------------------------</td>
<td>------------------------------------------------------</td>
<td>------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-deep</td>
<td>UWA - N. Wright</td>
<td>West Pandana</td>
<td>416139.7</td>
<td>8014182.5</td>
<td>34.87</td>
<td>15.1</td>
<td>Broome Sandstone</td>
<td>2.42</td>
<td>1.87</td>
<td>0.75</td>
<td>2.16</td>
<td>0.65</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E_shallow</td>
<td>UWA - N. Wright</td>
<td>Central Pandana</td>
<td>416434.8</td>
<td>8013797.4</td>
<td>24.01</td>
<td>20.45</td>
<td>Pindar and Green</td>
<td>2.59</td>
<td>2.02</td>
<td>1.2</td>
<td>1.3</td>
<td>1.53</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E_deep</td>
<td>UWA - N. Wright</td>
<td>Central Pandana</td>
<td>416634.1</td>
<td>8013797.4</td>
<td>35.87</td>
<td>20.45</td>
<td>Broome Sandstone</td>
<td>2.48</td>
<td>2.02</td>
<td>1.01</td>
<td>1.01</td>
<td>0.56</td>
<td>1.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_shallow</td>
<td>UWA - N. Wright</td>
<td>West of Golf Course</td>
<td>416914.6</td>
<td>8012834.6</td>
<td>17.55</td>
<td>15.37</td>
<td>Broome Sandstone</td>
<td>2.23</td>
<td>1.82</td>
<td>2.07</td>
<td>4.17</td>
<td>0.55</td>
<td>3.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_deep</td>
<td>UWA - N. Wright</td>
<td>West of Golf Course</td>
<td>416914.6</td>
<td>8012834.6</td>
<td>35.81</td>
<td>15.37</td>
<td>Broome Sandstone</td>
<td>2.07</td>
<td>1.84</td>
<td>3.35</td>
<td>13.05</td>
<td>2.77</td>
<td>12.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G_shallow</td>
<td>UWA - N. Wright</td>
<td>West of Golf Course</td>
<td>416532.4</td>
<td>8012407</td>
<td>15.85</td>
<td>11.52</td>
<td>BS &amp; gravel</td>
<td>2</td>
<td>1.71</td>
<td>2.77</td>
<td>6.19</td>
<td>2.57</td>
<td>626</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G_deep</td>
<td>UWA - N. Wright</td>
<td>West of Golf Course</td>
<td>416532.5</td>
<td>8012406.3</td>
<td>29.87</td>
<td>11.52</td>
<td>Broome Sandstone</td>
<td>1.64</td>
<td>1.50</td>
<td>0.69</td>
<td>2.63</td>
<td>0.61</td>
<td>2.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_shallow</td>
<td>UWA - N. Wright</td>
<td>South-East Pandana</td>
<td>415450.3</td>
<td>8010626.2</td>
<td>15.28</td>
<td>10.17</td>
<td>Broome Sandstone</td>
<td>1.5</td>
<td>1.42</td>
<td>0.95</td>
<td>2.03</td>
<td>0.85</td>
<td>1.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_deep</td>
<td>UWA - N. Wright</td>
<td>South-East Pandana</td>
<td>415450.8</td>
<td>8010626.4</td>
<td>31.86</td>
<td>10.17</td>
<td>Broome Sandstone</td>
<td>1.5</td>
<td>1.43</td>
<td>7.29</td>
<td>5.88</td>
<td>3.19</td>
<td>5.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KBO</td>
<td>Shire</td>
<td>Town</td>
<td>410371</td>
<td>8014546</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.78</td>
<td>3.05</td>
<td>48.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bore Name</td>
<td>Owner/Installed by</td>
<td>Location</td>
<td>Easting</td>
<td>Northing</td>
<td>Basehole Depth (m)</td>
<td>Ground Surface Elevation (m AHD)</td>
<td>Scoured Geology</td>
<td>Wet Season (Hearm’s Date: 03/05/2014) Water Level (m AHD)</td>
<td>Wet Season (WaterCorp Date: 03/05/2014) Water Level (m AHD)</td>
<td>Dry Season (Weight’s Date: 10/2013) TN Conc (mg/L)</td>
<td>Wet Season (Weight’s Date: 10/2013) TN Conc (mg/L)</td>
<td>Dry Season (Weight’s Date: 10/2013) Nitrate Conc (mg/L)</td>
<td>Dry Season (Weight’s Date: 10/2013) Nitrate Conc (mg/L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------</td>
<td>---------</td>
<td>---------</td>
<td>----------</td>
<td>-------------------</td>
<td>---------------------------------</td>
<td>---------------</td>
<td>-----------------------------------------------------</td>
<td>-----------------------------------------------------</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
<td>---------------------------------</td>
<td>-----------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO</td>
<td>Shire</td>
<td>Town</td>
<td>4197.40</td>
<td>8014546</td>
<td></td>
<td></td>
<td></td>
<td>2.12</td>
<td>0.99</td>
<td>456</td>
<td>3.24</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB</td>
<td>Shire</td>
<td>Cable Beach</td>
<td>416407</td>
<td>8017356</td>
<td></td>
<td></td>
<td></td>
<td>3.24</td>
<td>3.71</td>
<td>312</td>
<td>3.24</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HP</td>
<td>Shire</td>
<td>Town</td>
<td>418596</td>
<td>8014906</td>
<td></td>
<td></td>
<td></td>
<td>0.99</td>
<td>3.24</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>Shire</td>
<td>Airport</td>
<td>417850</td>
<td>8015156</td>
<td></td>
<td></td>
<td></td>
<td>3.24</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP</td>
<td>Shire</td>
<td>Bedford Park</td>
<td>419407</td>
<td>8013806</td>
<td></td>
<td></td>
<td></td>
<td>3.24</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TB</td>
<td>Shire</td>
<td>Town Beach</td>
<td>418915.9</td>
<td>8013526.9</td>
<td>19.19</td>
<td>11.02</td>
<td></td>
<td>3.24</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BS</td>
<td>Shire</td>
<td>Fire Station</td>
<td>419077.3</td>
<td>8012970.4</td>
<td>19.89</td>
<td>9.17</td>
<td></td>
<td>3.24</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.04</td>
<td>WaterCorp/URS</td>
<td>BWWTP</td>
<td>4174.27</td>
<td>8012266.5</td>
<td>21.4</td>
<td>10.73</td>
<td></td>
<td>1.85</td>
<td>2.75</td>
<td>5</td>
<td>8.5</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.04</td>
<td>WaterCorp/URS</td>
<td>BWWTP</td>
<td>4176.26</td>
<td>801682</td>
<td>24</td>
<td>13</td>
<td></td>
<td>2.59</td>
<td>0.6</td>
<td>3.24</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.13b</td>
<td>WaterCorp/URS</td>
<td>BWWTP</td>
<td>4174.39</td>
<td>8013256.6</td>
<td>14.5</td>
<td>16.65</td>
<td></td>
<td>3.99</td>
<td>1.5</td>
<td>539</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.13d</td>
<td>WaterCorp/URS</td>
<td>BWWTP</td>
<td>4174.39</td>
<td>8013299.8</td>
<td>17.5</td>
<td>16.65</td>
<td></td>
<td>2.15</td>
<td>4.1</td>
<td>21.5</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.9%</td>
<td>WaterCorp/URS</td>
<td>BWWTP</td>
<td>4174.96</td>
<td>8012662.3</td>
<td>12.8</td>
<td>13</td>
<td></td>
<td>2.05</td>
<td>2.42</td>
<td>1.58</td>
<td>3.71</td>
<td>3.71</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bore Name</td>
<td>Owner/Installed by</td>
<td>Location</td>
<td>Earthing</td>
<td>Borehole Depth (m bgl)</td>
<td>Ground Surface Elevation (m AHD)</td>
<td>Scoured Geology</td>
<td>Wet Season (Hearst's Date: 05/2/2014) Water Level (m AHD)</td>
<td>Wet Season (WaterCorp Date: 05/2/2014) Water Level (m AHD)</td>
<td>Dry Season (Weight's Date: 06/2013) Water Level (m AHD)</td>
<td>Dry Season (Weight's Date: 06/2013) TN Conc (mg/L)</td>
<td>Wet Season (Hearst's Date: 05/2/2014) TN Conc (mg/L)</td>
<td>Dry Season (Hearst's Date: 05/2/2014) Nitrate Conc (mg/L)</td>
<td>Dry Season (Weight's Date: 10/2013) Nitrate Conc (mg/L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------</td>
<td>----------</td>
<td>----------</td>
<td>------------------------</td>
<td>----------------------------------</td>
<td>-----------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3_97</td>
<td>WaterCorp / URS</td>
<td>BWWWTP</td>
<td>417744</td>
<td>8012245 26</td>
<td>13</td>
<td>Silty SAND: fines=fine grained</td>
<td>21</td>
<td>2.53</td>
<td>11.6</td>
<td>148</td>
<td>28</td>
<td>98</td>
<td>156</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3_86b</td>
<td>WaterCorp / URS</td>
<td>BWWWTP</td>
<td>417773.1</td>
<td>8012471.9 13</td>
<td>11.8</td>
<td>Silty SAND: high plasticity</td>
<td>2.15</td>
<td>0.24</td>
<td>0.8</td>
<td>0.8</td>
<td>28</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3_13a</td>
<td>WaterCorp / URS</td>
<td>WWTP</td>
<td>418018.3</td>
<td>8012394.8 11.5</td>
<td>9.37</td>
<td>Silty SAND: high plasticity</td>
<td>2.19</td>
<td>0.37</td>
<td>1.6</td>
<td>1.56</td>
<td>28</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4_13b</td>
<td>WaterCorp / URS</td>
<td>East of WWTP</td>
<td>417902.4</td>
<td>8012340.3 11.5</td>
<td>9.99</td>
<td>Silty Claysy SAND: fine grained</td>
<td>1.61</td>
<td>2.43</td>
<td>7.2</td>
<td>62</td>
<td>34</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4_95b</td>
<td>WaterCorp / URS</td>
<td>WWTP</td>
<td>417765.4</td>
<td>8012285.4 14.5</td>
<td>9.91</td>
<td>SANDSTONE: fine f= fine grained</td>
<td>2.35</td>
<td>0.37</td>
<td>3.4</td>
<td>4.4</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6_13a</td>
<td>WaterCorp / URS</td>
<td>WWTP</td>
<td>417437.6</td>
<td>8012405.5 16</td>
<td>11.29</td>
<td>Clayey SAND: f=fine grained</td>
<td>2.58</td>
<td></td>
<td></td>
<td>188</td>
<td>188</td>
<td>188</td>
<td>188</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7_13b</td>
<td>WaterCorp / URS</td>
<td>Golf Course</td>
<td>416978.7</td>
<td>8012140.8 11.5</td>
<td>10.67</td>
<td>Silty Clayey SAND: high plasticity</td>
<td>2.11</td>
<td>1.31</td>
<td></td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8_13a</td>
<td>WaterCorp / URS</td>
<td>Golf Course</td>
<td>417051.3</td>
<td>8011813.9 13.5</td>
<td>9.85</td>
<td>Silty SAND: high plasticity</td>
<td>2.08</td>
<td>0.51</td>
<td>6.83</td>
<td>64.9</td>
<td>64.9</td>
<td>64.9</td>
<td>64.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bore Name</td>
<td>Owner/Installed by</td>
<td>Location</td>
<td>Easting</td>
<td>Northing</td>
<td>Borehole Depth (m AHD)</td>
<td>Ground Surface Elevation (m AHD)</td>
<td>Scoured Geology</td>
<td>Wet Season (Winter's Date: 03/05/2014) Water Level (m AHD)</td>
<td>Wet Season (Winter's Date: 03/05/2014) Water Level (m AHD)</td>
<td>Dry Season (Weight's Date: 03/02/2014) TN Conc (mg/L)</td>
<td>Dry Season (Weight's Date: 03/02/2014) TN Conc (mg/L)</td>
<td>Dry Season (Weight's Date: 03/02/2014) TN Conc (mg/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>------------------</td>
<td>---------</td>
<td>--------</td>
<td>----------</td>
<td>------------------------</td>
<td>-------------------------------</td>
<td>----------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9_34</td>
<td>WaterCorp Goldie</td>
<td>Golf</td>
<td>41658.2</td>
<td>8011700.9</td>
<td>11.5</td>
<td>10.22</td>
<td>Silty Claysy SAND</td>
<td>2.04</td>
<td>0.35</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2_97</td>
<td>WaterCorp Goldie</td>
<td>WWTP</td>
<td>417620</td>
<td>8012453</td>
<td>28.7</td>
<td>12.63</td>
<td>Pindan Sand</td>
<td>2.72</td>
<td>0.35</td>
<td>2.4</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8_97</td>
<td>WaterCorp Goldie</td>
<td>WWTP</td>
<td>417631</td>
<td>8012274</td>
<td>24.4</td>
<td>12.2</td>
<td>Pindan Sand</td>
<td>2.55</td>
<td>2.56</td>
<td>0.35</td>
<td>9.9</td>
<td>9.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Historical hydrogeological information used to generate conceptual and numerical models

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Storativity/Specific Yield (Sy)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pindan Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic Conductivity (m/d) - Kh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imported Irrigated Area Fill</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pindan Sand</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.7</td>
<td>0.7-3.55</td>
<td>0.3-1.9</td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td>7.5</td>
<td>12 to 23</td>
<td>2 to 4</td>
<td>5 &amp; 15</td>
<td>2 to 42</td>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hydraulic Conductivity (m/d) - Kv
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pindan Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer Thickness (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pindan Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 to 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broome Sandstone</td>
<td></td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyd raidic Gradient (m/m)</td>
<td></td>
<td>0.001</td>
<td></td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge Estimate (m/d) or (%)</td>
<td></td>
<td>4 to 5</td>
<td>1.47 (GL/a)</td>
<td>0.00012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN Discharge Loads into Roebuck Bay (kg/yr)</td>
<td>470</td>
<td>32,826</td>
<td></td>
<td></td>
<td>43,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt Water Interface (m/bgl)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50-100 (below WWTP)</td>
<td>8.5 (below location F &amp; G)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------</td>
<td>--------------</td>
<td>-------------------</td>
<td>---------------</td>
<td>--------------</td>
<td>------------------</td>
<td>---------------</td>
<td>------------</td>
<td>----------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>GWL Fluctuation - Tidal Influence (m)</td>
<td>0.35-0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.36</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>