Curtin University
Department of Applied Geology

# Hydrogeology and Hydrochemistry of the Unconfined Aquifer of the Broome Peninsula

**By**

**Nicholas Wright**
14280605

Honours Manuscript
Curtin University
Perth Western Australia

November 2013

Supervisor: Ryan Vogwill

A Research Project in partial fulfillment of the requirements of the unit Geology Honours Dissertation 400 for Bachelor of Science (Honours) Science.

## List of Contents

## List of Figures



## List of Tables

## Abstract

To further the ongoing investigations in to the Lyngbya blooms in Roebuck Bay a hydrogeological and hydrochemical investigation of the Broome Peninsula was completed with significant results. The unconfined aquifer of the Broome Peninsula contains an 8-12 m thick layer of Pindan Sand underlain by Broome Sandstone. A multifaceted empirical approach was taken to quantify the hydraulic conductivity of the surficial sediments. This suggested a horizontal hydraulic conductivity of 1.7 m/day for the Pindan Sand. Groundwater levels were typically elevated in the centre of the peninsula and were lowest near the ocean. This confirms previous investigations which indicated that groundwater outflow to the ocean occurs on all sides of the Broome Peninsula, excluding the area to the north-east where groundwater inflow from the regional unconfined aquifer occurs. Given that most wastewater disposal sites are south of the centre of the peninsula, any contamination present will be migrating towards Roebuck Bay.

Nutrient contamination was clearly identified and the associated submarine groundwater discharge (SGD) flux was estimated, including the likely range. In most instances these locations were directly linked to the wastewater treatment facility located within Broome. The causal relationship between nutrient contamination and Lyngbya blooms has been well established in previous works. The current study indicates that there is significant potential for nutrients from wastewater disposal in Broome to be contributing to Lyngbya blooms in Roebuck Bay.

**Keywords:** Broome Peninsula, Roebuck Bay, Lyngbya, Groundwater, Nutrients, Submarine Groundwater Discharge.

# 1.0 Introduction

The Broome Peninsula is located in the north-west of the onshore Canning Basin in the south-west of the Dampier Peninsula (Figure 1). The shallow aquifer system of the Broome Peninsula is found within the Quaternary cover of Pindan Sand and the Cretaceous Broome Sandstone. The Pindan Sand is a surficial iron and clay rich silty deposit that unconformably overlies the Broome Sandstone (Department of Water, 2012a). The Broome Sandstone is a laterally extensive unit, about 300 m thick and is the principal unconfined aquifer for much of the West Canning Basin, including Broome (Vogwill, 2003). The town of Broome occurs on the Broome Peninsula and immediately south of Broome is Roebuck Bay, a high value biodiversity asset (Department of Environment and Conservation, 2009) and "the world's most biodiverse intertidal tropical wetland"(Oldmeadow, 2007). The area also has significant indigenous heritage, western heritage, economic and tourism values (Department of Environment and Conservation, 2009).

*Lyngbya Majuscula* or Lyngbya is a form of Cyanobacteria, it is a marine based nitrogen fixing and highly pervasive organism which can be toxic in certain parts of its life cycle (Department of Environment and Conservation, 2009). Lyngbya blooms typically occur due to the presence of elevated concentrations of anthropogenic nutrients (nitrogen and phosphorous) and iron (Estrella, 2013). Since 2005 Lyngbya blooms have occurred on the north shore of Roebuck Bay, suspected to be a result of anthropogenic nutrient pollution from the town of Broome (Estrella, 2013). Lyngbya is a native species in the Broome marine environment (Estrella, 2013) however due to the sustained anthropogenic nutrient contamination large blooms occur which represent a major threat to the biodiversity and long-term sustainability of the Roebuck Bay ecosystem. Roebuck Bay has been declared a wetland of international importance (Estrella, 2013).

In 2012-13 a Broome townsite stormwater study (under final preparation) investigated runoff and nutrient loads entering Roebuck Bay. This study found that nutrient blooms began before any significant local stormwater runoff and that there is an intense seasonal first flush (or shock loading) effect. Consequently it was hypothesised that surface water runoff was not the only cause of nutrients facilitating blooms hence submarine groundwater discharge (SGD) must also be contributing. SGD into the intertidal zone occurs year round, constantly elevating the nutrient levels allowing Lyngbya to persist in greater amounts than under pristine conditions. Actual Lyngbya blooms will occur if the first flush of nutrients from the stormwater occurs when conditions are optimal. To understand and propose remediation of these blooms a greater understanding of groundwater flow and nutrient concentrations is necessary (Vogwill, 2013).

## 2.0 Aim

This manuscript aims to investigate the hydrogeology and hydrochemistry of the shallow aquifer of the Broome Peninsula. Water table elevation and nutrient concentrations will be mapped and nutrient loads discharging to Roebuck Bay will be estimated. To achieve this data was collected from 16 purpose drilled bores at 8 different locations, as well as 6 other existing sites across the Broome Peninsula. All other available groundwater data was compiled and included in the assessment.

## 3.0 Background Hydrogeology

### 3.1 Pindan Sand

Pindan Sand, the surficial sediment cover of the Broome Peninsula, has been deposited by aeolian and alluvial processes (Vogwill, 2003). It has a grain size ranging from fine grained sand to silt with a deep red colour, with the red coloration due to the iron oxide staining of the individual grains and clay content. It is non-water repellent and takes its name from the unique vegetation which dominates the area (Vogwill, 2003). The unit is Quaternary in age and unconformably overlies the Broome Sandstone (Department of Water, 2012a). From pump and slug tests the hydraulic conductivity has been measured to be within the range of 0.3 to 1.9 m/day (Department of Agriculture and Food and Department of Regional Development and Lands, 2013).

### 3.2 Broome Sandstone

The Broome Sandstone is a variable sandstone unit which can be broken down into two major facies, the lower fluvial facies and the upper deltaic facies (Vogwill, 2003). In general this units grain size ranges from very fine to very coarse with the very coarse fraction dominating. These coarse grains are more rounded and spherical than the finer grains which are poorly rounded and have low sphericity (Vogwill, 2003).

The unit contains abundant dinosaur trace fossils (footprints) at multiple locations where it outcrops along the coast (Vogwill, 2003). These were created during the early Cretaceous when a sea regression was depositing large amounts of sediment in the area (Laws, 1984), a favourable environment for the creation of trace fossils. In the south of the Dampier Peninsula lithological logs have been carried out which show in general an upwards fining nature of the Broome Sandstone. The logs also show a consolidated and clay rich upper zone which also has a lower resistivity and relatively high gamma count. Much deeper within the unit are unconsolidated gravels that have higher resistivity and lower gamma counts (Department of Water, 2012b)

Substantial hydraulic data has been obtained for this unit, from slug and aquifer pump tests the hydraulic conductivity appears to range from 2 to 4 m/day (Department of Agriculture and Food and Department of Regional Development and Lands, 2013). Leach (1979) also conducted pumping tests in this unit and found the representative hydraulic conductivity to be 7.5 m/day (Leech, 1979). Aquifer tests in the Broome Sandstone at the horticultural lots (18km north-east of the Broome town site) determined a hydraulic conductivity of 15 m/day with a range from 12 to 23 m/day (Laws, 1984). Leech (1979) also estimated the porosity to be around 30% and recharge from rainfall has been estimated at 6% (Laws, 1984). Based on a hydraulic conductivity of 7.5 m/day (derived from previous investigations (Laws, 1984; Leech, 1979; Vogwill, 2003)) the total throughflow has been estimated to be around 20 GL/year (Holder and Rozlapa, 2009). This unit has been estimated to have a $8x10^5$ GL of water stored (Vogwill, 2003).

### 3.3 Jarlemai Siltstone

This unit underlies the Broome Sandstone and is dominated by siltstone and mudstone with some minor inclusions of sandstone within the lower strata (Laws, 1984). The siltstone itself is light to dark grey and is up to 259 m thick (Department of Water, 2012b). This unit was formed during the Late Jurassic to the Cretaceous throughout a period of marine transgression (Holder and Rozlapa, 2009). The unit is highly impermeable and for our purposes a basement aquiclude to the Broome Sandstone aquifer as per (Department of Water, 2012b), consequentially deeper units will not be discussed. This unit has a horizontal hydraulic conductivity of 0.001 m/day and a vertical hydraulic conductivity of 0.0001 m/day (Cadman et al., 1993). The specific yield for this unit has been estimated to be 3.5% by (Holder and Rozlapa, 2009).

## 4.0 Climate

Broome experiences the influences of three distinct climatic regimes of the Kimberley, “the Northern, the dry interior and the North-Western” (Department of Water, 2012a). While each of these systems influence the local climate Broome is generally considered to be sub-tropical. It is dominated by two seasons the wet season and the dry season. The wet season extends from December to March this is when the vast majority of rainfall occurs, it is also hotter and has a higher humidity. This is opposed to the dry season when a relatively small amount of precipitation occurs, the mean temperature and humidity are also significantly lower (Bureau of Meteorology, 2013). Broome has an annual mean rainfall of 608 mm with an annual potential evaporation of 2700 mm (Bureau of Meteorology, 2013) almost 4.5 times the rainfall. Extreme precipitation events are common during the wet season, these are driven by low pressure systems that often cause substantial property damage and environmental disturbance due to the high wind speeds and flooding. It is these weather systems which are the dominant cause of groundwater recharge in the region (Holder and Rozlapa, 2009). Occasionally the wet season will not deliver significant rain which results in very low aquifer recharge (Department of Water, 2012a).

# 5.0 Methods

## 5.1 Bore Construction

Sixteen bores at eight locations were constructed in and around the Broome town site. These were comprised of a shallow and a deep bore at each location. The bores were constructed in such a manner that drill chips, soil samples, ground water samples and ground water heads could be collected and analysed. The initial shallow bore at each location was drilled with mud rotary to penetrate the saturated portion of the aquifer to a depth of approximately 6 m. In general the shallow bores were between 15 to 20 m in total depth (from surface) depending on the water table and ground surface elevation.

For the drilling of the deep holes air rotary drilling was utilized, this was done to facilitate sediment sampling with minimal contamination. Once below the water table mud rotary was used (to prevent the side walls of the hole from collapsing) and drilling proceeded to 26 m below the water table. This was done to sample the water table significantly deeper than the shallow bore. This was important to assess any vertical changes in groundwater chemistry through the aquifer as well as see if vertical head gradients existed in the aquifer

When the desired depth had been reached the drill rods were removed and 50 mm PVC pipe was lowered down in to the bore. The bottom 6 m of the PVC was slotted to allow water to move into the bore. After the PVC had been lowered the slotted section was surrounded by a fine gravel to prevent the ingress of fine sediments. The top of the slotted sections gravel pack was sealed with a bentonite plug, the hole was then backfilled with natural fill (drill cuttings) to near the land surface where a concrete collar was installed to stop surface water flowing down the annulus. A bore design diagram can be seen in Figure 2.

## 5.2 Lithological Logging

During drilling of the deep bores representative samples of the drill chips were collected and stored at 1 m intervals. Chips were taken from the deeper bore as this contained a deeper stratagraphic section. These chips were collected in trays and logged for hydrogeologically relevant properties, including grain size, mica content, iron content and level of consolidation. To create the visual lithological logs an application called EasyLog by EasySolve run on Microsoft Windows XP was utilised. This application created visual representations of the lithological data which was recorded from the drill chips.

### 5.3 Grain Size Distribution Analysis

Three samples, a top, middle and bottom, were taken from the Pindan Sand at each drilling location, to represent the variation within the unit. These samples were taken from the section of drilling done with air core as to obtain a representative sample. The samples were bagged and transported to The University of Western Australia were the grain size distribution analysis was undertaken using a Malvern Mastersizer 2000. This equipment uses laser diffraction to calculate grain size by recording the scatter of the laser beam as it penetrates the sample. The scatter pattern data is then analysed to determine the grain size distribution. This method of grain size analysis was chosen because it is inexpensive, very rapid compared to manual sieving and determines a full range of grain sizes from 2 mm to sub-micron (Malvern, 2013).

### 5.4 Hydraulic Conductivity Calculation

To calculate hydraulic conductivity an application called SizePerm by EasySolve run on Microsoft Windows XP was used. This application was utilised because it has the functionality to calculate hydraulic conductivity using nine different methods from a grain size distribution. All nine methods of calculating hydraulic conductivity were used on the 24 samples taken from the Pindan Sand. The methods utilised by SizePerm were the Hazen method, Slichter method, Terzaghi method, Beyer method, Sauerbrei method, Kruger method, Kozeny method, Zunker method and the USBR method. All the methods calculate horizontal hydraulic conductivity, this can be simply transformed into vertical hydraulic conductivity by dividing the values by ten (Todd, 1980).

A vital parameter in many of these equations is the $d_{10}$ value, which is defined as the grain size diameter in mm that 10% of the sediment is finer than (Salarashayeri and Siosemarde, 2012). All methods also require the specific gravity (SG) of each grain size group. It was outside of the scope of this project to measure SG for grainsize fractions precisely so it was assumed that the sample was homogenous in this respect. Sand has a SG from 2.63 to 2.67 and clay has a SG of 2.7 to 2.8 (The University of Toledo, 2006) so the SG values are similar and regardless the effect SG has on the hydraulic conductivity calculations should be minimal. A brief description of each of the methods to estimate hydraulic conductivity from grain size distribution is given below, including their limitations, advantages and disadvantages. The descriptions are base mostly on (Rosas et al., 2013), (Rosas, 2013). The formulas for each method can be found in Appendix 1.

*5.4.1 Hazen method*

This method was one of the original methods for estimating hydraulic conductivity from grain size distribution. Consequentially it has been widely cited in the literature and other methods are often compared to it. The ideal $d_{10}$ range for the Hazen method is between 0.1 mm and 3 mm. This method has been validated for the following depositional environments, beach (generic), beach (siliciclastic), beach (carbonate) and dune (generic) (Rosas et al., 2013).

*5.4.2 Slichter method*

Another early method for calculating hydraulic conductivity was the Slicher method, this method is one of the most applicable formulas for the Pindan Sand grain size distribution. The Slichter methods ideal grain size encompasses sediments with a $d_{10}$ value between 0.01 mm to 5 mm, which allows it to be applied to many different sedimentary units (Rosas et al., 2013) including the Pindan Sand.

*5.4.3 Terzaghi method*

This method relies on a large grain size (Rosas et al., 2013) which is not present in the Pindan Sand. It has been shown in previous investigations that this method is not well adapted for many environments (Rosas et al., 2013). However it was suggested that this method is well suited for streambed sediments (Lu et al., 2012).

*5.4.4 Beyer method*

This method has been proposed for the following environments Beach (siliciclastic), Beach (mixed), Beach (carbonate), Dune (general), Dune (interior), Offshore (siliciclastic), River (general) and River (Wadi) by previous investigations (Rosas et al., 2013). According to this it should give a good estimate of the hydraulic conductivity for the Pindan Sand. This method also has a tight $d_{10}$ parameter of between 0.6 mm and 0.06 mm (Rosas et al., 2013). Unfortunately the Pindan Sand $d_{10}$ value is still significantly lower than 0.06 mm.

*5.4.5 Sauerbrei method*

This method is best suited to $d_{17}$ values smaller than 0.5 mm and works best on sand, sandy clays, coastal dunes and mixed offshore sediments (Rosas et al., 2013). It has also been suggested that this method is adequate to use with streambed sediments (Lu et al., 2012). This makes this method very applicable to the Pindan Sand samples.

*5.4.6 Kruger method*

This method was developed to model hydraulic conductivity of water at 0°C through a permeable medium (Vogwill, 2003). For this specific situation it is not very helpful because in the Broome climate groundwater temperatures of 0°C are essentially never experienced (Bureau of Meteorology, 2013). This method was included for the sake of being comprehensive, comparison and as a data check. This method is most reliable when applied to fine grained sediments deposited offshore (Rosas et al., 2013).

*5.4.7 Kozeny method*

This method is one of the most widely used equations for finding hydraulic conductivity. It is not appropriate for soils with high clay content or for soils with an effective grain size grater than 3 mm (Takounjou et al., 2012). This method has been experimentally applied to many different environments and found to be sub par when compared to other methods (Rosas et al., 2013).

*5.4.8 Zunker method*

This method is been recommended as a good way of estimating hydraulic conductivity in fine to medium grain sands (Morin, 2006). It has also been recommended to be used on mixed beach and most offshore environments (Rosas et al., 2013).

*5.4.9 USBR method*

The origin of this method is unclear (Vienken and Dietrich, 2011), however it is known that this method is best suited for calculating hydraulic conductivities for medium grain sands. To accomplish this it uses a $d_{20}$ value as opposed to the more common $d_{10}$ (Rosas et al., 2013).

**5.5 Water Level Measurements**

At each of the sixteen monitoring bores and two Shire of Broome ex-production bores the head of the water table relative to the Australian Height Datum (AHD) was measured, at least 24 hours after air lifting and sampling. This was done with the use of an electronic water level meter and measurement of the groundwater depth relative to the ground level. At a later date all the bores were surveyed using a differential global positioning system with an error of less than 30 mm (Portz, 2013). This was also done to measure the ground level height above sea level with an error of less than 40 mm (Portz, 2013).

**5.6 Water Sampling**

The two bores constructed at each location were used to sample groundwater in the upper (0-6 m) and lower (20-26m) levels of the saturated part of the aquifer. All bores were air lifted for at least half an hour before samples were taken, to minimise contamination and ensure adequate bore development.

Water samples were also taken from four Shire of Broome production bores (groundwater levels affected) and groundwater level measurements were taken from two historic production bores. These samples were then tested onsite for Electrical Conductivity (EC), pH and alkalinity. A 50 ml sample was filtered and frozen (dissolved nutrients) and another (total nutrients) was just frozen. These samples were sent to The University of Western Australia Water Quality Laboratory for analysis of nitrate, total nitrogen (TN), ammonia, total phosphorous (TP) and phosphate. The analysis methodologies for these tests are explained in more detail below.

In some samples filtration took an extended period of time because of the high amount of suspended fine sediments. When it was not possible to filter a sample immediately it was left stationary for a maximum of 20 hours to allow the sediments to fall out of suspension before filtering. This was noted in the database in case it had an effect on the results. All the chemistry data can be found in Appendix 2.

**5.7 Measurement of Field Parameters**

The EC, pH and temperature of the water was measured with a WTW pH/Cond 340i. This was done immediately after sample collection to minimise any error associated with sample stagnation. EC was also converted in to Total Dissolved Solids (TDS) in mg/L by multiplying the EC values by 1000 and then by 0.67 as per (Atekwana et al., 2004).

A digital titration was done with a HACH Digital Titrator model 16900 kit from each bore to determine total alkalinity, this required a 50 ml sample of filtered water. After filtration a bromcresol green methyl red indicator was added to the sample. Then 1.6 N $H_2SO_4$ acid was slowly added to the mixture with a hand held digital titration unit until the mixture turned from green to red at a pH of 4.5. The digital readout of the titration unit was recorded and then the HACH user manual was used to convert the values to find the Alkalinity of the samples.

**5.8 Nutrient Analysis**

After the samples were collected they were frozen (within 4 hours of collection) and transported to The University of Western Australia Environmental research and water quality laboratory. From the date of collection to the date of analysis a maximum of 2 weeks had transpired. Analysis was completed using a Lachat flow-injection analyser. For TN and TP concentrations the Persulphate method was used on the unfiltered samples. Nitrate was analysed using the standardised cadmium reduction method (American Public Health Association et al., 1999).

### 5.8 Groundwater Data Interpolation Technique

EasyContour 2.9 (TYevolution, 2013) (run on Apple OS X 10.9) was used to generate the contour maps of the hydrochemical distribution. The maps were interpolated from the data using the Modified Shepard Method (constant nodal function) which is a inverse distance weighting method as used by (Srinivasan and Natesan, 2012) This method differs from the Shepard method in that it only uses nearest neighbours in the interpolation of the data set. This method was used as it was found to give a fair representation of the data.

### 5.9 Roebuck Bay Groundwater Discharge

The SGD into Roebuck Bay was calculated using Dupuit's modification of Darcy's Law (Kasenow, 2006). Two input variables were varied across the range of likely values to construct a matrix with the range of possible discharges. Hydraulic conductivity was altered from 1 m/day (lower limit), 7.5 m/day (best estimate derived from previous investigations), 15 m/day and 25 m/day (upper limit). These values were chosen based on the documented range of hydraulic properties within the Broome Sandstone/Pindan Sand (Laws, 1984), (Leech, 1979), (Vogwill, 2003) and (Department of Agriculture and Food and Department of Regional Development and Lands, 2013). The other variable was the fresh water aquifer depth discharging to the Bay. The ranges assumed (based on the results of this study) were 30 m (lower limit), 40 m (best estimate) and 50 m (upper limit).

The Roebuck Bay coast along the south side of the Broome Peninsula was split into 4 sections (Figure 3) to allow for the heterogeneity in groundwater gradient and pollutant concentrations. Bores C,F,H,G and the Shire bores were used as estimates for groundwater gradients and pollutant concentrations. Technically coastal sections 3 and 4 do not directly discharge into Roebuck Bay however the nutrients from the SGD in these locations is highly likely to end up in Roebuck Bay via the tidal creeks.

## 6.0 Results

### 6.1 Geological units

The Pindan Sand ranged from 8 m to 12 m in thickness and had a medium to very fine grain size with a high iron content. On the Broome Peninsula this unit had a small clay fraction normally less than 2% by mass. Depositional environments were identified from the grain size distribution data. Samples contained a mixture of sediments deposited from aeolian and alluvial processes, this is similar to the result of a previous investigation (Vogwill, 2003).

At the interface between the Pindan Sand and the underlying Broome Sandstone was a gravel to boulder sized highly ferruginised conglomerate, a stratigraphic unconformity. The conglomerate was highly variable in respect to clast grain size, grain composition, roundness, sphericity and sorting. Clasts of both ironstone and silicified sandstone were common and often highly cemented. The gravel lag was found outcropping along the tip of the Broome Peninsula interbedded with the Pindan Sand and the Broome Sandstone, Figure 4 shows an exposed section of the gravel within Pindan Sand.

Beneath the Pindan Sand and its basal conglomeratic lag was the Broome Sandstone, the upper part of which is deeply weathered. Ferruginised material was found as nodules within this upper deeply weathered Broome Sandstone. These nodules are resistant to weathering hence are often found extruding out of the surrounding less resistant deeply weathered Broome Sandstone. Cliff sections were pitted on erosional surfaces where the nodules had been eroded away. Some nodules were solid and others were hollow shells. Hollow nodules had prominent iron oxide rims that became obvious when broken open.

The Broome Sandstone had a highly variable iron content which was expressed in the colour of the sandstone. The high concentrations of iron were normally found in the top of the strata. Once through the weathering profile and into fresh Broome Sandstone it was found to be generally fine grained with varying amounts of mica. Throughout this unit were lenses of siltstone which were seemingly randomly distributed. The unit varied from friable to well silicified depending on location and depth and it was normally intercepted at a depth of around 15 m from the surface. Visual representations of the lithological logs and raw chip data can be found in Appendix 3.

**6.2 Grain Size Distribution**

The grain size distribution data of the Pindan Sand, Table 1, was transformed into a linear graph, Figure 5. This grain size distribution graph suggests five distinct grainsize groups, three with a normal distribution and two with a bimodal distribution, Figure 6. Figure 7 shows the cumulative grain size distribution, with intervals indicating the grain size ranges. The data that was used to construct this graph was also used to calculate the hydraulic conductivity of the Pindan Sand. It was also found that the mean $d_{10}$ value for these samples was 0.02 mm.

**6.3 Hydraulic Conductivity**

Table 2 shows the results of different methods for calculating the hydraulic conductivity for each of the Pindan Sand samples. Figure 8 shows that most methods produce similar trends but the Hazen, Beyer and Sauerbrei methods constantly produce relatively higher values. The Kruger, Kozeny and

Zunker methods are on the other end of the spectrum producing low values. The Slichter and Terzaghi methods both produce values which are close to the mean. The USBR method generated values which had a different trend to the other methods and did not vary far from 1.5 m/day.

**6.4 Water Table**

The regional groundwater elevation map, Figure 9, shows the morphology of the water table in the Broome Peninsula and surrounding area. Based on this morphology, groundwater appears to be discharging along the coast of the Broome Peninsula, the coast north of Broome and into Roebuck Plains to the south-east of Broome. It is also evident that groundwater flows into the peninsula from the relative high in the north-east.

The A to H groundwater head cross section, Figure 10, shows how the groundwater heads vary with depth in the Broome Peninsula. It indicates that ground water is moving from Location A in the north-east towards H in the south-west. It also shows that the horizontal gradient decreases as it approaches Location H, which has been shown to be an area of significant local runoff derived recharge, Figure 11. The D-C cross section Figure 12 reinforces that there will be groundwater discharge on both sides of the Broome Peninsula. Vertical head gradients were present but minor compared to horizontal gradients. All collected water table data is in Appendix 4.

**6.5 Electrical Conductivity**

Groundwater with the highest EC is located in the deep bores in locations F and G, at 18.5 mS/cm and 21.5 mS/cm respectively. These locations are 700 m away from each other and just over 1000 m from the coast. When the Ghyben-Herzberg (Kasenow, 2006) relationship (saline groundwater depth is 40 times the height of the water table above sea level) is applied to this area it appears that the saltwater interface should be about 85 m below the surface. The EC values suggest a significantly shallower interface at approximately 40m, hence why this was used as the approximate thickness of fresh groundwater discharging into Roebuck Bay.

The shallow bore at Location D had a relatively high EC value (5.44 mS/cm) when compared to the other shallow bores, only being exceeded by the shallow bore at Location F (8.15 mS/cm). Location H had very low values for both the deep and the shallow bores. Figure 13 and Figure 14 are cross sections showing the vertical distribution of EC throughout the peninsula. These values were also converted into TDS using a common conversion factor (Atekwana et al., 2004).

### 6.6 pH

The shallow and deep aquifer pH maps, Figure 15 and Figure 16 respectively, show that pH is neutral across the peninsula and that there was very little variation between the shallow and deep bores. The greatest vertical variation at one site occurs at Location C which had a deep pH of 7.83 and a shallow pH of 7.32. A relatively high pH of 8.2 occurs in the shallow and deep parts of the aquifer in the centre of the peninsula. These were the only values that were found to be outside the 6-8 range that is generally considered neutral, however 8.2 is essentially still neutral.

### 6.7 Alkalinity

It was found that the mean deep bore alkalinity values were higher than that of the shallow bores, 277 mg/L and 238 mg/L respectively. The collected values in general were found to be elevated with the highest levels being greater than 600 mg/L. There was no observable correlation between the shallow and deep values at any of the locations.

### 6.8 Nitrate

The shallow and deep nitrate distribution maps, Figures 17 and 18 respectively, show a general trend of high values running down the southern side of the centre of the peninsula in a south-west orientation. This trend is more obvious, and concentrations are greater, deeper in the aquifer. The highest points are located around the wastewater treatment facility and Broome Golf Course. Nitrate values are only high in the shallow bores around locations A, B and G. There are also high groundwater nitrate concentrations to the north-east of Broome, likely due to the presence of cattle yards. Location C had significantly higher values in the deep aquifer than in the shallow. There is a very strong correlation between nitrate and TN (correlation determination of 0.99+) this relationship can be observed in Figure 19.

### 6.9 Ammonium

The concentrations of ammonium in most of the samples was very low. It occupied less than 1% of the TN in most locations. The only major exception was location E which had an anomalous value of 143 ug/L, 14% of the TN in that location.

### 6.10 Total Nitrogen

The TN distribution maps show that the highest concentrations occur in the peninsula in an elliptical distribution extending in a south-west north-east direction Figure 20 and Figure 21. This is evident in both shallow and deep bores, but greater concentrations occur in the deep sites. The highest concentrations are located around the wastewater treatment facility and Broome Golf Course. Relatively low concentrations occur between locations D and E and high concentrations occur at locations A and B, this is seen in both shallow and deep distribution maps. There are also two highs located to the north-east of Broome these values were anomalous in comparison to the other values in the area and indicate a local source of TN. About 74% of the TN in the shallow bores and 85% of the TN in the deep bores was in the form of nitrate.

**6.11 Phosphate**

The phosphate values were found to represent about 70% of the TP in the deep bore water samples and about 50% of the TP in the shallow bores. It was also found that the correlation between the phosphate and TP was less in the shallow bores, this had a coefficient of determination of 0.16. The relation between phosphate and TP in the deep bores was much stronger with a coefficient of determination of 0.46.

**6.12 Total Phosphorous**

The TP was generally found in higher concentrations in the shallow bores, Figure 22, than in the deep bores, Figure 23. The only exception to this was Location D where significantly higher values occurred at depth. Location A had a much higher shallow value compared to that of Location B. This suggests a localised TP source in the vicinity of Location A. There is also an area of elevated TP concentration between locations C and F, proximal to the wastewater treatment facility and the Broome Golf Course. The most significant high in the deep TP distribution map was located to the north-east of Broome. These values were anomalous in comparison to the other values in the area and indicate a local source of TP or could relate to inaccurate sampling or analysis methods from the omitted data provider.

**6.13 Roebuck Bay Discharge**

Table 3 shows the possible range of SGD in to Roebuck Bay. Using the best estimate for hydraulic conductivity of 7.5 m/day and 40m depth SGD is about 20,000$m^3$/day or 7.2 gigalitres/year. This ranges from 0.7 to 30 gigalitres/year depending on the depth of the fresh water in the aquifer and the hydraulic conductivity. Assuming a TN and TP concentration in each Dupit-Darcy's Law calculation allows the total nutrient discharge to be estimated as can be seen in Table 4. The best estimate of TN is 43 tonnes/year and the range is 4.3 to 179 tonnes/year. The best estimate of TP is 0.39 tonnes/year and the range is 0.0 to 1.6 tonnes/year. The TN concentrations across the peninsula are about twice that of background values while TP concentrations were only mildly higher than background.

# 7.0 Discussion

## 7.1 Geological units

### *7.1.1 Pindan Sand*

The Pindan Sand was found in the upper part of the subsurface in all the bore locations. It appears to be derived from two major depositional processes as evident from its grain size distribution, in agreement with previous investigations (Vogwill, 2003) (Todd, 1980). These are aeolian and flood derived sediments (Todd, 1980) which will be discussed in further detail in the grain size distribution section. All of the Pindan Sand grain size samples were also plotted in a Shepherd ternary diagram Figure 24 as is commonly done (Poppe and Eliason, 2008), which showed that all bar one of the samples were classified as sand. The one outlier was from the bottom of the Pindan Sand in Location E, this sample plotted as a clayey silt which was expected based on visual analysis of the sample.

In general the differences within the Pindan Sand were small and difficult to identify, the unit is homogenous in hand sample. This unit had a mean hydraulic conductivity using the Hazen method of 1.7 m/day horizontally and 0.17 m/day vertically. The vertical hydraulic conductivity was calculated from the horizontal hydraulic conductivity using the 1:10 ratio described in (Todd, 1980). This is similar to the results from (Holder and Rozlapa, 2009) which stated the horizontal hydraulic conductivity of 1 m/day and vertical of 0.1 m/day.

Gravel sized highly ferruginised sandstone lag was encountered at the interface between the Pindan Sand and Broome Sandstone. This lag was discovered also along coastal outcrops. It is surmised that this unit was derived from erosion of a regolith profile, with course sediment being left behind while fine material was transported away. However the origins are unable to be conclusively determined, to do so requires further study.

### *7.1.2 Broome Sandstone*

The Broome Sandstone varied in colour from white to purple to yellow to red, due to iron content and degree of regolith development. Due to the drilling method used no samples were available for grain size analysis or detailed lithological assessment. This resulted in no hydraulic conductivity calculations for the unit however this has been covered previously (Leech, 1979), (Laws, 1984), (Vogwill, 2003) and (Department of Agriculture and Food and Department of Regional Development and Lands, 2013). Individual facies and subfacies were difficult to identify within the Broome Sandstone due to the mud rotary drilling method used. The mild range of mineral composition and grain size within unit suggested a variable depositional environment, potentially from the Deltaic Facies (Vogwill, 2003).

Reaffirming this were lenses of siltstone which were seemingly randomly distributed and probably related to the transitional depositional environment of the Deltaic Facies (Vogwill, 2003). However with the lack of evidence of structural features it is very difficult to assess depositional environment in detail.

### 7.2 Grain Size Distribution

When the grain size distribution data was plotted as a linear graph it became obvious that there were five distinct distributions these can be seen in Figure 6. These five distributions can be explained with two distinct depositional environments. The first of the two was likely aeolian derived and the second was likely flood derived. All of the five distributions show different ratios of these two styles of deposition and each is discussed below.

#### *7.2.1 Distribution 1*

This distribution was very consistent and had the closest form to a standard distribution. All three samples which composed this were taken from Location C at different heights. The only mild variation within these three samples was the top sample which was relatively lacking a small amount of finer material (Figure 5), a common theme amongst all of the locations. This relative lack of fine grained material is potentially a product of aeolian or fluvial surface processes removing fine material and/or grain sorting during groundwater recharge causing the fine material to migrate downward. The aeolian nature of the surficial sediments was particularly evident at Location C, which was located within a vegetated sand dune.

#### *7.2.2 Distribution 2*

This distribution shows a significantly wider grain size range than Distribution 1, but as the modal grain size is in the same vicinity as Distribution 1 it is likely to be derived from a similar process. These samples do however have a larger coarse fraction, this coarser material has likely been delivered by a higher energy process. This is probably due to the process of rapid overland flow known as sheet wash. Broome has dramatic flooding events in the wet season, hence this coarser material has likely been deposited by runoff. The effect of this is more evident in the bimodal distributions (4 and 5) described below.

#### *7.2.3 Distribution 3*

This distribution is similar to Distribution 2 but with a greater variability and a mildly coarser modal grain size. This distribution appears to be a midpoint between the two depositional regimes (aeolian and sheet wash) showing characteristics of both. These being the initial steep upward climb of the grain size distribution of the aeolian processes and the very wide distribution of the sheet wash.

*7.2.4 Distribution 4*

This distribution is the first of the bimodal grain size patterns, which is similar in the early part of the grain size curve to Distribution 2 but with a broader range. This distribution was found in samples taken from the medium to deep parts of the Pindan Sand. The gradient flattening event at 500 microns (also seen in Distribution 5) suggests a greater fluvial influence in the depositional regime.

*7.2.5 Distribution 5*

This distribution is somewhat an inverse of Distribution 4. These samples have a grain size peak at 500 microns after an initial lack of fine material to 200 microns. This distribution is dominated by sheet wash sediment transport as can be seen by the coarse modal grain size peak and general broad distribution.

**7.3 Hydraulic conductivity**

Hydraulic conductivity was calculated using nine different methods. Figure 8 shows that the Hazen, Beyer and Sauerbrei methods give very similar results. According to the literature (Rosas et al., 2013) the Sauerbrei method should be the most appropriate for Pindan Sand, consequentially the results produced from this method are what the hydraulic conductivity estimates used in the study are based on. The USBR method returned values that were typically unlike that of any other method and was not recommended for use in grain size distributions like the Pindan Sand. The Terzaghi method produced consistent results, in-between that of the Beyer and the Slichter methods, generally closest to the mean. All nine methods were included for the sake of future comparison and completeness.

**7.4 Water table**

The water table elevation map that was constructed is similar to those from previous investigations in the area (Water Authority of Western Australia, 1994), (Rockwater, 2008) where there was overlap. A significant proportion of the data which was used to create the regional groundwater table map was collected by a third party under confidential conditions, hence many data points have not been shown. The data points that were not shown were located out of town and hardly affected the groundwater model within the study area. This third party data was collected during a variety of dates, so some of the data points used to create the regional water table map Figure 9 may be mildly inaccurate. Changes in groundwater usage, seasonal fluctuations and groundwater recharge would have all caused the water table to vary (Holder and Rozlapa, 2009). The water table elevation and chemistry should not have changed significantly, over the time frame from 2008 to 2013 that the included data has been collected. Another source of groundwater level error could have come from tidal influences on the groundwater levels in bores near the coast, but it was outside the scope of this project to address this.

**7.5 Geochemistry**

Only very limited consistent and systematic recordings of geochemical data could be obtained from within the Broome Peninsula. This lack of consistent time series groundwater geochemical data makes it very difficult to determine seasonal variation and long term trends. The only consistent long term geochemical data that could be found was surrounding the wastewater treatment facility. This information was not helpful in determining seasonal variation and long term trends as the area has such elevated water table levels and high values of nutrients from localised pollution.

**7.6 Electric Conductivity**

Most of the locations in the peninsula had significantly higher EC values in the deeper bores compared to that of the shallow bores, this was due to the presence of the salt water-fresh water interface. Locations F and G both show very high EC values in there deep bores due to the proximity of the saltwater interface. This is backed up by the surface water runoff map, Figure 11,which shows the surface flow paths based on the topography. Due to the presence of divergent flow away from Locations F and G it is suggested that a reduced amount of recharge is occurring in these locations. This would reduce groundwater levels which would cause upwelling of the saltwater interface due to reduced groundwater head.

Location D has a significantly higher shallow EC value when compared to the deep bore, as can be seen in Figure 14. This could be related to salt spray from the ocean depositing salt on the land surface. As natural recharge occurs salts are redissolved and transported into the shallow depths of the aquifer where they then follow the normal discharge path north-west to the ocean. This is backed up by the prevailing winds rose diagram Figure 25. This diagram shows the 60%+ of the winds recorded at 9 am are traveling east or south-east which would deliver saltwater spray inland towards location D. The more south easterly locations within the peninsular do not show this salt spray effect. These locations are influenced by other more local forces such as high infiltration from runoff and or irrigation (diluting the salt) or high runoff transporting the surface salt away. Conversely this high EC at location D could be related to the proximity of this site to a part of the salt water interface known as the subterranean estuary (Robinson et al., 2006) where saline water overlies freshwater.

Location H had a very low EC value in both the shallow and deep bores. This is most likely a result of the large amount of recharge experienced in this area. This recharge is derived from the pooling of the runoff in the area Figure 11. This recharge would be suppressing the saltwater interface deeper in to the Broome Sandstone as can be observed in Figure 13.

### 7.8 pH

There was very little variation within the groundwater pH levels, this could be a result of the high alkalinity in the region providing a large amount of pH buffering capacity. The only significant outlier was site B where both shallow and deep bores received a pH value of 8.2. This is likely related to the irrigation of wastewater depositing large amounts of alkaline material.

Away from any anthropogenic influences in the north-east of the study area the shallow aquifer has a background pH of 6.7 while that of the deep aquifer is 6.4. This has been incorporated in the pH mapping, so given that the shallow map has a higher background value there is a tendency for the shallow aquifer map to have a greater pH. This could also be related to geochemical processes such as nitrification/dinitrifcation however more data is required to make a conclusive analysis.

### 7.9 TDS and Alkalinity

Local geology can play a large role in the alkalinity of groundwater (Appelo and Postma, 2005) . Geological units such as limestone can influence alkalinity as carbonate minerals are dissolved and carried within the water. The geology of the Broome Peninsula is not limestone based and only the Deltaic Facies within the Broome Sandstone showed significant amounts of carbonate material (Vogwill, 2003). Some shell fragments within the Pindan Sand have also been found, notably at Bore C, dissolution of these shells could also contribute to alkalinity.

Groundwater alkalinity could also be affected by anthropogenic contamination such as landfills. There has been speculation of a historic landfill in the vicinity of Location A which could explain elevated levels of alkalinity. No documentation could be found supporting this claim but it is colloquially confirmed by multiple sources. Water being used to irrigate public open space from the wastewater treatment facility is elevated in alkalinity, derived from soaps and detergents which pass through the facility. In other studies (Verbanck et al., 1989) alkalinity concentrations in wastewater were approximately 1.5 to 2 times the local tap water. This shows the distinct effect of anthropogenic impacts on alkalinity.

The Cable Beach production bore had very low TDS and a fair alkalinity level. The deep bore at Location H also had very low TDS in comparison to alkalinity, potentially the effect of groundwater recharge in this location dissolving carbonate minerals present in the coastal sand dunes (Oldmeadow, 2007) or the presence of wastewater. Locations F and G both have slightly reduced alkalinity values and very high TDS values when compared to the other locations. This is potentially a result of the saltwater interface upconing in the middle of the peninsula. The shallow bore at Location F is also an outlier this is because of the high TDS, again potentially due to saltwater interface upconing.

**7.10 Nitrogen Species**

TN is a measurement of all forms of nitrogen, the prominent form in the study area was nitrate. Large concentrations were found in multiple locations throughout the study area specifically in the deep bores at location A, C and F .One value of nitrate was as high as 20,000 ug/L which is two orders of magnitude greater than the ANZECC trigger value for marine ecosystems in the tropics of Australia (Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, 2000). These high concentrations of Nitrate in the groundwater are very detrimental in respect to the marine environment when they discharge via SGD.

Nitrogen in the form of nitrate in highly concentrated levels within the environment can lead to serious impacts. It is toxic to most marine life and can cause death by methemoglobinemia in humans (Kross et al., 1992). Nitrate is also very mobile once it has entered the ground water. The Australian Drinking Water Guidelines recommend that water with nitrate and nitrite levels over 100 mg/L should not be consumed (Department of Health, 2011), this is breached in many parts of the Broome Peninsula. Within Broome two major contributing factors to nitrate pollution have been identified, these are the wastewater treatment facility and sites irrigated with the by-products of the wastewater treatment facility Figure 26. Other sources of contamination may be present but are insignificant in the context of the apparent widespread contamination from wastewater.

The correlation between locations where treated wastewater is used to irrigate and high TN (and nitrate) values was found is very strong, this can be observed in Figure 27. A prime example of this can be seen in the bores at locations A and B. The multiple wastewater treatment facility breaches in the 1990s (Rangelands NRN Western Australia et al., 2013) are also responsible for some of the very high values. When these breaches of the facility occurred vast amounts of unprocessed wastewater was flushed directly into Roebuck Bay and the surrounding dunes, this can be seen in Figure 28. The effect of this can still be observed in the deep bore at Location C.

The two distinct highs located to the north-east of Broome are from some of the bores used to create the background values. However the data which caused these highs was removed from the background value as they were not seen to be giving a fair representation of the aquifer. Both the data points which created these highs were located in the drainage path of a cattle holding yard. These yards are probably the source of these high nitrate readings in the top of the aquifer.

### 7.11 Phosphorous Species

It is evident that in Figure 22, the shallow TP distribution, that there is a tendency for phosphorous to be in high concentrations in the middle of the Broome Peninsula. This trend is less prominent in the deep distribution Figure 23. The shallow map also shows three major highs, these are located near the wastewater treatment facility/Broome Golf Course, Location E and Location A. All bar one of the samples collected exceeded the TP guidelines for water being discharged onto marine environments in tropical Australia (Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, 2000).

There is a distinct correlation between the locations associated with wastewater usage and those with high TP values especially in the shallow aquifer, this relationship can be observed in Figure 29. The general trend for the TP in the shallow bores was high in the centre of the peninsula with a very distinct high near the wastewater treatment facility. It is likely that this second high is associated with the 1990s breaches and ongoing operations. These breaches also appear to be evident in the deep bore at Location C. Some locations show significantly lower values in the deep bores compared to the shallow bores. This is probably due to advective dispersion of TP as it migrates downwards.

Some locations appear not to have a direct TP source but still have significant TP concentrations, this is apparent in locations F and H. This could be a result of a distant point contamination source such as the waste water irrigated cricket oval located 1.4 km away in a north-easterly (up gradient) direction. It may also be related to waste water disposal dispersing phosphorous over the entire shallow aquifer of the peninsula.

### 7.12 Roebuck Bay Discharge

Quantifying the SGD into Roebuck Bay is a crucial part of understanding Lyngbya blooms. The Dupuit’s modification of Darcy’s law was used to estimate SGD as it is well adapted to unconfined aquifers (Kanenow, 2006). With the hydrochemical and hydrological data collected it was possible to estimate the amount of nutrient pollution being discharged via SGD into Roebuck Bay. The range of values calculated for discharge to Roebuck Bay represents the range of possible nutrient loads, bearing in mind that biogeochemical reactions can occur in the subterranean estuary which could decrease, but not eliminate, the actual load entering the Bay (Robinson et al., 2006). Two of the major assumptions made while calculating nutrient loads in SGD were that the water table along the coast was 0 m relative to the AHD and that the pollutant concentration data collected from the bores was representative of the aquifer in the surrounding area. More data would help confirm these values. Regardless the highly elevated concentrations of nutrients within the SGD are a significant contributing factor in the ongoing Lyngbya blooms within Roebuck Bay.

## 8.0 Conclusion

The unconfined aquifer of the Broome Peninsula is made of an 8-12 m thick layer of Pindan Sand underlain by Broome Sandstone. Grain size analysis of the Pindan Sand suggests that there were two distinct processes that deposited this unit, these were aeolian and alluvial. Additionally from this data the hydraulic conductivity was estimated to be 1.7 m/day. Low in the Pindan Sand was an interbedded gravel lag which was highly variable. Below this was the Broome Sandstone which was found to be variable in respect to composition and cohesion.

There are multiple sources of nutrient pollution within the Broome Peninsula. Almost all of these pollution sources have been linked directly to the wastewater treatment facility or to disposal sites of the by-products of the facility. This pollution has a highly heterogeneous distribution within the aquifer. With help from the nutrient pollution and the groundwater contour maps the possible range of the SGD flux and the total nutrient discharge in to Roebuck Bay was determined and is very significant in the context of Lyngbya blooms in Roebuck Bay. With the current groundwater contamination it is suggested that the groundwater within the Broome Peninsula is not consumed in any quantities as it contains very high levels of nutrients (potentially with other toxins or pathogens) which could be detrimental to health.

## 9.0 Recommendations

Based on the outcome of this study, the following recommendations can be made.

- Detailed assessment of groundwater quality and nutrient dynamics in the subterranean estuary is urgently needed to assess the nutrient load discharging into Roebuck Bay.
- Radon and radium isotope testing of seawater from Roebuck Bay to validate the SGD results.
- Ongoing sampling of the constructed monitoring bores, including the use of high resolution data loggers to assess timing and magnitude of recharge events.

- Vast reduction or termination of the use of wastewater as irrigation within the Broome Town Site.
- Preventative steps to eliminate the chance of the wastewater treatment facility breaching in the future.

## 10.0 Acknowledgements

The Kimberley Branch of Rangelands NRM funded this work. My supervisor, Ryan Vogwill is thanked for acquiring the funding, his supervision, editing and guidance. The Department of Parks and Wildlife Broome office, in particular Darren Stevens, is thanked for arranging accommodation and transport during the time spent in Broome as well as funding the surveying of the bores. The Shire of Broome is thanked for their cooperation and assistance in the construction of the monitoring bores and sampling of their operational bores. Nyamba Buru Yawuru ltd is thanked for their cooperation and assistance in the cultural monitoring of the construction of the monitoring bores.

## 11.0 References

American Public Health Association, American Water Works Association, Water Environment Federation, 1999. Standard Methods for the Examination of Water and Wastewater, in: American Public Health Association, American Water Works Association, Water Environment Federation (Eds.).

Appelo, C.A.J., Postma, D., 2005. Geochemistry Groundwater and Pollution. A.A. Balkema Publishers, New York.

Atekwana, E.A., Atekwana, E.A., Rowe, R.S., Werkema Jr, D.D., Legall, F.D., 2004. The relationship of total dissolved solids measurements to bulk electrical conductivity in an aquifer contaminated with hydrocarbon. Journal of Applied Geophysics 56, 281-294.

Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand, 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality,, in: Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand (Eds.).

Bureau of Meteorology, 2013. Climate statistics for Australian locations. Bureau of Meteorology.

Cadman, S.J., Pain, L., Vuckovic, V., Poidevin, S.R., 1993. Canning Basin, in: Department of Primary Industries and Energy Bureau of Resource Sciences (Ed.). Geoscience Australia.

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

Department of Environment and Conservation, 2009. Ecological Character Description for Roebuck Bay, in: Department of Environment and Conservation (Ed.).

Department of Health, 2011. Nitrate in Drinking Water, in: Department of Health (Ed.). Department of Health,, Perth.

Department of Water, 2008. Study for Broome Groundwater Management Plan Review, in: Water, D.o. (Ed.).

Department of Water, 2012a. Broome Water Reserve, in: Department of Water (Ed.). Department of Water, Perth.

Department of Water, 2012b. Groundwater resource review Dampier Peninsula, in: Department of Water (Ed.). Department of Water, Perth.

EasySolve, 2013. SizePerm.

Estrella, S.M., 2013. Effects of nutrient enrichment and toxic Lyngbya blooms on benthic invertebrates and migratory shorebird communities of Roebuck Bay Ramsar site. The University of Western Australia, The University of Western Australia.

Google, 2013. Google Earth, 7.1.1 ed. Google.
Holder, K., Rozlapa, R., 2009. West Canning Basin Model Design Report, in: Department of Water (Ed.). Department of Water.
Kanenow, M., 2006. Aquifer Test Data: Analysis and Evaluation Water Resources Publications.
Kasenow, M., 2006. Aquifer Test Data: Analysis and Evaluation Water Resources Publications.
Kross, B.C., A.D, A., L.J, F., 1992. Methemoglobinemia: nitrate toxicity in rural America. American Family Physician 42, 5.
LandCorp, 2009. Report for Broome North, Local water management strategy.
Laws, A.T., 1984. Availability of Groundwater for Horticultural Lots - Broome Area, in: Geological Survey (Ed.). Geological Survey, Perth.
Leech, R.E.J., 1979. Geology and groundwater resources of the Southwestern Canning Basin, in: Geological Survey of Western Australia (Ed.). Geological Survey of Western Australia, Perth.
Lu, C., Chen, X., Cheng, C., Ou, G., Shu, L., 2012. Horizontal hydraulic conductivity of shallow streambed sediments and comparison with the grain-size analysis results. Hydrological Processes 26, 454-466.
Malvern, 2013. Mastersizer 2000.
Morin, R.H., 2006. Negative correlation between porosity and hydraulic conductivity in sand-and-gravel aquifers at Cape Cod, Massachusetts, USA. Journal of Hydrology 316, 43-52.
Oldmeadow, E., 2007. Geological and Hydrogeochemical Investigations into the Holocene Carbonate Dominated Wetlands, Roebuck Bay and Roebuck Plains, Western Australia, Applied Geology. Curtin University of Technology, Perth.
Poppe, L., J., Eliason, A., H., 2008. A Visual Basic program to plot sediment grain-size data on ternary diagrams. Computers & Geosciences 34, 4.
Portz, J., 2013. Personal Communications.
Rangelands NRN Western Australia, Roebuck Bay Working Group, Caring For Our Country, 2013. Nutrient enrichment of Roebuck Bay. Roebuck Bay Working Group.
Robinson, C., Gibbes, B., Li, L., 2006. Driving mechanisms for groundwater flow and salt transport in a subterranean estuary. Geophysical Research Letters 33, L03402.
Rockwater, 2008. Broome North WWTP Numerical modelling to determine the impacts of seepage of treated wastewater from ponds and irrigation area.
Rosas, J., . 2013. Analysis of Grain Size Distribution and Hydraulic Conductivity for a Variety of Sediment Types with Application to Wadi Sediments, Science. King Abdullah University of Science and Technology, Saudi Arabia.

Rosas, J., Lopez, O., Missimer, T.M., Coulibaly, K.M., Dehwah, A.H.A., Sesler, K., Lujan, L.R., Mantilla, D., 2013. Determination of Hydraulic Conductivity from Grain-Size Distribution for Different Depositional Environments. Groundwater.
Salarashayeri, A.F., Siosemarde, M., 2012. Prediction of Soil Hydraulic Conductivity from Particle-Size Distribution. World Academy of Science, Engineering and Technology 61.
Srinivasan, K., Natesan, U., 2012. Spatio-temporal variations in water quality of Muttukadu Backwaters, Tamilnadu, India. Water Environment Research 85, 8.
Takounjou, F.A., Fantong, W., Ngoupayou, J., Nkamdjou, L., 2012. Comparative Analysis for Estimating Hydraulic Conductivity Values to Improve the Estimation of Groundwater Recharge in Yaoundé- Cameroon. British Journal of Environment & Climate Change 2, 8.
The University of Toledo, 2006. The University of Toledo Soil Mechanics Laboratory, in: Toledo, T.U.o. (Ed.). The University of Toledo.
Todd, D., K,. 1980. Groundwater Hydrology John Wiley & Sons New York.
TYevolution, 2013. EasyContour, 2.9 ed.
Verbanck, M., Vanderborght, J., T, Wollast, R., 1989. Major ion content of urban wastewater: assessment of per capita loading. Research Journal of the Water Pollution Control Federation 61, 6.
Vienken, T., Dietrich, P., 2011. Field evaluation of methods for determining hydraulic conductivity from grain size data. Journal of Hydrology 400, 58-71.
Vogwill, R.I.J., 2003. Hydrogeology and Aspects of the Environmental Geology of the Broome Area, Western Australia, Geology. Curtin University
Vogwill, R.I.J., 2013. Personal Communications.
Water Authority of Western Australia, 1994. Broome Groundwater Managment plan, in: Water Authority of Western Australia (Ed.). Water Authorityof Western Australia,, p. 81.

## 12.0 Affirmation of Research

Work done by Nicholas Wright:

- Repositioning of planned bores and dial before you dig paperwork
- Supervision of the construction of six of the eight bores
- Collection of water samples
- In field testing of pH, EC and alkalinity
- Collection and logging of drill chips
- Collection of Pindan Sand samples for grain size analysis

Work done by Ryan Vogwill:

- Conception of project
- Acquisition of funding
- Supervision of construction on two of the eight bores

The Department of Parks and Wildlife Broome office:

- Funding of the surveying

The Kimberley Branch of Rangelands NRM:

- Funding of the project

Survey North:

- Surveying of the bores

The University of Western Australia Environmental Research and Water Quality Laboratory:

- Determining TN, TP, ammonium, phosphate and nitrate for all the water samples

The University of Western Australia School of Earth and Environment:

- Determining grain size distribution data for the Pindan Sand samples.

Kimberley Water:

- Drilling of the monitoring bores

## 13.0 Figure Captions

Figure 1: Location of Broome within the Broome and Dampier Peninsulas (adapted from (Google, 2013)).

Figure 2: Diagram showing bore construction.

Figure 3: Locations of the monitoring bores within Broome (adapted from (Google, 2013)).

Figure 4: Photograph showing an outcrop of the gravel lag within the Pindan Sand, taken from 414702.98 m E, 8010351.63 m S (WGS84).

Figure 5: Grain size distribution of the Pindan Sand samples.

Figure 6: The five grain size distributions of the Pindan Sand.

Figure 7: Cumulative grain size distribution of the Pindan Sand samples.

Figure 8: Hydraulic conductivities of the Pindan Sand samples from nine different calculations.

Figure 9: Groundwater morphology within the Broome region.

Figure 10: A-H cross section showing the groundwater heads within the Broome Peninsula.

Figure 11: Surface run off within the Broome Peninsula (adapted from (Google, 2013) and (LandCorp, 2009)).

Figure 12: D-C cross section showing the groundwater heads within the Broome Peninsula.

Figure 13: A-H cross section showing the electrical conductivity concentration and distribution within the Broome Peninsula.

Figure 14: D-C cross section showing the electrical conductivity concentration and distribution within the Broome Peninsula.

## 14.0 Table Captions

Table 1: Grain size distribution data of the Pindan Sand samples.

Table 2: Hydraulic conductivity results using all nine different methods from grain size distribution data.

Table 3: Range of total possible SGD into Roebuck Bay, (K) = hydraulic conductivity.

Table 4: Range of possible SGD of TP, TN, background TP and background TN into Roebuck Bay, "K" = hydraulic conductivity.

## 15.0 Figures

Figure 1 (Wright 2013)

Figure 2 (Wright 2013)

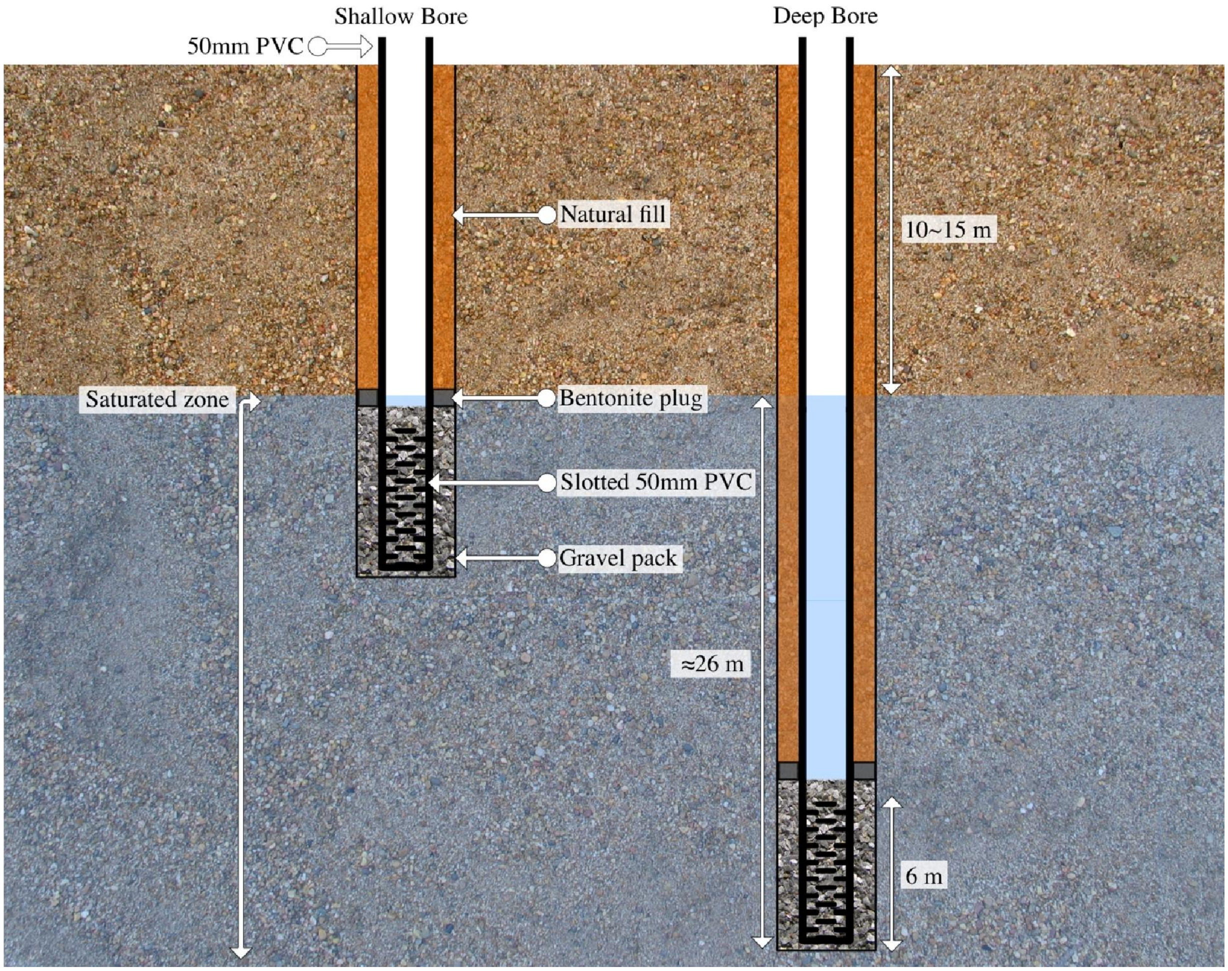


Figure 3 (Wright 2013)

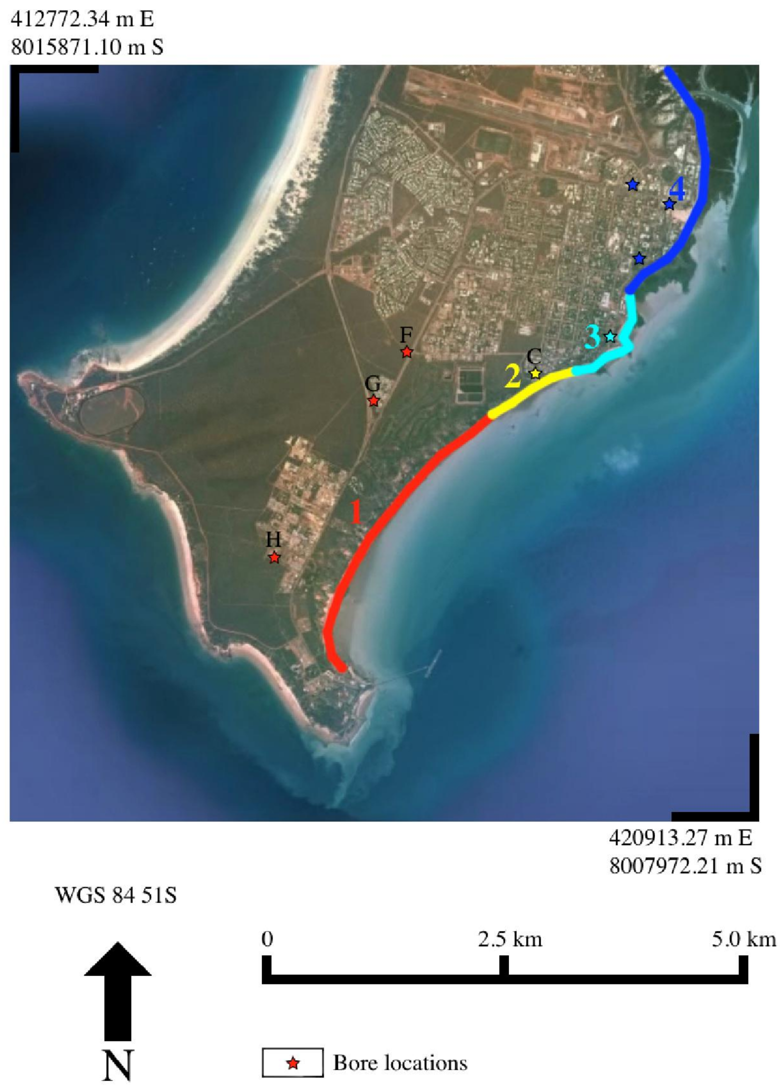


Figure 4 (Wright 2013)

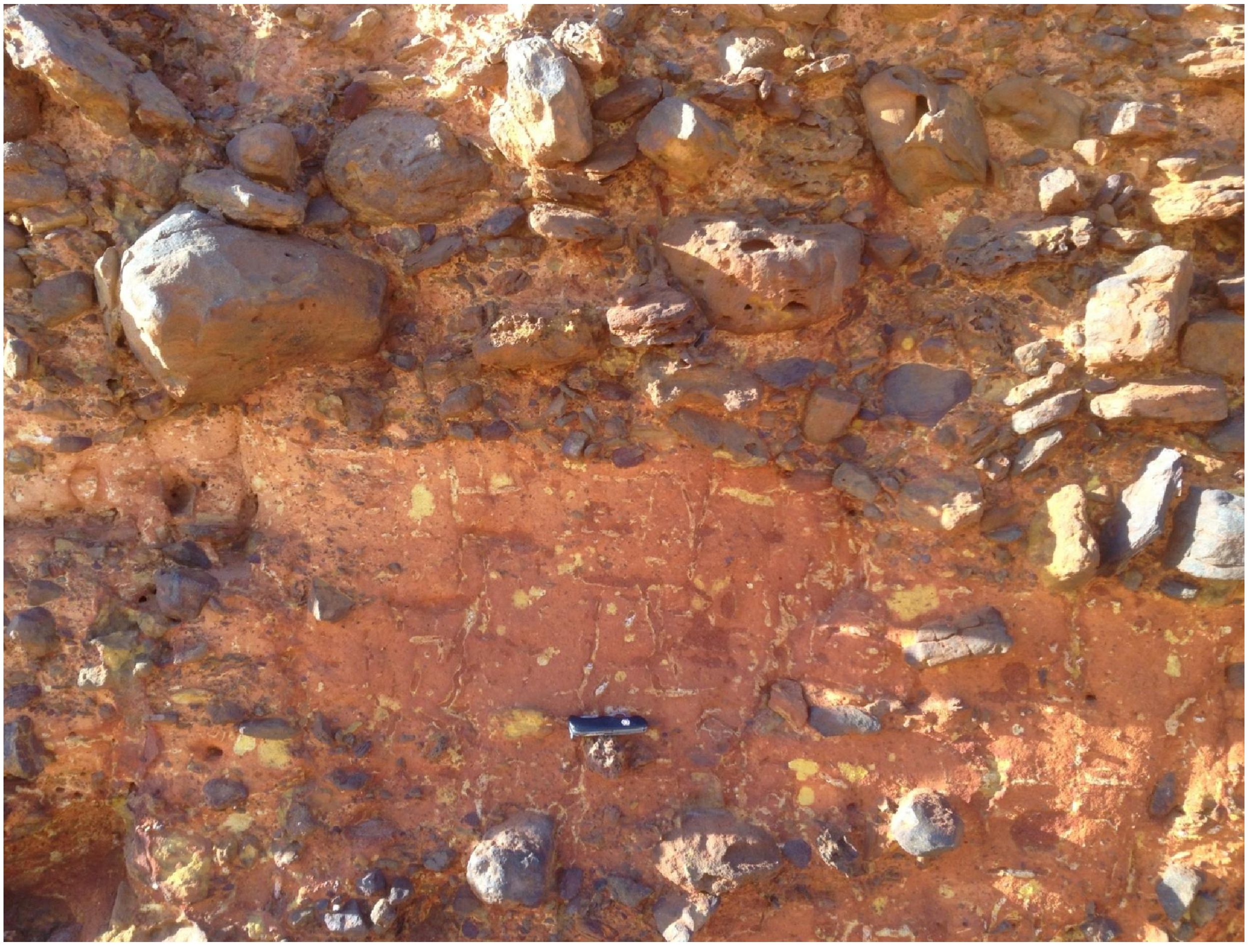


Figure 5 (Wright 2013)

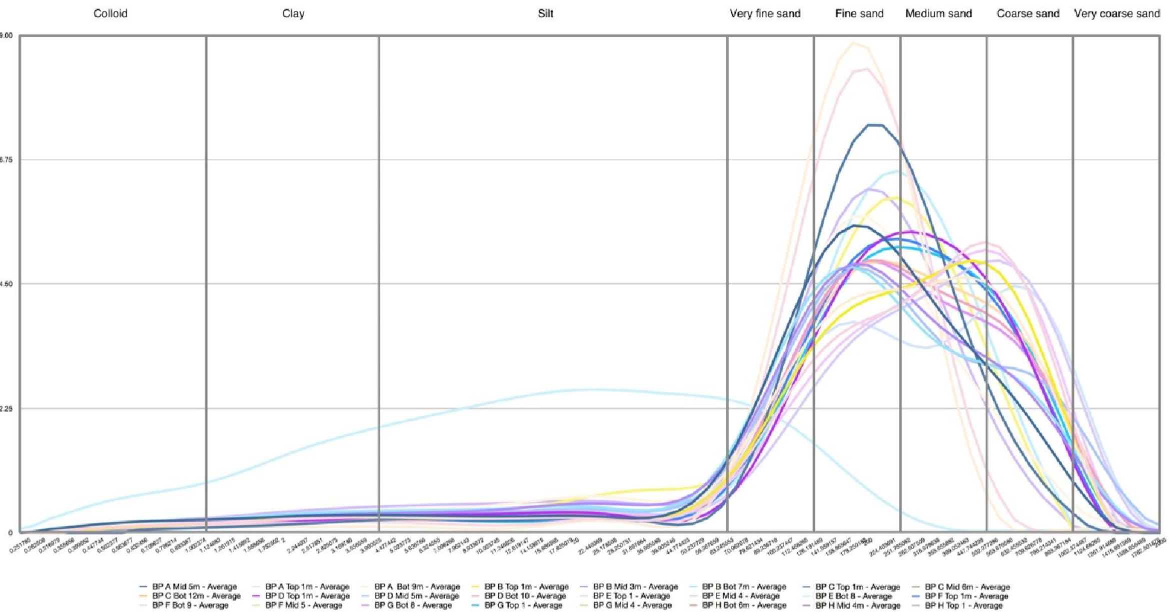



Figure 6 (Wright 2013)

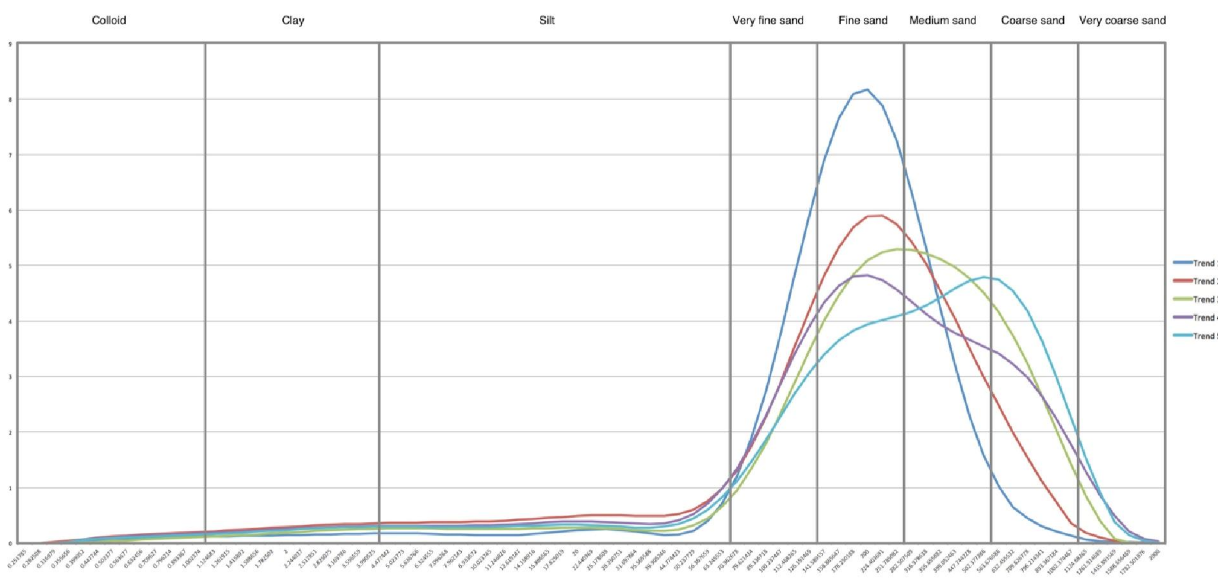


Figure 7 (Wright 2013)

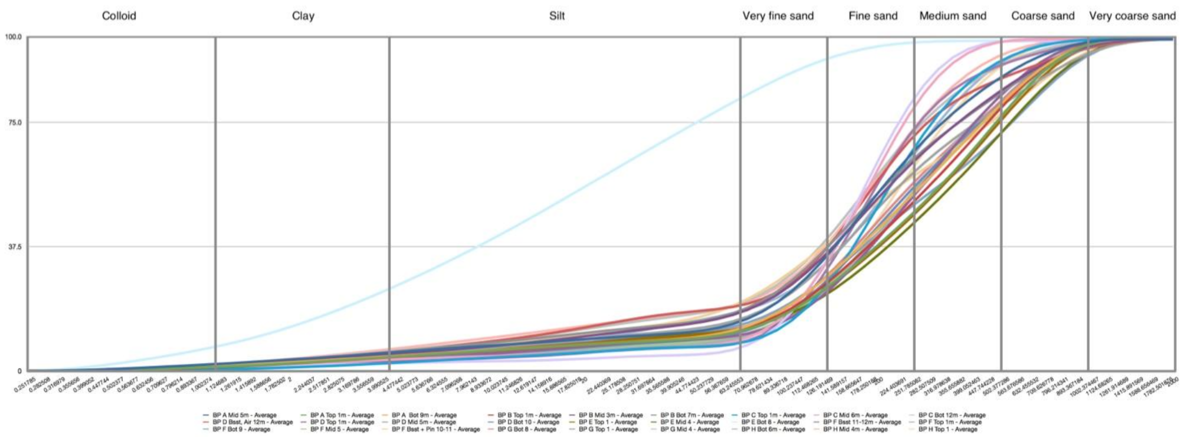



Figure 8 (Wright 2013)

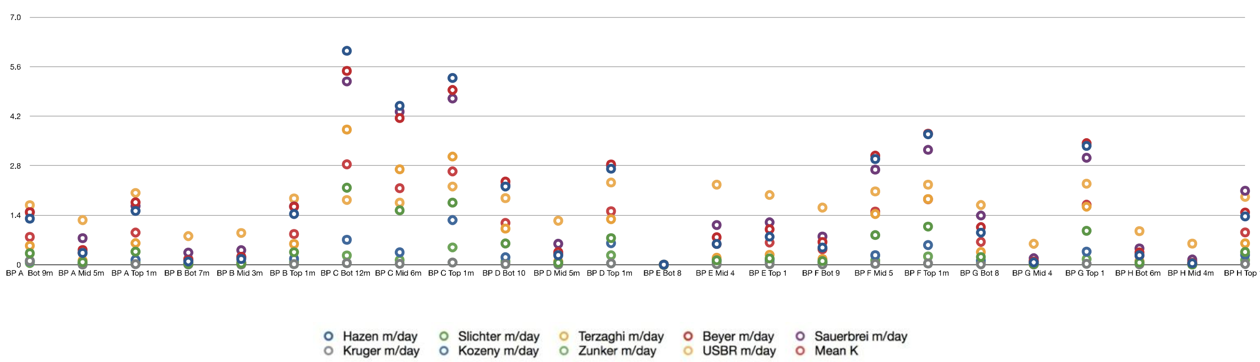


Figure 9 (Wright 2013)

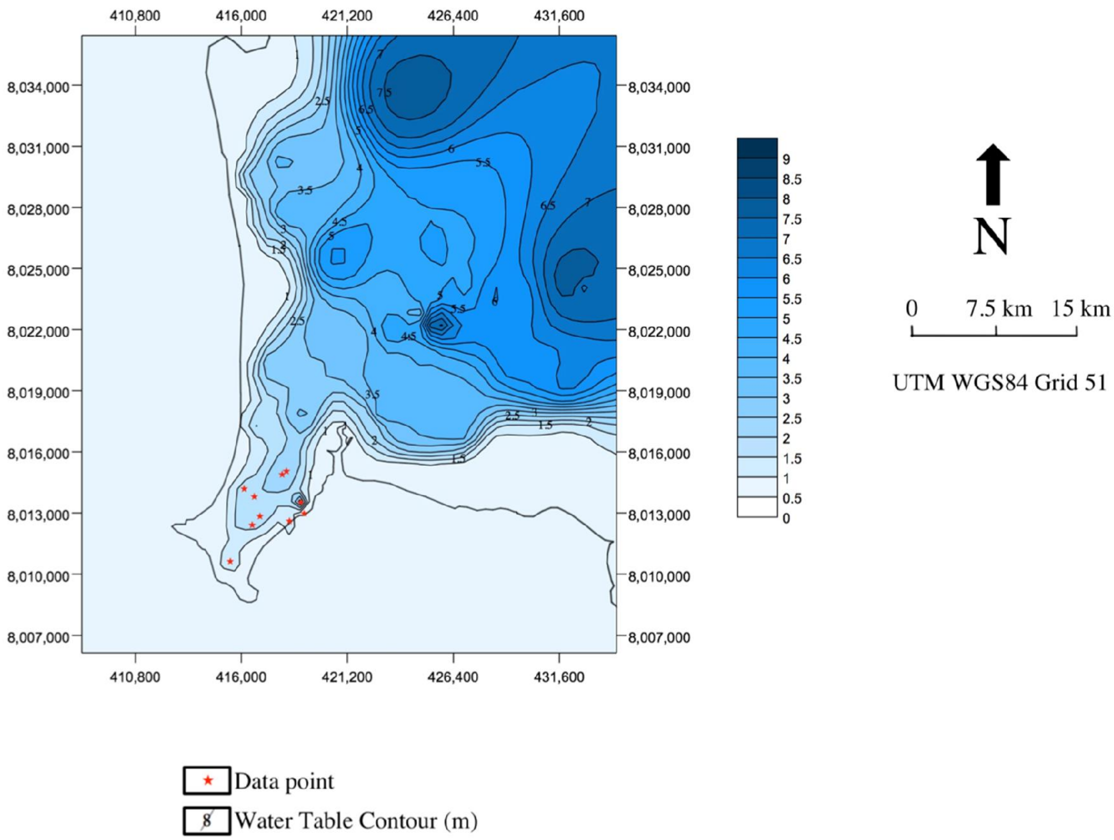


Figure 10 (Wright 2013)

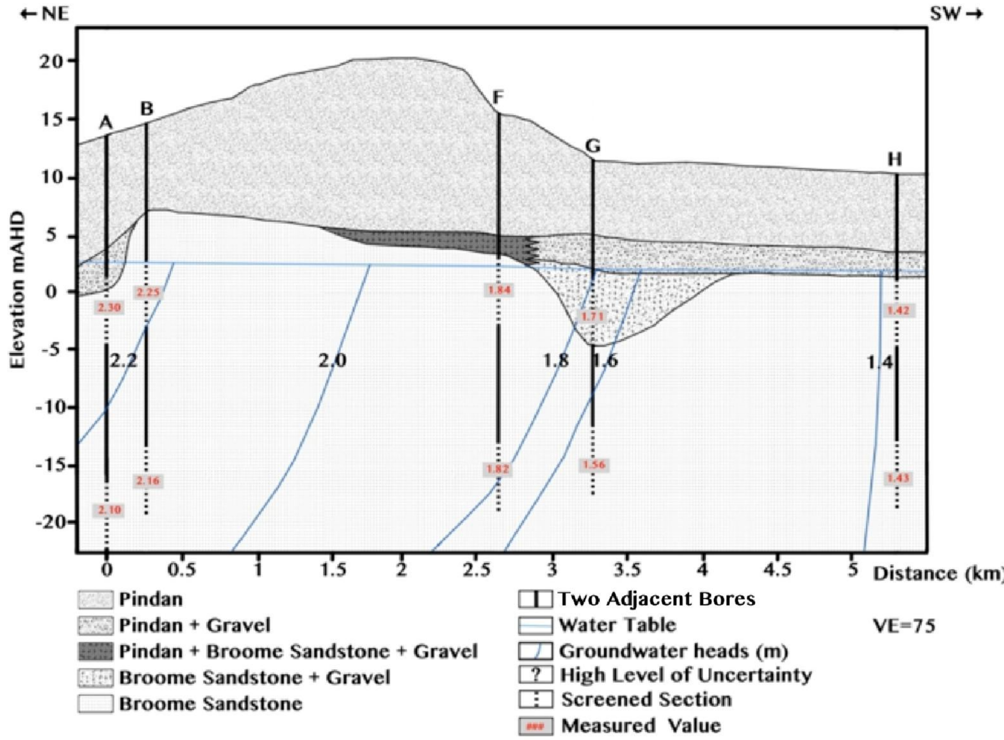


Figure 11 (Wright 2013)

Figure 12 (Wright 2013)

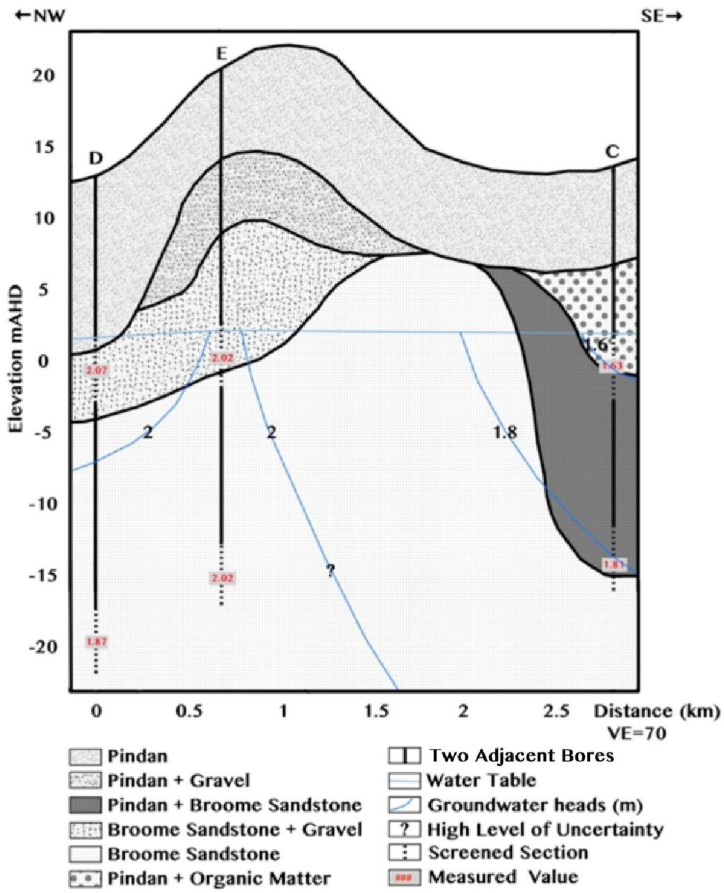


Figure 13 (Wright 2013)

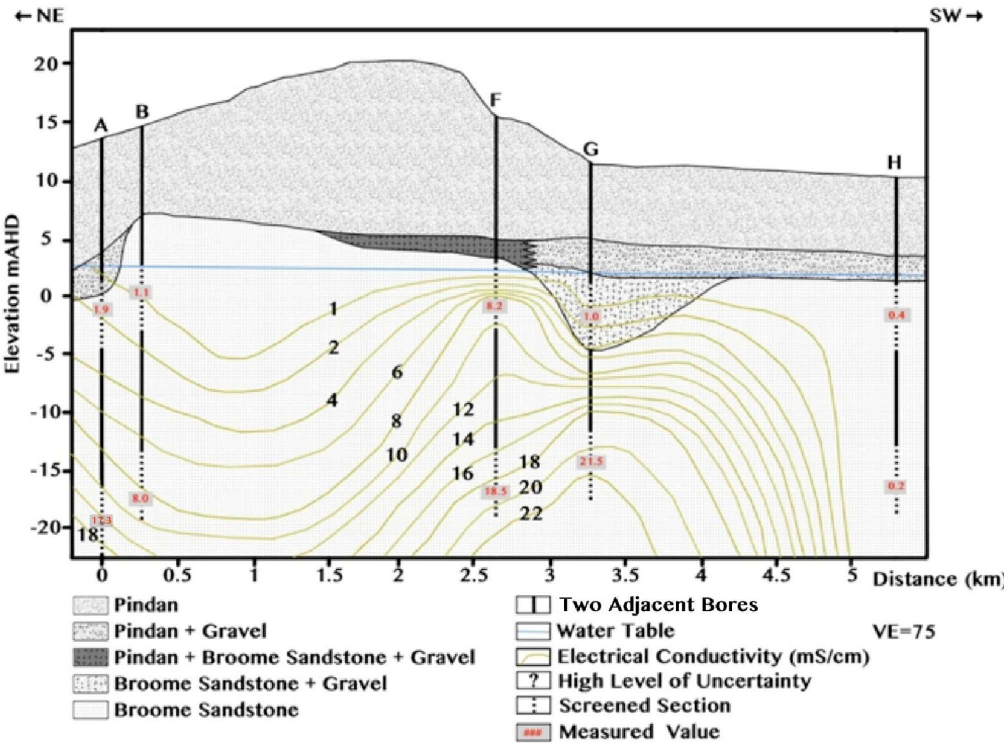


Figure 14 (Wright 2013)

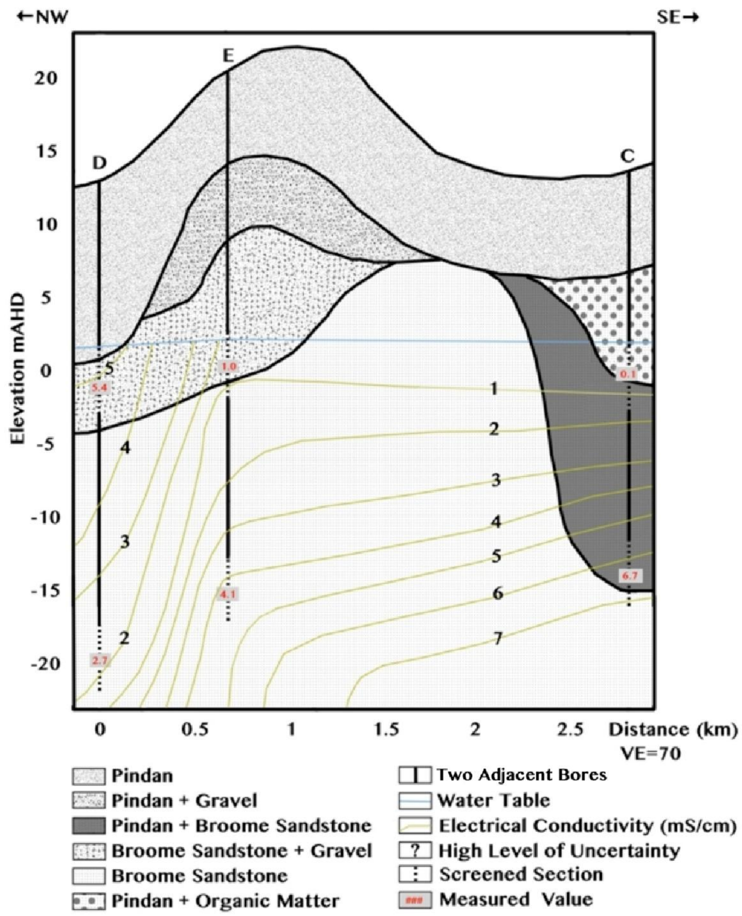


Figure 15 (Wright 2013)

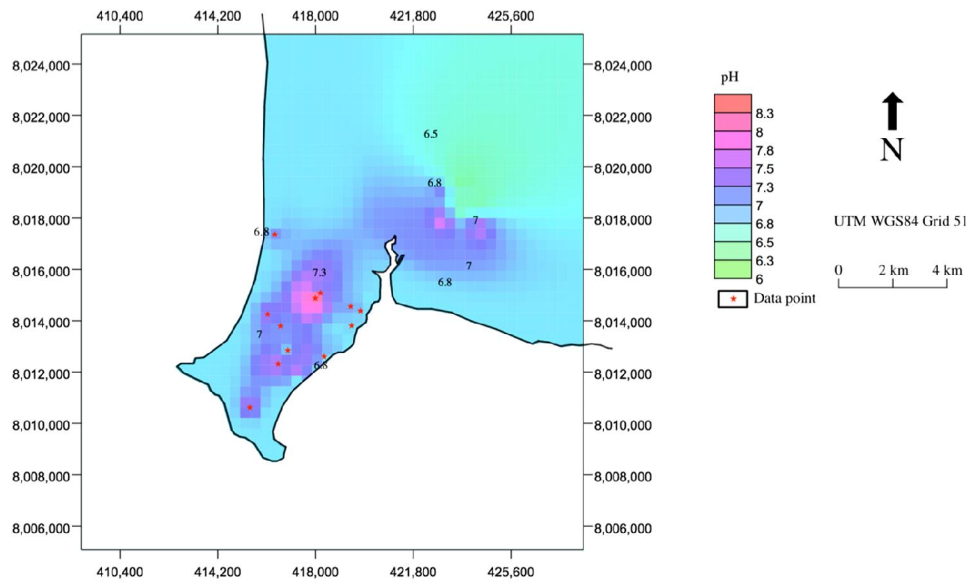



Figure 16 (Wright 2013)

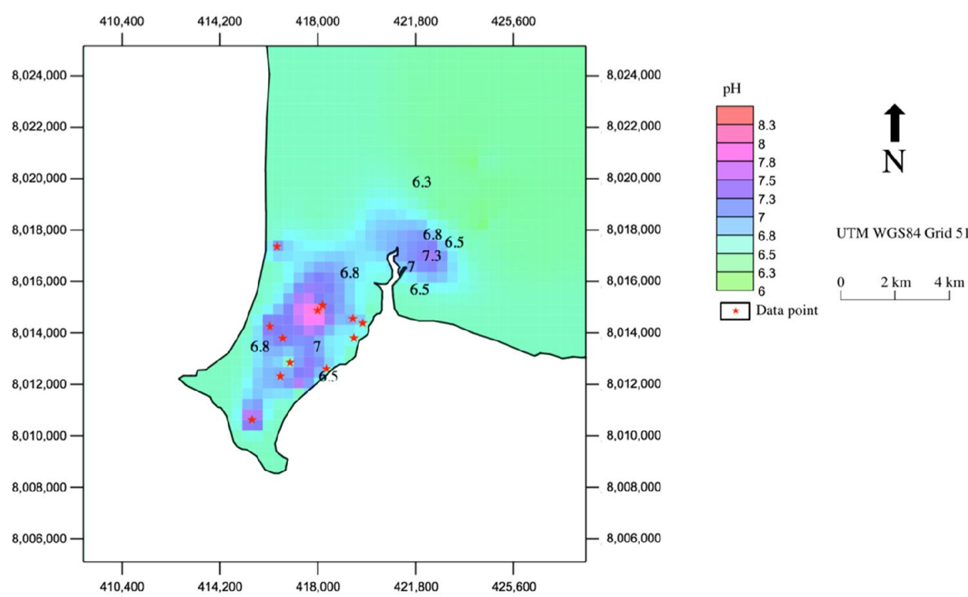


Figure 17 (Wright 2013)

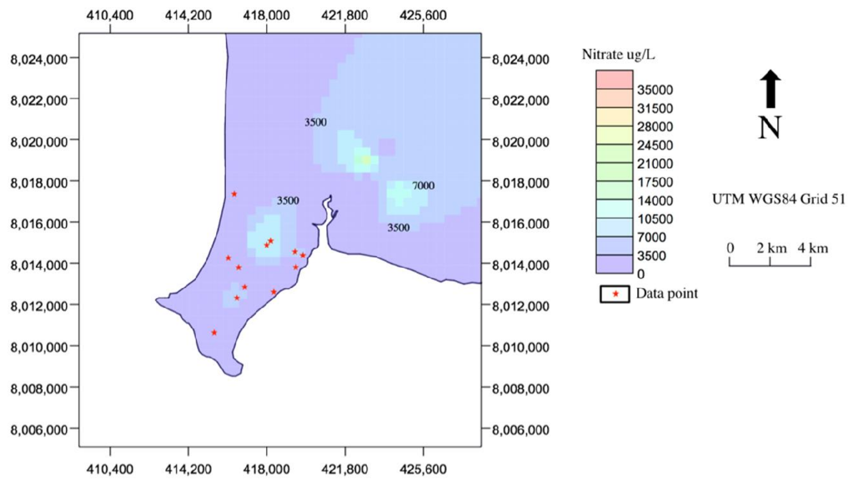



Figure 18 (Wright 2013)

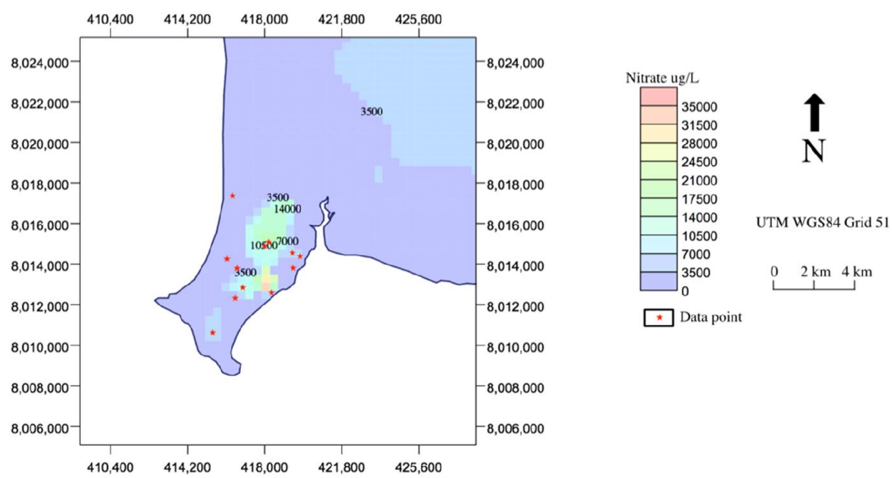


Figure 19 (Wright 2013)

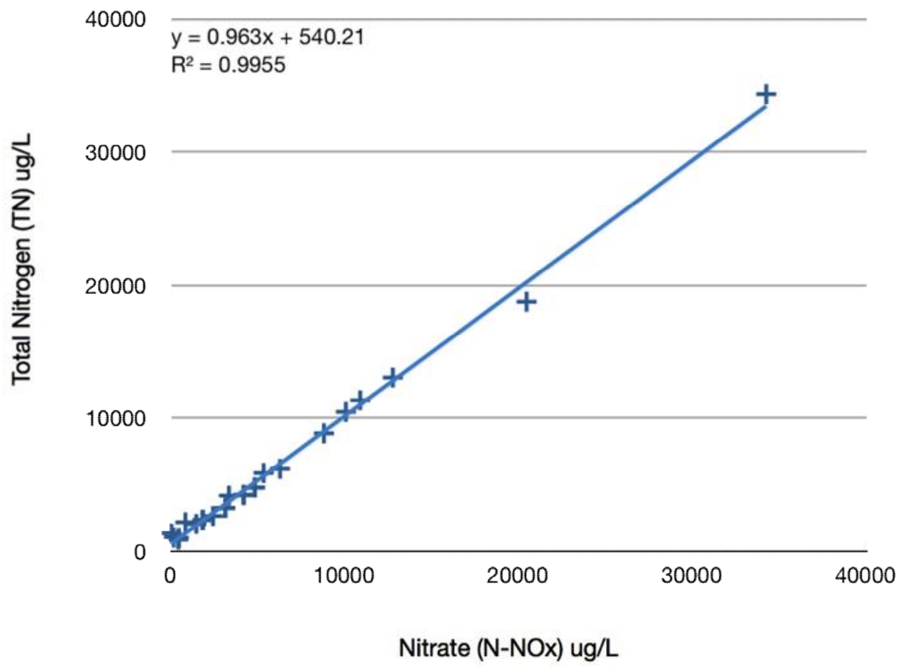



Figure 20 (Wright 2013)

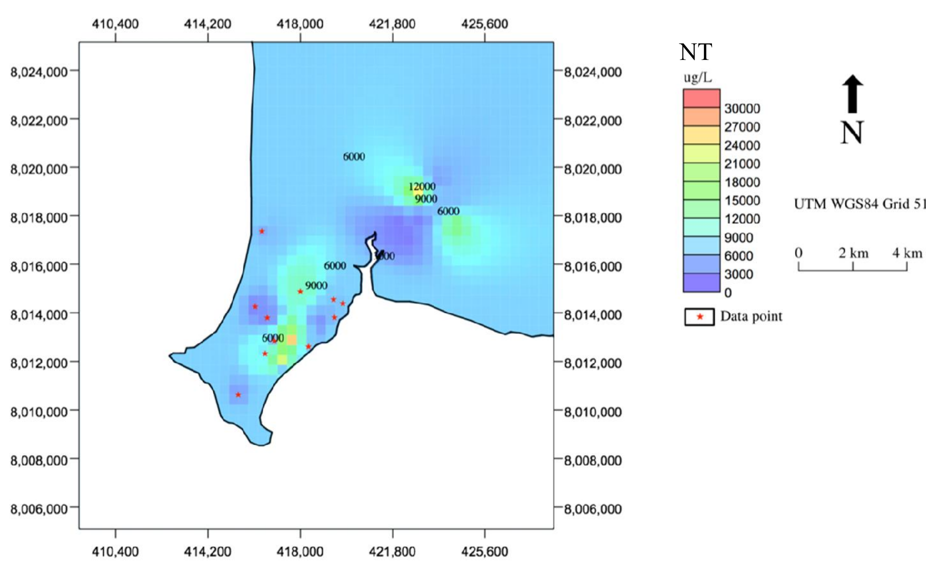


Figure 21 (Wright 2013)

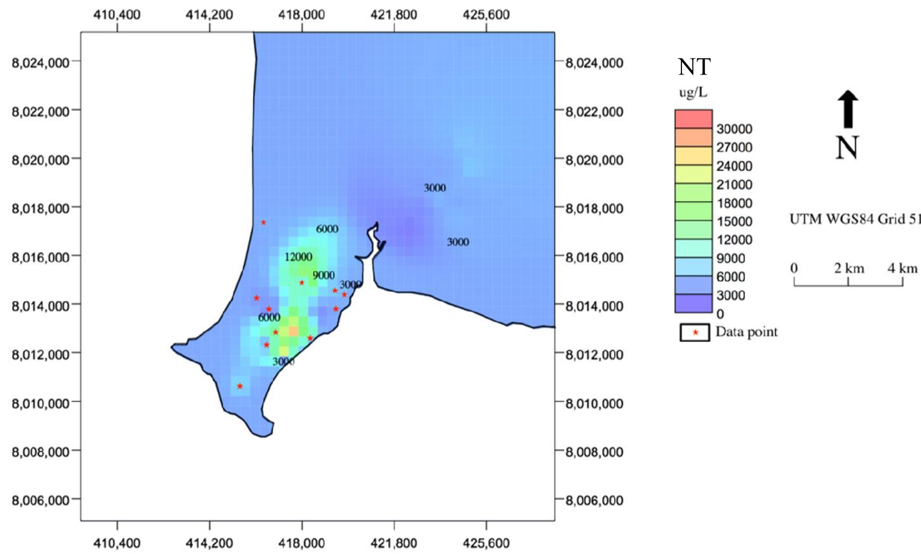



Figure 22 (Wright 2013)

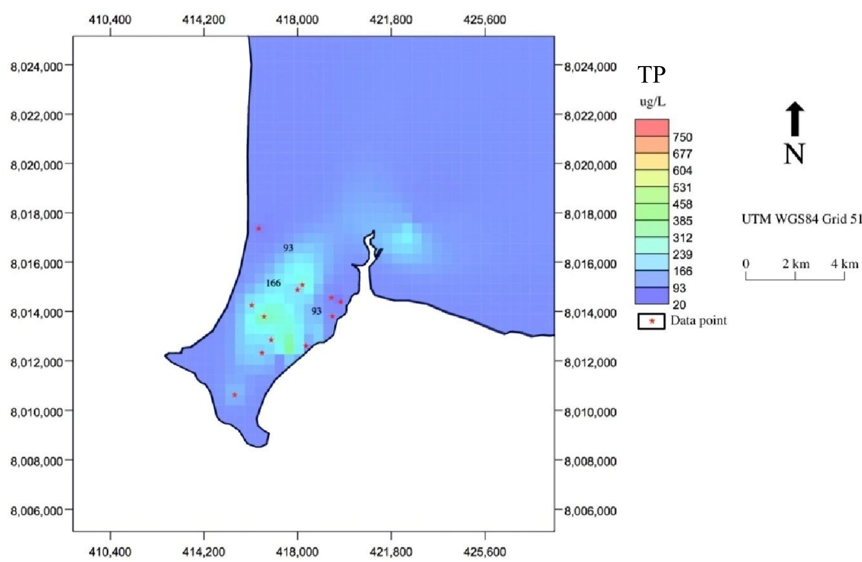


Figure 23 (Wright 2013)

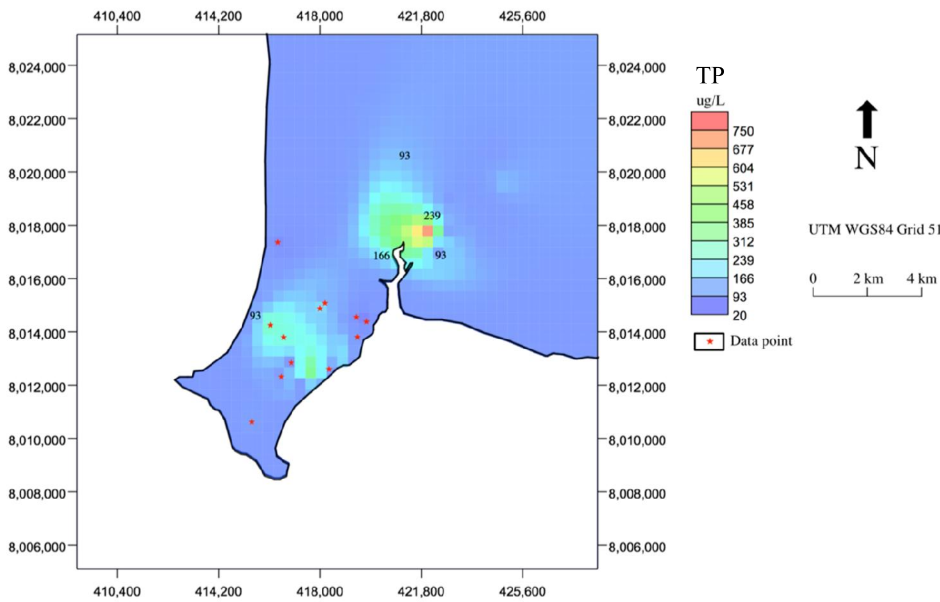



Figure 24 (Wright 2013)

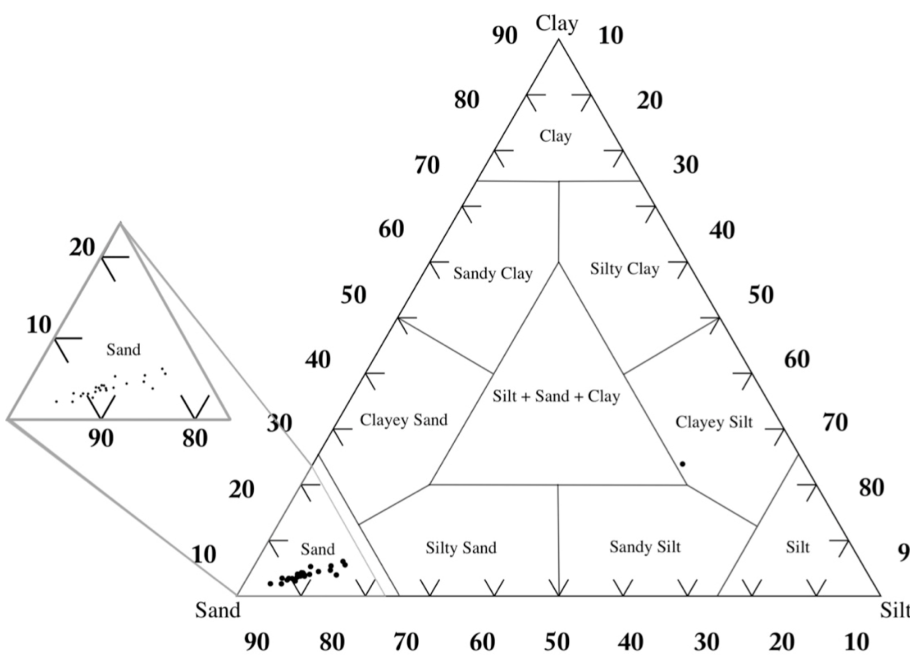


Figure 25 (Wright 2013)

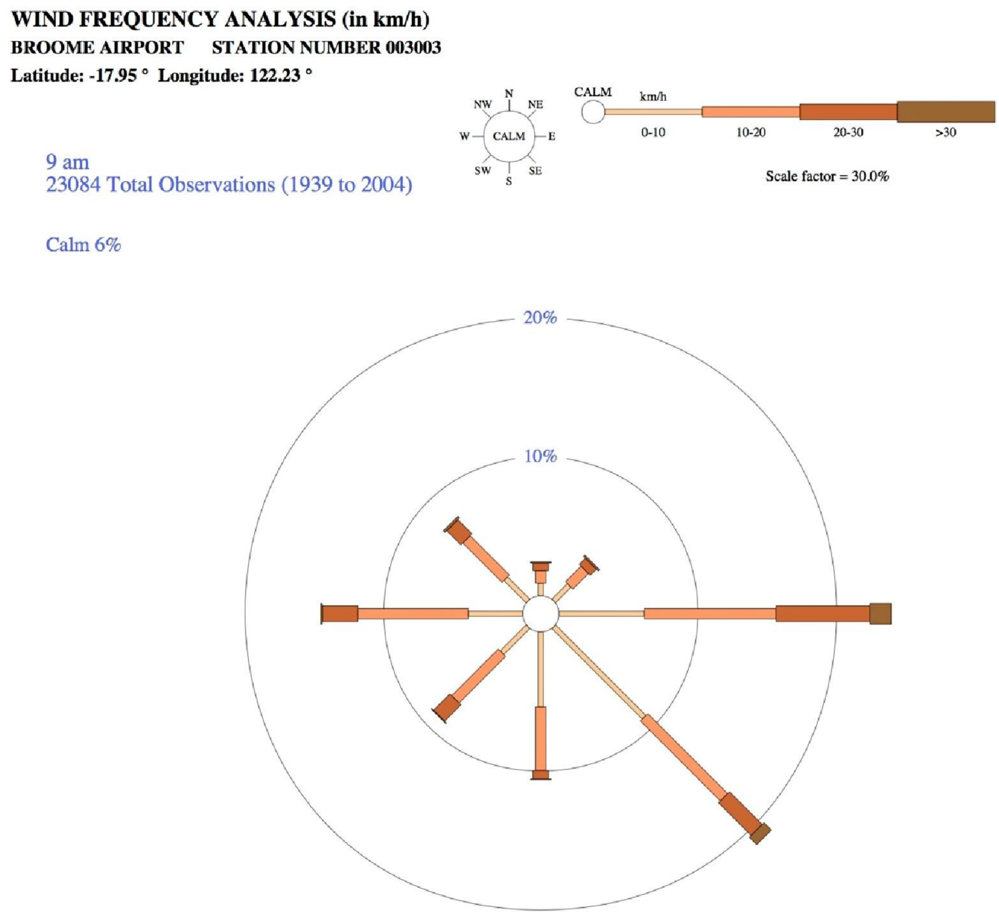


Figure 26 (Wright 2013)

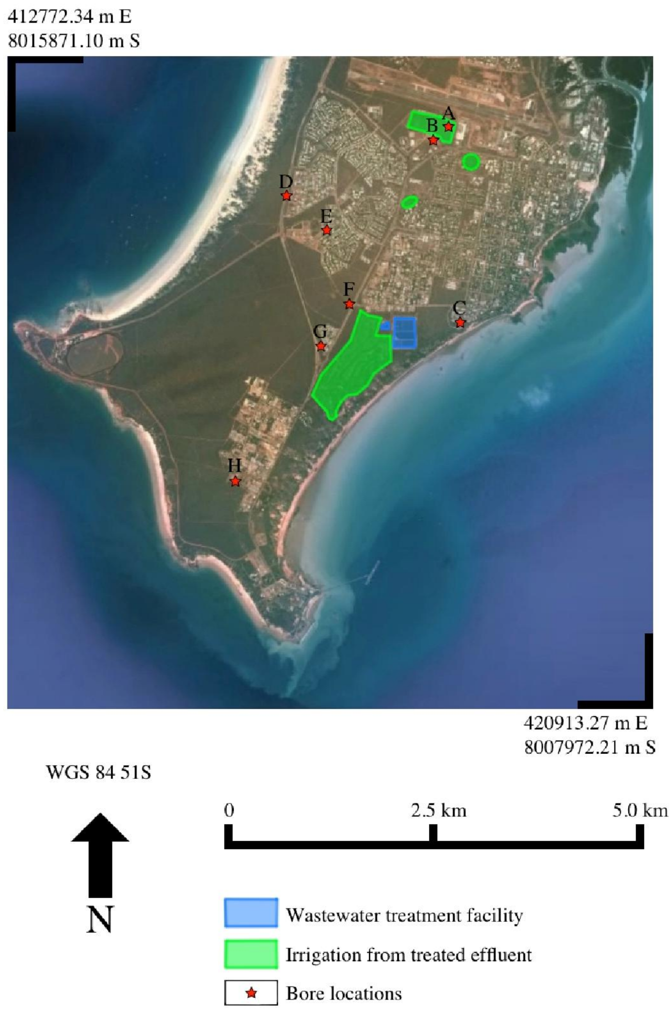


Figure 27 (Wright 2013)

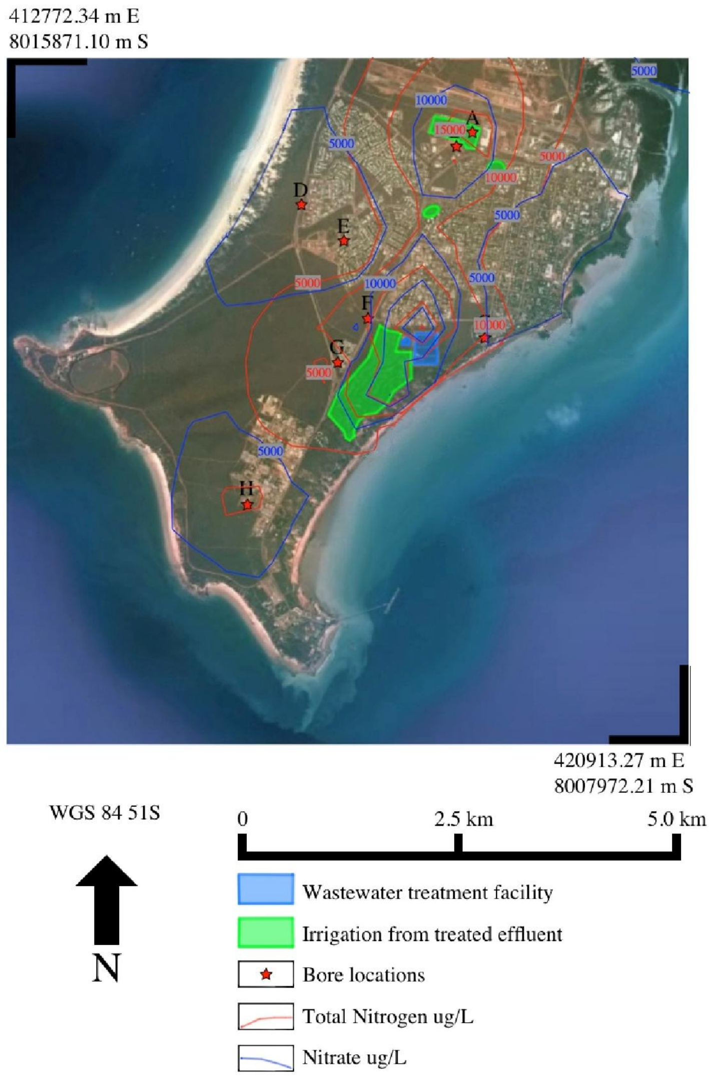
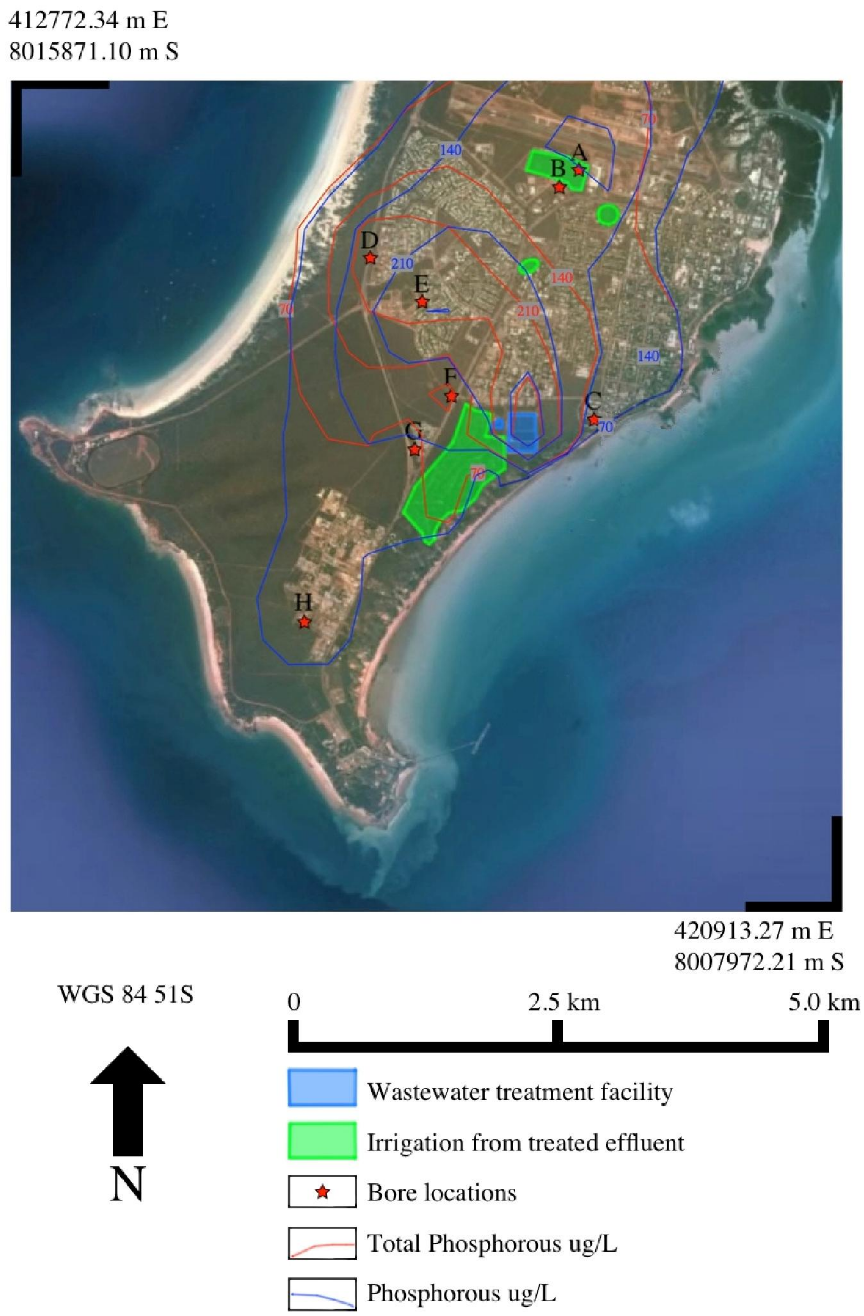


Figure 28 (Rangelands NRN Western Australia et al., 2013)

Figure 29 (Wright 2013)



# 16.0 Tables

Table 1

| Sample Name/ Grain size in microns | 0.252 | 0.283 | 0.317 | 0.356 | 0.399 | 0.448 | 0.502 | 0.564 | 0.632 | 0.710 | 0.796 | 0.893 | 1.002 | 1.125 | 1.262 | 1.416 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BP A Mid 5m | 0.000 | 0.021 | 0.065 | 0.089 | 0.117 | 0.144 | 0.166 | 0.185 | 0.200 | 0.211 | 0.219 | 0.225 | 0.232 | 0.238 | 0.246 | 0.256 |
| BP A Top 1m | 0.000 | 0.000 | 0.000 | 0.000 | 0.059 | 0.079 | 0.095 | 0.108 | 0.120 | 0.131 | 0.140 | 0.149 | 0.159 | 0.170 | 0.182 | 0.196 |
| BP A Bot 9m | 0.000 | 0.000 | 0.010 | 0.066 | 0.085 | 0.104 | 0.122 | 0.137 | 0.149 | 0.158 | 0.165 | 0.171 | 0.177 | 0.184 | 0.192 | 0.202 |
| BP B Top 1m | 0.000 | 0.000 | 0.000 | 0.000 | 0.044 | 0.066 | 0.078 | 0.093 | 0.106 | 0.119 | 0.131 | 0.143 | 0.156 | 0.170 | 0.185 | 0.202 |
| BP B Mid 3m | 0.000 | 0.000 | 0.000 | 0.000 | 0.060 | 0.082 | 0.102 | 0.119 | 0.136 | 0.152 | 0.167 | 0.181 | 0.196 | 0.212 | 0.228 | 0.245 |
| BP B Bot 7m | 0.000 | 0.000 | 0.009 | 0.063 | 0.085 | 0.106 | 0.129 | 0.147 | 0.165 | 0.180 | 0.195 | 0.209 | 0.223 | 0.239 | 0.256 | 0.274 |
| BP C Top 1m | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.048 | 0.061 | 0.069 | 0.077 | 0.086 | 0.095 | 0.103 | 0.112 |
| BP C Mid 6m | 0.000 | 0.000 | 0.007 | 0.051 | 0.069 | 0.086 | 0.104 | 0.118 | 0.130 | 0.139 | 0.145 | 0.149 | 0.152 | 0.154 | 0.157 | 0.160 |
| BP C Bot 12m | 0.000 | 0.000 | 0.000 | 0.000 | 0.050 | 0.074 | 0.085 | 0.098 | 0.109 | 0.116 | 0.121 | 0.123 | 0.123 | 0.121 | 0.118 | 0.115 |
| BP D Top 1m | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.050 | 0.065 | 0.074 | 0.084 | 0.097 | 0.109 | 0.122 | 0.137 |
| BP D Mid 5m | 0.000 | 0.000 | 0.000 | 0.000 | 0.053 | 0.080 | 0.094 | 0.112 | 0.127 | 0.142 | 0.156 | 0.169 | 0.183 | 0.197 | 0.213 | 0.229 |
| BP D Bot 10 | 0.000 | 0.000 | 0.000 | 0.000 | 0.061 | 0.082 | 0.098 | 0.110 | 0.121 | 0.130 | 0.137 | 0.143 | 0.148 | 0.154 | 0.160 | 0.168 |
| BP E Top 1 | 0.000 | 0.000 | 0.000 | 0.000 | 0.026 | 0.052 | 0.067 | 0.077 | 0.088 | 0.100 | 0.112 | 0.126 | 0.140 | 0.157 | 0.175 | 0.195 |
| BP E Mid 4 | 0.000 | 0.000 | 0.000 | 0.000 | 0.043 | 0.064 | 0.076 | 0.089 | 0.102 | 0.113 | 0.124 | 0.135 | 0.146 | 0.158 | 0.170 | 0.184 |
| BP E Bot 8 | 0.067 | 0.134 | 0.250 | 0.334 | 0.422 | 0.501 | 0.570 | 0.628 | 0.677 | 0.719 | 0.760 | 0.804 | 0.856 | 0.920 | 0.997 | 1.087 |
| BP F Top 1m | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.025 | 0.058 | 0.064 | 0.075 | 0.084 | 0.094 | 0.103 | 0.113 | 0.123 | 0.134 | 0.147 |
| BP F Bot 9 | 0.000 | 0.000 | 0.000 | 0.042 | 0.069 | 0.086 | 0.102 | 0.115 | 0.127 | 0.136 | 0.144 | 0.151 | 0.158 | 0.166 | 0.176 | 0.187 |
| BP F Mid 5 | 0.000 | 0.000 | 0.000 | 0.000 | 0.054 | 0.078 | 0.090 | 0.102 | 0.114 | 0.122 | 0.129 | 0.134 | 0.139 | 0.144 | 0.149 | 0.155 |
| BP G Bot 8 | 0.000 | 0.000 | 0.000 | 0.000 | 0.060 | 0.082 | 0.100 | 0.114 | 0.128 | 0.140 | 0.151 | 0.161 | 0.171 | 0.182 | 0.194 | 0.208 |
| BP G Top 1 | 0.000 | 0.000 | 0.000 | 0.000 | 0.025 | 0.053 | 0.070 | 0.081 | 0.091 | 0.101 | 0.109 | 0.118 | 0.126 | 0.136 | 0.146 | 0.158 |
| BP G Mid 4 | 0.000 | 0.000 | 0.011 | 0.067 | 0.090 | 0.117 | 0.139 | 0.160 | 0.178 | 0.194 | 0.208 | 0.222 | 0.235 | 0.249 | 0.264 | 0.281 |
| BP H Bot 6m | 0.000 | 0.000 | 0.000 | 0.000 | 0.049 | 0.073 | 0.086 | 0.100 | 0.114 | 0.127 | 0.138 | 0.149 | 0.160 | 0.172 | 0.183 | 0.196 |
| BP H Mid 4m | 0.000 | 0.000 | 0.012 | 0.073 | 0.096 | 0.124 | 0.147 | 0.168 | 0.188 | 0.205 | 0.221 | 0.236 | 0.252 | 0.270 | 0.289 | 0.310 |
| BP H Top 1 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.029 | 0.069 | 0.077 | 0.091 | 0.103 | 0.116 | 0.129 | 0.142 | 0.156 | 0.171 | 0.187 |
| | | | | | | | | | | | | | | | | |
| Sample Name/ Grain size in microns | 1.589 | 1.783 | 2.000 | 2.244 | 2.518 | 2.825 | 3.170 | 3.557 | 3.991 | 4.477 | 5.024 | 5.637 | 6.325 | 7.096 | 7.962 | 8.934 |
| BP A Mid 5m | 0.267 | 0.279 | 0.290 | 0.300 | 0.308 | 0.313 | 0.317 | 0.319 | 0.320 | 0.319 | 0.317 | 0.314 | 0.310 | 0.306 | 0.301 | 0.297 |
| BP A Top 1m | 0.211 | 0.227 | 0.243 | 0.258 | 0.271 | 0.282 | 0.291 | 0.297 | 0.301 | 0.302 | 0.300 | 0.296 | 0.291 | 0.285 | 0.279 | 0.274 |
| BP A Bot 9m | 0.214 | 0.227 | 0.240 | 0.252 | 0.262 | 0.270 | 0.276 | 0.280 | 0.281 | 0.280 | 0.277 | 0.273 | 0.268 | 0.263 | 0.260 | 0.257 |
| BP B Top 1m | 0.219 | 0.236 | 0.251 | 0.265 | 0.277 | 0.286 | 0.291 | 0.294 | 0.295 | 0.293 | 0.289 | 0.284 | 0.279 | 0.273 | 0.269 | 0.267 |
| BP B Mid 3m | 0.261 | 0.277 | 0.292 | 0.305 | 0.316 | 0.325 | 0.333 | 0.339 | 0.345 | 0.350 | 0.355 | 0.360 | 0.365 | 0.371 | 0.378 | 0.389 |
| BP B Bot 7m | 0.293 | 0.312 | 0.330 | 0.346 | 0.359 | 0.370 | 0.379 | 0.386 | 0.391 | 0.395 | 0.398 | 0.401 | 0.403 | 0.406 | 0.410 | 0.417 |
| BP C Top 1m | 0.122 | 0.133 | 0.144 | 0.157 | 0.170 | 0.185 | 0.199 | 0.213 | 0.227 | 0.237 | 0.245 | 0.249 | 0.249 | 0.245 | 0.239 | 0.232 |
| BP C Mid 6m | 0.163 | 0.167 | 0.172 | 0.177 | 0.181 | 0.185 | 0.189 | 0.191 | 0.191 | 0.189 | 0.184 | 0.178 | 0.169 | 0.158 | 0.147 | 0.138 |
| BP C Bot 12m | 0.111 | 0.108 | 0.106 | 0.105 | 0.105 | 0.106 | 0.107 | 0.108 | 0.109 | 0.108 | 0.105 | 0.100 | 0.092 | 0.083 | 0.074 | 0.067 |
| BP D Top 1m | 0.151 | 0.167 | 0.184 | 0.201 | 0.218 | 0.236 | 0.254 | 0.270 | 0.286 | 0.299 | 0.310 | 0.319 | 0.325 | 0.329 | 0.331 | 0.334 |
| BP D Mid 5m | 0.246 | 0.262 | 0.278 | 0.292 | 0.304 | 0.314 | 0.323 | 0.329 | 0.334 | 0.337 | 0.339 | 0.341 | 0.342 | 0.344 | 0.347 | 0.353 |
| BP D Bot 10 | 0.176 | 0.186 | 0.196 | 0.206 | 0.215 | 0.224 | 0.231 | 0.236 | 0.240 | 0.242 | 0.243 | 0.242 | 0.240 | 0.239 | 0.239 | 0.242 |
| BP E Top 1 | 0.215 | 0.235 | 0.255 | 0.274 | 0.291 | 0.306 | 0.318 | 0.327 | 0.333 | 0.335 | 0.335 | 0.333 | 0.328 | 0.323 | 0.319 | 0.316 |
| BP E Mid 4 | 0.198 | 0.212 | 0.225 | 0.238 | 0.249 | 0.259 | 0.267 | 0.274 | 0.279 | 0.284 | 0.288 | 0.292 | 0.297 | 0.303 | 0.310 | 0.321 |
| BP E Bot 8 | 1.185 | 1.289 | 1.390 | 1.488 | 1.578 | 1.659 | 1.735 | 1.804 | 1.870 | 1.933 | 1.994 | 2.054 | 2.113 | 2.172 | 2.229 | 2.287 |
| BP F Top 1m | 0.160 | 0.174 | 0.188 | 0.202 | 0.214 | 0.225 | 0.234 | 0.241 | 0.245 | 0.247 | 0.245 | 0.242 | 0.236 | 0.230 | 0.224 | 0.219 |
| BP F Bot 9 | 0.199 | 0.213 | 0.227 | 0.241 | 0.255 | 0.267 | 0.278 | 0.288 | 0.295 | 0.301 | 0.304 | 0.307 | 0.309 | 0.311 | 0.315 | 0.321 |
| BP F Mid 5 | 0.162 | 0.171 | 0.180 | 0.189 | 0.199 | 0.207 | 0.215 | 0.222 | 0.227 | 0.230 | 0.231 | 0.230 | 0.227 | 0.225 | 0.223 | 0.224 |
| BP G Bot 8 | 0.223 | 0.239 | 0.254 | 0.269 | 0.283 | 0.295 | 0.305 | 0.313 | 0.319 | 0.322 | 0.322 | 0.320 | 0.316 | 0.310 | 0.304 | 0.299 |
| BP G Top 1 | 0.172 | 0.186 | 0.200 | 0.214 | 0.227 | 0.238 | 0.247 | 0.253 | 0.256 | 0.256 | 0.253 | 0.246 | 0.238 | 0.228 | 0.219 | 0.210 |
| BP G Mid 4 | 0.298 | 0.316 | 0.332 | 0.348 | 0.363 | 0.376 | 0.388 | 0.398 | 0.407 | 0.415 | 0.423 | 0.429 | 0.436 | 0.444 | 0.454 | 0.468 |
| BP H Bot 6m | 0.208 | 0.220 | 0.232 | 0.244 | 0.254 | 0.265 | 0.275 | 0.285 | 0.295 | 0.305 | 0.315 | 0.325 | 0.334 | 0.344 | 0.355 | 0.368 |
| BP H Mid 4m | 0.332 | 0.354 | 0.375 | 0.394 | 0.412 | 0.427 | 0.442 | 0.454 | 0.466 | 0.477 | 0.486 | 0.494 | 0.501 | 0.507 | 0.512 | 0.518 |
| BP H Top 1 | 0.203 | 0.220 | 0.236 | 0.251 | 0.266 | 0.279 | 0.290 | 0.298 | 0.305 | 0.309 | 0.311 | 0.310 | 0.307 | 0.302 | 0.297 | 0.292 |
| | | | | | | | | | | | | | | | | |
| Sample Name/ Grain size in microns | 10.024 | 11.247 | 12.619 | 14.159 | 15.887 | 17.825 | 20.000 | 22.440 | 25.179 | 28.251 | 31.698 | 35.566 | 39.905 | 44.774 | 50.238 | 56.368 |
| BP A Mid 5m | 0.295 | 0.295 | 0.297 | 0.301 | 0.305 | 0.308 | 0.306 | 0.300 | 0.287 | 0.273 | 0.263 | 0.268 | 0.305 | 0.391 | 0.545 | 0.792 |
| BP A Top 1m | 0.271 | 0.271 | 0.272 | 0.274 | 0.277 | 0.277 | 0.273 | 0.263 | 0.250 | 0.234 | 0.221 | 0.221 | 0.244 | 0.302 | 0.409 | 0.578 |
| BP A Bot 9m | 0.257 | 0.260 | 0.264 | 0.269 | 0.273 | 0.275 | 0.273 | 0.266 | 0.257 | 0.247 | 0.244 | 0.257 | 0.299 | 0.383 | 0.520 | 0.728 |
| BP B Top 1m | 0.267 | 0.270 | 0.275 | 0.281 | 0.287 | 0.291 | 0.290 | 0.284 | 0.274 | 0.261 | 0.251 | 0.254 | 0.279 | 0.342 | 0.453 | 0.630 |
| BP B Mid 3m | 0.403 | 0.421 | 0.442 | 0.465 | 0.488 | 0.509 | 0.523 | 0.528 | 0.524 | 0.514 | 0.501 | 0.497 | 0.516 | 0.575 | 0.691 | 0.888 |
| BP B Bot 7m | 0.425 | 0.436 | 0.449 | 0.463 | 0.474 | 0.480 | 0.478 | 0.467 | 0.448 | 0.425 | 0.406 | 0.403 | 0.432 | 0.514 | 0.665 | 0.906 |
| BP C Top 1m | 0.226 | 0.223 | 0.225 | 0.232 | 0.244 | 0.259 | 0.275 | 0.285 | 0.285 | 0.271 | 0.241 | 0.201 | 0.160 | 0.139 | 0.162 | 0.265 |
| BP C Mid 6m | 0.133 | 0.134 | 0.141 | 0.156 | 0.178 | 0.203 | 0.228 | 0.246 | 0.254 | 0.247 | 0.227 | 0.200 | 0.183 | 0.200 | 0.283 | 0.475 |
| BP C Bot 12m | 0.066 | 0.071 | 0.084 | 0.106 | 0.135 | 0.167 | 0.196 | 0.214 | 0.217 | 0.201 | 0.167 | 0.127 | 0.101 | 0.120 | 0.222 | 0.458 |
| BP D Top 1m | 0.337 | 0.342 | 0.348 | 0.356 | 0.363 | 0.368 | 0.368 | 0.359 | 0.340 | 0.311 | 0.274 | 0.236 | 0.207 | 0.202 | 0.239 | 0.341 |
| BP D Mid 5m | 0.361 | 0.372 | 0.386 | 0.400 | 0.413 | 0.422 | 0.426 | 0.423 | 0.413 | 0.399 | 0.385 | 0.383 | 0.405 | 0.469 | 0.588 | 0.786 |
| BP D Bot 10 | 0.248 | 0.258 | 0.271 | 0.288 | 0.305 | 0.320 | 0.330 | 0.333 | 0.326 | 0.313 | 0.295 | 0.282 | 0.287 | 0.325 | 0.415 | 0.579 |
| BP E Top 1 | 0.314 | 0.315 | 0.317 | 0.321 | 0.324 | 0.325 | 0.324 | 0.319 | 0.311 | 0.302 | 0.295 | 0.298 | 0.319 | 0.368 | 0.455 | 0.594 |
| BP E Mid 4 | 0.334 | 0.351 | 0.368 | 0.386 | 0.402 | 0.414 | 0.419 | 0.416 | 0.403 | 0.383 | 0.358 | 0.335 | 0.322 | 0.331 | 0.373 | 0.462 |
| BP E Bot 8 | 2.342 | 2.397 | 2.447 | 2.492 | 2.531 | 2.560 | 2.580 | 2.588 | 2.586 | 2.577 | 2.561 | 2.543 | 2.523 | 2.504 | 2.484 | 2.459 |
| BP F Top 1m | 0.217 | 0.218 | 0.223 | 0.229 | 0.238 | 0.245 | 0.249 | 0.248 | 0.240 | 0.227 | 0.212 | 0.203 | 0.210 | 0.249 | 0.336 | 0.490 |
| BP F Bot 9 | 0.331 | 0.345 | 0.361 | 0.378 | 0.393 | 0.404 | 0.408 | 0.403 | 0.387 | 0.365 | 0.342 | 0.328 | 0.336 | 0.383 | 0.483 | 0.654 |
| BP F Mid 5 | 0.228 | 0.235 | 0.247 | 0.261 | 0.277 | 0.291 | 0.301 | 0.303 | 0.297 | 0.283 | 0.265 | 0.252 | 0.254 | 0.289 | 0.373 | 0.528 |
| BP G Bot 8 | 0.295 | 0.294 | 0.296 | 0.300 | 0.304 | 0.308 | 0.310 | 0.307 | 0.298 | 0.286 | 0.273 | 0.268 | 0.281 | 0.329 | 0.427 | 0.597 |
| BP G Top 1 | 0.204 | 0.200 | 0.201 | 0.204 | 0.211 | 0.219 | 0.226 | 0.232 | 0.235 | 0.235 | 0.234 | 0.238 | 0.257 | 0.301 | 0.384 | 0.525 |
| BP G Mid 4 | 0.487 | 0.511 | 0.539 | 0.569 | 0.601 | 0.628 | 0.648 | 0.656 | 0.650 | 0.631 | 0.603 | 0.577 | 0.568 | 0.597 | 0.686 | 0.863 |
| BP H Bot 6m | 0.384 | 0.406 | 0.434 | 0.468 | 0.509 | 0.555 | 0.604 | 0.652 | 0.697 | 0.732 | 0.757 | 0.771 | 0.779 | 0.790 | 0.817 | 0.880 |
| BP H Mid 4m | 0.524 | 0.532 | 0.542 | 0.552 | 0.562 | 0.570 | 0.574 | 0.573 | 0.564 | 0.548 | 0.527 | 0.508 | 0.502 | 0.524 | 0.594 | 0.736 |
| BP H Top 1 | 0.289 | 0.287 | 0.288 | 0.292 | 0.298 | 0.307 | 0.316 | 0.324 | 0.329 | 0.330 | 0.327 | 0.325 | 0.329 | 0.350 | 0.403 | 0.507 |
| | | | | | | | | | | | | | | | | |
| Sample Name/ Grain size in microns | 63.246 | 70.963 | 79.621 | 89.337 | 100.23 | 112.46 | 126.19 | 141.58 | 158.86 | 178.25 | 200.00 | 224.40 | 251.78 | 282.50 | 316.97 | 355.65 |
| BP A Mid 5m | 1.134 | 1.587 | 2.131 | 2.750 | 3.405 | 4.043 | 4.626 | 5.088 | 5.407 | 5.551 | 5.526 | 5.351 | 5.067 | 4.715 | 4.347 | 3.984 |
| BP A Top 1m | 0.810 | 1.112 | 1.467 | 1.864 | 2.277 | 2.675 | 3.038 | 3.337 | 3.571 | 3.738 | 3.861 | 3.966 | 4.088 | 4.252 | 4.466 | 4.724 |
| BP A Bot 9m | 1.004 | 1.354 | 1.761 | 2.211 | 2.674 | 3.117 | 3.519 | 3.842 | 4.087 | 4.244 | 4.332 | 4.373 | 4.398 | 4.430 | 4.482 | 4.548 |
| BP B Top 1m | 0.872 | 1.189 | 1.566 | 1.991 | 2.438 | 2.875 | 3.282 | 3.622 | 3.893 | 4.085 | 4.217 | 4.308 | 4.389 | 4.483 | 4.600 | 4.734 |
| BP B Mid 3m | 1.168 | 1.544 | 2.000 | 2.521 | 3.072 | 3.608 | 4.096 | 4.479 | 4.741 | 4.857 | 4.835 | 4.694 | 4.473 | 4.209 | 3.948 | 3.710 |
| BP B Bot 7m | 1.237 | 1.666 | 2.169 | 2.725 | 3.292 | 3.820 | 4.272 | 4.595 | 4.776 | 4.799 | 4.681 | 4.455 | 4.168 | 3.866 | 3.599 | 3.386 |
| BP C Top 1m | 0.478 | 0.838 | 1.359 | 2.048 | 2.886 | 3.818 | 4.800 | 5.716 | 6.510 | 7.076 | 7.374 | 7.370 | 7.081 | 6.549 | 5.854 | 5.053 |
| BP C Mid 6m | 0.806 | 1.318 | 2.016 | 2.901 | 3.935 | 5.044 | 6.158 | 7.136 | 7.901 | 8.334 | 8.390 | 8.049 | 7.353 | 6.374 | 5.245 | 4.050 |
| BP C Bot 12m | 0.858 | 1.468 | 2.284 | 3.299 | 4.459 | 5.670 | 6.848 | 7.834 | 8.546 | 8.868 | 8.761 | 8.225 | 7.327 | 6.159 | 4.877 | 3.575 |
| BP D Top 1m | 0.519 | 0.794 | 1.163 | 1.626 | 2.163 | 2.742 | 3.340 | 3.899 | 4.403 | 4.810 | 5.115 | 5.313 | 5.415 | 5.438 | 5.397 | 5.298 |
| BP D Mid 5m | 1.065 | 1.437 | 1.888 | 2.404 | 2.953 | 3.491 | 3.986 | 4.380 | 4.654 | 4.778 | 4.754 | 4.596 | 4.342 | 4.031 | 3.721 | 3.444 |
| BP D Bot 10 | 0.823 | 1.165 | 1.593 | 2.098 | 2.653 | 3.216 | 3.757 | 4.218 | 4.583 | 4.816 | 4.922 | 4.911 | 4.814 | 4.665 | 4.504 | 4.352 |
| BP E Top 1 | 0.784 | 1.036 | 1.337 | 1.682 | 2.053 | 2.425 | 2.785 | 3.104 | 3.382 | 3.606 | 3.792 | 3.952 | 4.107 | 4.277 | 4.468 | 4.681 |
| BP E Mid 4 | 0.604 | 0.809 | 1.073 | 1.393 | 1.755 | 2.138 | 2.527 | 2.888 | 3.214 | 3.484 | 3.702 | 3.874 | 4.017 | 4.153 | 4.296 | 4.459 |
| BP E Bot 8 | 2.424 | 2.372 | 2.296 | 2.190 | 2.050 | 1.878 | 1.675 | 1.455 | 1.222 | 0.995 | 0.778 | 0.582 | 0.412 | 0.271 | 0.166 | 0.093 |
| BP F Top 1m | 0.722 | 1.046 | 1.457 | 1.949 | 2.500 | 3.074 | 3.648 | 4.164 | 4.610 | 4.947 | 5.173 | 5.290 | 5.314 | 5.267 | 5.173 | 5.041 |
| BP F Bot 9 | 0.899 | 1.225 | 1.614 | 2.051 | 2.504 | 2.932 | 3.307 | 3.584 | 3.755 | 3.807 | 3.757 | 3.637 | 3.495 | 3.380 | 3.339 | 3.404 |
| BP F Mid 5 | 0.761 | 1.088 | 1.500 | 1.988 | 2.528 | 3.080 | 3.617 | 4.084 | 4.464 | 4.726 | 4.871 | 4.908 | 4.862 | 4.764 | 4.646 | 4.525 |
| BP G Bot 8 | 0.846 | 1.190 | 1.620 | 2.126 | 2.683 | 3.248 | 3.791 | 4.251 | 4.609 | 4.829 | 4.914 | 4.874 | 4.744 | 4.561 | 4.370 | 4.196 |
| BP G Top 1 | 0.733 | 1.024 | 1.396 | 1.845 | 2.355 | 2.896 | 3.444 | 3.948 | 4.392 | 4.737 | 4.979 | 5.115 | 5.164 | 5.146 | 5.084 | 4.991 |
| BP G Mid 4 | 1.139 | 1.535 | 2.039 | 2.641 | 3.306 | 3.979 | 4.618 | 5.145 | 5.528 | 5.718 | 5.708 | 5.508 | 5.154 | 4.693 | 4.189 | 3.677 |
| BP H Bot 6m | 0.999 | 1.198 | 1.490 | 1.887 | 2.385 | 2.965 | 3.608 | 4.253 | 4.873 | 5.395 | 5.789 | 6.014 | 6.058 | 5.922 | 5.628 | 5.191 |
| BP H Mid 4m | 0.966 | 1.310 | 1.766 | 2.337 | 3.002 | 3.717 | 4.447 | 5.110 | 5.667 | 6.045 | 6.217 | 6.162 | 5.895 | 5.447 | 4.878 | 4.227 |
| BP H Top 1 | 0.679 | 0.942 | 1.306 | 1.781 | 2.362 | 3.024 | 3.750 | 4.473 | 5.166 | 5.752 | 6.201 | 6.468 | 6.540 | 6.417 | 6.120 | 5.664 |
| | | | | | | | | | | | | | | | | |
| Sample Name/ Grain size in microns | 399.05 | 447.74 | 502.37 | 563.67 | 632.45 | 709.62 | 796.21 | 893.36 | 1002.3 | 1124.6 | 1261.9 | 1415.8 | 1588.6 | 1782.5 | 2000.0 | |
| BP A Mid 5m | 3.654 | 3.345 | 3.052 | 2.751 | 2.429 | 2.081 | 1.701 | 1.317 | 0.930 | 0.595 | 0.297 | 0.092 | 0.018 | 0.000 | 0.000 | |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BP A Top 1m | 4.976 | 5.176 | 5.256 | 5.161 | 4.856 | 4.346 | 3.648 | 2.851 | 1.995 | 1.237 | 0.553 | 0.065 | 0.000 | 0.000 | 0.000 | |
| BP A Bot 9m | 4.603 | 4.611 | 4.533 | 4.334 | 3.998 | 3.535 | 2.958 | 2.332 | 1.674 | 1.100 | 0.571 | 0.169 | 0.033 | 0.000 | 0.000 | |
| BP B Top 1m | 4.853 | 4.916 | 4.877 | 4.694 | 4.346 | 3.840 | 3.193 | 2.481 | 1.734 | 1.087 | 0.504 | 0.073 | 0.007 | 0.000 | 0.000 | |
| BP B Mid 3m | 3.513 | 3.342 | 3.185 | 3.011 | 2.800 | 2.537 | 2.212 | 1.846 | 1.445 | 1.053 | 0.689 | 0.388 | 0.194 | 0.073 | 0.031 | |
| BP B Bot 7m | 3.240 | 3.141 | 3.062 | 2.966 | 2.821 | 2.608 | 2.313 | 1.957 | 1.553 | 1.147 | 0.766 | 0.450 | 0.224 | 0.073 | 0.024 | |
| BP C Top 1m | 4.250 | 3.474 | 2.781 | 2.178 | 1.669 | 1.247 | 0.889 | 0.593 | 0.354 | 0.134 | 0.033 | 0.000 | 0.000 | 0.000 | 0.000 | |
| BP C Mid 6m | 2.946 | 1.970 | 1.203 | 0.660 | 0.239 | 0.087 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | |
| BP C Bot 12m | 2.421 | 1.455 | 0.743 | 0.266 | 0.052 | 0.007 | 0.017 | 0.039 | 0.063 | 0.078 | 0.083 | 0.079 | 0.063 | 0.046 | 0.026 | |
| BP D Top 1m | 5.144 | 4.920 | 4.617 | 4.222 | 3.736 | 3.174 | 2.548 | 1.916 | 1.288 | 0.758 | 0.300 | 0.000 | 0.000 | 0.000 | 0.000 | |
| BP D Mid 5m | 3.239 | 3.106 | 3.038 | 3.005 | 2.967 | 2.883 | 2.716 | 2.456 | 2.100 | 1.687 | 1.250 | 0.845 | 0.528 | 0.253 | 0.132 | |
| BP D Bot 10 | 4.223 | 4.105 | 3.978 | 3.812 | 3.577 | 3.259 | 2.843 | 2.360 | 1.824 | 1.290 | 0.806 | 0.428 | 0.103 | 0.020 | 0.000 | |
| BP E Top 1 | 4.883 | 5.043 | 5.111 | 5.042 | 4.801 | 4.380 | 3.778 | 3.056 | 2.253 | 1.479 | 0.784 | 0.247 | 0.012 | 0.000 | 0.000 | |
| BP E Mid 4 | 4.629 | 4.787 | 4.896 | 4.916 | 4.809 | 4.548 | 4.115 | 3.540 | 2.842 | 2.108 | 1.396 | 0.794 | 0.356 | 0.097 | 0.026 | |
| BP E Bot 8 | 0.045 | 0.023 | 0.026 | 0.029 | 0.033 | 0.037 | 0.040 | 0.040 | 0.042 | 0.037 | 0.034 | 0.029 | 0.022 | 0.015 | 0.009 | |
| BP F Top 1m | 4.879 | 4.672 | 4.409 | 4.073 | 3.654 | 3.160 | 2.590 | 1.994 | 1.381 | 0.840 | 0.358 | 0.030 | 0.000 | 0.000 | 0.000 | |
| BP F Bot 9 | 3.573 | 3.825 | 4.102 | 4.339 | 4.460 | 4.404 | 4.133 | 3.659 | 3.010 | 2.283 | 1.552 | 0.920 | 0.460 | 0.150 | 0.047 | |
| BP F Mid 5 | 4.413 | 4.298 | 4.165 | 3.987 | 3.740 | 3.408 | 2.978 | 2.475 | 1.911 | 1.348 | 0.829 | 0.416 | 0.119 | 0.048 | 0.000 | |
| BP G Bot 8 | 4.056 | 3.938 | 3.822 | 3.674 | 3.464 | 3.171 | 2.780 | 2.317 | 1.795 | 1.270 | 0.787 | 0.404 | 0.095 | 0.018 | 0.000 | |
| BP G Top 1 | 4.872 | 4.712 | 4.497 | 4.204 | 3.819 | 3.347 | 2.788 | 2.189 | 1.575 | 0.997 | 0.513 | 0.221 | 0.045 | 0.007 | 0.000 | |
| BP G Mid 4 | 3.209 | 2.783 | 2.409 | 2.069 | 1.750 | 1.441 | 1.128 | 0.827 | 0.528 | 0.319 | 0.216 | 0.132 | 0.057 | 0.033 | 0.000 | |
| BP H Bot 6m | 4.659 | 4.045 | 3.395 | 2.730 | 2.087 | 1.484 | 0.946 | 0.524 | 0.068 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | |
| BP H Mid 4m | 3.569 | 2.924 | 2.335 | 1.807 | 1.351 | 0.963 | 0.635 | 0.384 | 0.128 | 0.040 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | |
| BP H Top 1 | 5.102 | 4.449 | 3.754 | 3.042 | 2.351 | 1.702 | 1.117 | 0.649 | 0.136 | 0.008 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | |
| Sample Name | 0.252 | 0.283 | 0.317 | 0.356 | 0.399 | 0.448 | 0.502 | 0.564 | 0.632 | 0.710 | 0.796 | 0.893 | 1.002 | 1.125 | 1.262 | |
| BP A Mid 5m | 0.000 | 0.021 | 0.065 | 0.089 | 0.117 | 0.144 | 0.166 | 0.185 | 0.200 | 0.211 | 0.219 | 0.225 | 0.232 | 0.238 | 0.246 | |
| BP A Top 1m | 0.000 | 0.000 | 0.000 | 0.000 | 0.059 | 0.079 | 0.095 | 0.108 | 0.120 | 0.131 | 0.140 | 0.149 | 0.159 | 0.170 | 0.182 | |
| BP A Bot 9m | 0.000 | 0.000 | 0.010 | 0.066 | 0.085 | 0.104 | 0.122 | 0.137 | 0.149 | 0.158 | 0.165 | 0.171 | 0.177 | 0.184 | 0.192 | |
| BP B Top 1m | 0.000 | 0.000 | 0.000 | 0.000 | 0.044 | 0.066 | 0.078 | 0.093 | 0.106 | 0.119 | 0.131 | 0.143 | 0.156 | 0.170 | 0.185 | |
| BP B Mid 3m | 0.000 | 0.000 | 0.000 | 0.000 | 0.060 | 0.082 | 0.102 | 0.119 | 0.136 | 0.152 | 0.167 | 0.181 | 0.196 | 0.212 | 0.228 | |

# Table 2

| Locations/ Methods | Hazen m/day | Slichter m/day | Terzaghi m/day | Beyer m/day | Sauerbrei m/day | Kruger m/day | Kozeny m/day | Zunker m/day | USBR m/day |
|---|---|---|---|---|---|---|---|---|---|
| BP A Bot 9m | 1.305 | 0.323 | 0.537 | 1.486 | 1.486 | 0.110 | 0.098 | 0.046 | 1.685 |
| BP A Mid 5m | 0.334 | 0.075 | 0.119 | 0.418 | 0.753 | 0.006 | 0.039 | 0.020 | 1.261 |
| BP A Top 1m | 1.521 | 0.370 | 0.612 | 1.763 | 1.659 | 0.014 | 0.141 | 0.068 | 2.030 |
| BP B Bot 7m | 0.092 | 0.019 | 0.028 | 0.128 | 0.342 | 0.005 | 0.034 | 0.020 | 0.808 |
| BP B Mid 3m | 0.163 | 0.034 | 0.052 | 0.222 | 0.413 | 0.007 | 0.060 | 0.033 | 0.899 |
| BP B Top 1m | 1.434 | 0.354 | 0.588 | 1.642 | 1.650 | 0.015 | 0.169 | 0.081 | 1.875 |
| BP C Bot 12m | 6.048 | 2.177 | 3.819 | 5.478 | 5.184 | 0.045 | 0.707 | 0.261 | 1.832 |
| BP C Mid 6m | 4.493 | 1.538 | 2.696 | 4.147 | 4.329 | 0.025 | 0.349 | 0.133 | 1.754 |
| BP C Top 1m | 5.279 | 1.754 | 3.059 | 4.942 | 4.700 | 0.063 | 1.261 | 0.490 | 2.212 |
| BP D Bot 10 | 2.212 | 0.600 | 1.020 | 2.350 | 2.246 | 0.018 | 0.212 | 0.094 | 1.884 |
| BP D Mid 5m | 0.269 | 0.057 | 0.089 | 0.356 | 0.591 | 0.009 | 0.075 | 0.041 | 1.244 |
| BP D Top 1m | 2.713 | 0.753 | 1.287 | 2.834 | 2.799 | 0.037 | 0.609 | 0.267 | 2.324 |
| BP E Bot 8 | 0.001 | 0.000 | 0.000 | 0.001 | 0.001 | 0.000 | 0.002 | 0.001 | 0.001 |
| BP E Mid 4 | 0.587 | 0.125 | 0.195 | 0.775 | 1.123 | 0.013 | 0.114 | 0.061 | 2.264 |
| BP E Top 1 | 0.792 | 0.177 | 0.283 | 1.002 | 1.201 | 0.014 | 0.144 | 0.075 | 1.970 |
| BP F Bot 9 | 0.484 | 0.103 | 0.160 | 0.643 | 0.797 | 0.010 | 0.075 | 0.041 | 1.616 |
| BP F Mid 5 | 2.989 | 0.837 | 1.434 | 3.084 | 2.687 | 0.022 | 0.269 | 0.117 | 2.074 |
| BP F Top 1m | 3.689 | 1.080 | 1.858 | 3.707 | 3.249 | 0.034 | 0.556 | 0.235 | 2.264 |
| BP G Bot 8 | 0.907 | 0.218 | 0.359 | 1.063 | 1.391 | 0.012 | 0.120 | 0.058 | 1.689 |
| BP G Mid 4 | 0.066 | 0.013 | 0.020 | 0.092 | 0.184 | 0.004 | 0.030 | 0.017 | 0.592 |
| BP G Top 1 | 3.361 | 0.959 | 1.642 | 3.439 | 3.024 | 0.027 | 0.371 | 0.159 | 2.290 |
| BP H Bot 6m | 0.267 | 0.058 | 0.092 | 0.346 | 0.461 | 0.010 | 0.094 | 0.050 | 0.950 |
| BP H Mid 4m | 0.040 | 0.008 | 0.011 | 0.054 | 0.147 | 0.004 | 0.024 | 0.014 | 0.596 |
| BP H Top 1 | 1.365 | 0.359 | 0.606 | 1.477 | 2.091 | 0.020 | 0.277 | 0.126 | 1.918 |

Table 3

| L/day | K=1 | K=7.5 | K=15 | K=25 |
|---|---|---|---|---|
| 30 m | 1976513. | 14823848 | 29647696 | 49412827 |
| 40 m | 2635351 | 19765130 | 39530261 | 65883769 |
| 50 m | 3294188 | 24706413 | 49412827 | 82354711 |

Table 4

| TN kg/day | K=1 | K=7.5 | K=15 | K=25 |
|---|---|---|---|---|
| 30 m | 11.79461737 | 88.4596303 | 176.9192606 | 294.8654343 |
| 40 m | 15.7261565 | 117.9461737 | 235.8923475 | 393.1539124 |
| 50 m | 19.65769562 | 147.4327172 | 294.8654343 | 491.4423905 |
| | | | | |
| TP kg/day | K=1 | K=7.5 | K=15 | K=25 |
| 30 m | 0.10742412 | 0.805680903 | 1.611361805 | 2.685603009 |
| 40 m | 0.14323216 | 1.074241204 | 2.148482407 | 3.580804012 |
| 50 m | 0.179040201 | 1.342801505 | 2.685603009 | 4.476005015 |
| | | | | |
| Background TN kg/day | K=1 | K=7.5 | K=15 | K=25 |
| 30 m | 5.604007499 | 42.03005624 | 84.06011249 | 140.1001875 |
| 40 m | 7.472009999 | 56.04007499 | 112.08015 | 186.80025 |
| 50 m | 9.340012499 | 70.05009374 | 140.1001875 | 233.5003125 |
| | | | | |
| Background TP kg/day | K=1 | K=7.5 | K=15 | K=25 |
| 30 m | 0.098825653 | 0.7411924 | 1.4823848 | 2.470641334 |
| 40 m | 0.131767538 | 0.988256534 | 1.976513067 | 3.294188445 |
| 50 m | 0.164709422 | 1.235320667 | 2.470641334 | 4.117735557 |

## Appendix 1 (Hydraulic conductivity formulas)

This Appendix contains the formulas used to calculate the hydraulic conductivity from the grain size distribution data.

**The Hazen Method**

(EasySolve, 2013)

HAZEN METHOD

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81 \ \mathrm{m/s^2}$$

$$v = 1.14 \ \mathrm{mm^2/s}$$

$$C = 0.06$$

$$\varphi(n) = 1 + 10 \cdot (n - 0.26)$$

$$n = 0.255 \cdot (1 + 0.83^{\eta})$$

$$\eta = d_{60}/d_{10}$$

$$d_e = d_{10}$$

VARIABLES

| | | | |
|---|---|---|---|
| $K$ | - | Hydraulic conductivity | (cm/s) |
| $g$ | - | Acceleration due to gravity | $(\mathrm{m/s^2})$ |
| $v$ | - | Viscosity | $(\mathrm{mm^2/s})$ |
| $C$ | - | Coefficient | – |
| $\varphi(n)$ | - | Function of porosity | – |
| $n$ | | Porosity | – |
| $\eta$ | - | Uniformity | – |
| $d_e$ | - | Effective grain diameter | (mm) |
| $d_{10}$ | - | Diameter at 10% | (mm) |
| $d_{60}$ | - | Diameter at 60% | (mm) |

**The Slichter Method**

(EasySolve, 2013)

SLICHTER METHOD

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81 \text{ m/s}^2$$

$$v = 1.14 \text{ mm}^2/\text{s}$$

$$C = 1$$

$$\varphi(n) = n^{3.287}$$

$$n = 0.255 \cdot \left(1 + 0.83^{\eta}\right)$$

$$\eta = d_{60}/d_{10}$$

$$d_e = d_{10}$$

VARIABLES

| | | |
|---|---|---|
| $K$ | - Hydraulic conductivity | (cm/s) |
| $g$ | - Acceleration due to gravity | $(\text{m/s}^2)$ |
| $v$ | - Viscosity | $(\text{mm}^2/\text{s})$ |
| $C$ | - Coefficient | – |
| $\varphi(n)$ | - Function of porosity | – |
| $n$ | Porosity | – |
| $\eta$ | - Uniformity | – |
| $d_e$ | - Effective grain diameter | (mm) |
| $d_{10}$ | - Diameter at 10% | (mm) |
| $d_{60}$ | - Diameter at 60% | (mm) |

**Terzaghi Method**

(EasySolve, 2013)

TERZAGHI METHOD

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81 \ \mathrm{m/s^2}$$

$$v = 1.14 \ \mathrm{mm^2/s}$$

$$0.61 < C < 1.07$$

$$\varphi(n) = \left( \frac{n - 0.13}{\sqrt[3]{1-n}} \right)^2$$

$$n = 0.255 \cdot \left(1 + 0.83^{\eta}\right)$$

$$\eta = d_{60}/d_{10}$$

$$d_e = d_{10}$$

VARIABLES

| | | |
|---|---|---|
| $K$ | - Hydraulic conductivity | (cm/s) |
| $g$ | - Acceleration due to gravity | $(\mathrm{m/s^2})$ |
| $v$ | - Viscosity | $(\mathrm{mm^2/s})$ |
| $C$ | - Coefficient | – |
| $\varphi(n)$ | - Function of porosity | – |
| $n$ | Porosity | – |
| $\eta$ | - Uniformity | – |
| $d_e$ | - Effective grain diameter | (mm) |
| $d_{10}$ | - Diameter at 10% | (mm) |
| $d_{60}$ | - Diameter at 60% | (mm) |

**Beyer Formula**

(EasySolve, 2013)

<u>BEYER METHOD</u>

$$K = \frac{g}{v} \cdot C \cdot \varphi(\mathrm{n}) \cdot d_e^2 \quad where: \quad g = 9.81 \text{ m/s}^2$$

$$v = 1.14 \text{ mm}^2/\text{s}$$

$$C = 0.06 \cdot \log\left(\frac{500}{\eta}\right)$$

$$\varphi(n) = 1$$

$$n = 0.255 \cdot \left(1 + 0.83^{\eta}\right)$$

$$\eta = d_{60}/d_{10}$$

$$d_e = d_{10}$$

<u>VARIABLES</u>

| | | |
|---|---|---|
| $K$ | - Hydraulic conductivity | $(\text{cm/s})$ |
| $g$ | - Acceleration due to gravity | $(\text{m/s}^2)$ |
| $v$ | - Viscosity | $(\text{mm}^2/\text{s})$ |
| $C$ | - Coefficient | – |
| $\varphi(n)$ | - Function of porosity | – |
| $n$ | Porosity | – |
| $\eta$ | - Uniformity | – |
| $d_e$ | - Effective grain diameter | $(\text{mm})$ |
| $d_{10}$ | - Diameter at 10% | $(\text{mm})$ |
| $d_{60}$ | - Diameter at 60% | $(\text{mm})$ |

**Sauerbrei Method**

(EasySolve, 2013)

SAUERBREI METHOD

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81 \text{ m/s}^2$$

$$v = 1.14 \text{ mm}^2/\text{s}$$

$$C = 0.375$$

$$\varphi(n) = \frac{n^3}{(1-n)^2}$$

$$n = 0.255 \cdot (1 + 0.83^{\eta})$$

$$\eta = d_{60}/d_{10}$$

$$d_e = d_{17}$$

VARIABLES

| | | | |
|---|---|---|---|
| $K$ | - | Hydraulic conductivity | (cm/s) |
| $g$ | - | Acceleration due to gravity | $(\text{m/s}^2)$ |
| $v$ | - | Viscosity | $(\text{mm}^2/\text{s})$ |
| $C$ | - | Coefficient | – |
| $\varphi(n)$ | - | Function of porosity | – |
| $n$ | | Porosity | – |
| $\eta$ | - | Uniformity | – |
| $d_e$ | - | Effective grain diameter | (mm) |
| $d_{10}$ | - | Diameter at 10% | (mm) |
| $d_{17}$ | - | Diameter at 17% | (mm) |
| $d_{60}$ | - | Diameter at 60% | (mm) |

### The Kruger Method

(EasySolve, 2013)

**KRUGER METHOD**

$$K = \frac{g}{\nu} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81 \text{ m/s}^2$$

$$\nu = 1.14 \text{ mm}^2/\text{s}$$

$$C = 4.35 \cdot 10^{-3}$$

$$\varphi(n) = \frac{n}{(1-n)^2}$$

$$n = 0.255 \cdot (1 + 0.83^{\eta})$$

$$\eta = d_{60}/d_{10}$$

$$\frac{1}{d_e} = \sum_{i-1}^{j-1} (f_{i+1} - f_i) \cdot \frac{2}{d_{i+1} + d_i}$$

**VARIABLES**

| | | |
|---|---|---|
| $K$ | - Hydraulic conductivity | (cm/s) |
| $g$ | - Acceleration due to gravity | $(\text{m/s}^2)$ |
| $\nu$ | - Viscosity | $(\text{mm}^2/\text{s})$ |
| $C$ | - Coefficient | – |
| $\varphi(n)$ | - Function of porosity | – |
| $n$ | Porosity | – |
| $\eta$ | - Uniformity | – |
| $d_e$ | - Effective grain diameter | (mm) |
| $d_{10}$ | - Diameter at 10% | (mm) |
| $d_{60}$ | - Diameter at 60% | (mm) |
| $d_i$ | - Diameter of fraction $i$ | (mm) |
| $f_i$ | - Fraction $i$ of sample | – |
| $i$ | - Fraction number | – |
| $j$ | - Number of fractions | – |

**The Kozeny Method**

(EasySolve, 2013)

<u>KOZENY METHOD</u>

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81 \text{ m/s}^2$$

$$v = 1.14 \text{ mm}^2/\text{s}$$

$$C = 0.83$$

$$\varphi(n) = \frac{n^3}{(1-n)^2}$$

$$n = 0.255 \cdot (1 + 0.83^{\eta})$$

$$\eta = d_{60}/d_{10}$$

$$\frac{1}{d_e} = \sum_{i-1}^{j-1} (f_{i+1} - f_i) \cdot \frac{d_{i+1} + d_i}{2 \cdot d_{i+1} \cdot d_i}^{1}$$

[1] When $d_1 < 0.0025$ the following term is added: $\left( \frac{3}{2} \cdot \frac{f_2 - f_1}{d_1} \right)$

<u>VARIABLES</u>

| | | |
|---|---|---|
| $K$ | - Hydraulic conductivity | $(\text{cm/s})$ |
| $g$ | - Acceleration due to gravity | $(\text{m/s}^2)$ |
| $v$ | - Viscosity | $(\text{mm}^2/\text{s})$ |
| $C$ | - Coefficient | – |
| $\varphi(n)$ | - Function of porosity | – |
| $n$ | Porosity | – |
| $\eta$ | - Uniformity | – |
| $d_e$ | - Effective grain diameter | (mm) |
| $d_{10}$ | - Diameter at 10% | (mm) |
| $d_{60}$ | - Diameter at 60% | (mm) |
| $d_i$ | - Diameter of fraction $i$ | (mm) |
| $f_i$ | - Fraction $i$ of sample | – |
| $i$ | - Fraction number | – |
| $j$ | - Number of fractions | – |

**The Zunker Method**

(EasySolve, 2013)

ZUNKER METHOD

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81\ \text{m/s}^2$$

$$v = 1.14\ \text{mm}^2/\text{s}$$

$$0.007 < C < 0.24$$

$$\varphi(n) = \left(\frac{n}{1-n}\right)^2$$

$$n = 0.255 \cdot \left(1 + 0.83^{\eta}\right)$$

$$\eta = d_{60}/d_{10}$$

$$\frac{1}{d_e} = \sum_{i-1}^{j-1} \left(f_{i+1} - f_i\right) \cdot \frac{d_{i+1} - d_i}{d_{i+1} \cdot d_i \cdot \left(\ln d_{i+1} - \ln d_i\right)}^{1}$$

[1] When $d_1 < 0.0025$ the following term is added: $\left(\frac{3}{2} \cdot \frac{f_2 - f_1}{d_1}\right)$

VARIABLES

| | | |
|---|---|---|
| $K$ | - Hydraulic conductivity | (cm/s) |
| $g$ | - Acceleration due to gravity | $(\text{m/s}^2)$ |
| $v$ | - Viscosity | $(\text{mm}^2/\text{s})$ |
| $C$ | - Coefficient | – |
| $\varphi(n)$ | - Function of porosity | – |
| $n$ | Porosity | – |
| $\eta$ | - Uniformity | – |
| $d_e$ | - Effective grain diameter | (mm) |
| $d_{10}$ | - Diameter at 10% | (mm) |
| $d_{60}$ | - Diameter at 60% | (mm) |
| $d_i$ | - Diameter of fraction *i* | (mm) |
| $f_i$ | - Fraction *i* of sample | – |
| $i$ | - Fraction number | – |
| $j$ | - Number of fractions | – |

**USBR Method**

(EasySolve, 2013)

USBR METHOD

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2 \quad where: \quad g = 9.81 \ \mathrm{m/s^2}$$

$$v = 1.14 \ \mathrm{mm^2/s}$$

$$C = 0.048 \cdot d_{20}^{0.3}$$

$$\varphi(n) = 1$$

$$n = 0.255 \cdot \left(1 + 0.83^{\eta}\right)$$

$$\eta = d_{60} / d_{10}$$

$$d_e = d_{20}$$

VARIABLES

| | | | |
|---|---|---|---|
| $K$ | - | Hydraulic conductivity | $(\mathrm{cm/s})$ |
| $g$ | - | Acceleration due to gravity | $(\mathrm{m/s^2})$ |
| $v$ | - | Viscosity | $(\mathrm{mm^2/s})$ |
| $C$ | - | Coefficient | – |
| $\varphi(n)$ | - | Function of porosity | – |
| $n$ | | Porosity | – |
| $\eta$ | - | Uniformity | – |
| $d_e$ | - | Effective grain diameter | $(\mathrm{mm})$ |
| $d_{10}$ | - | Diameter at 10% | $(\mathrm{mm})$ |
| $d_{20}$ | - | Diameter at 20% | $(\mathrm{mm})$ |
| $d_{60}$ | - | Diameter at 60% | $(\mathrm{mm})$ |

## Appendix 2 (Chemistry Data)

This Appendix contains the raw chemistry data from each bore. Cells with a "(#)" indicate a delay in hours before measurement of the data. This was because the sample needed to be settled before it could be filtered. "BP" stands for Broome Peninsula.

| Locations | Ammonium (N-NH4+) ug/L | Nitrate (N-NOx) ug/L | Phosphate(P-PO43-) ug/L | TN ug/L | TP ug/L | pH | EC (mS/cm) | Alkalinity (mg/L) | TDS (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| BP"A" Deep | 33.66 | 20429.2 | 49.1 | 18751.592 | 67.7455 | 6.87 | 17.3 | 464 | 11591 |
| BP"B" Deep | 1.9999 | 8784.75 | 105.95 | 8850.182 | 144.5575 | 8.16 | 8 | 266 | 5360 |
| BP"C" Deep | 1.9999 | 34200 | 92.97 | 34359.542 | 52.8985 | 7.83 | 6.74 | 252 | 4515.8 |
| BP"D" Deep | 88.44 | 827.1 | 117.78 | 2155.859 | 267.0835 | 7.26 | 2.7 | 324 (8h) | 1809 |
| BP"E" Deep | 143.691 | 149.506 | 82.148 | 1010.909 | 232.7995 | 7.15 | 4.14 | 326 | 2773.8 |
| BP"F" Deep | 75.63 | 12745.65 | 83.25 | 13047.842 | 41.2045 | 6.42 | 18.54 | 116 | 12421.8 |
| BP"G" Deep | 1.9999 | 2415.33 | 82.02 | 2628.872 | 45.3955 | 6.96 | 21.5 | 194 | 14405 |
| BP"H" Deep | 51.21 | 5321.22 | 75.99 | 5875.022 | 58.545 | 7.69 | 0.198 | 584 | 132.66 |
| BP "A" Shallow | 11.7 | 10870 | 52.02 | 11331.242 | 260.5045 | 7.02 | 1.908 | 282 (20h) | 1278.36 |
| BP "B" Shallow | 36.96 | 10048.14 | 87.42 | 10456.682 | 147.4915 | 8.15 | 1.118 | 128 (5h) | 749.06 |
| BP "C" Shallow | 1.9999 | 421.29 | 87.54 | 854.711 | 113.4235 | 7.32 | 0.145 | 176 | 97.15 |
| BP "D" Shallow | 1.9999 | 445.14 | 102.93 | 982.985 | 172.2805 | 7.29 | 5.44 | 688 (6h) | 3644.8 |
| BP "E" Shallow | 8.392 | 21.845 | 32.919 | 1299.917 | 292.9615 | 7.05 | 1.045 | 200 (20h) | 700.15 |
| BP "F" Shallow | 1.9999 | 3327.81 | 96.6 | 4169.012 | 165.0835 | 6.85 | 8.15 | 246 (6h) | 5460.5 |
| BP "G" Shallow | 1.9999 | 6261.9 | 90.48 | 6190.922 | 136.2175 | 7.42 | 0.968 | 220 | 648.56 |
| BP "H" Shallow | 49.893 | 1458.05 | 53.495 | 2031.398 | 116.1115 | 7.41 | 0.35 | 116 | 234.5 |
| Cable Beach | 6.344 | 3115.3 | 30.773 | 3242.882 | 31.5925 | 7.05 | 0.129 | 246 | 86.43 |
| Bedford Park | 12.572 | 1821.05 | 22.819 | 2338.925 | 30.9835 | 6.85 | 5.24 | 192 | 3510.8 |
| Police Station | 29.879 | 4171.55 | 13.287 | 4218.632 | 7.0765 | 6.92 | 2.75 | 160 | 1842.5 |
| KRO | 66.605 | 4815.7 | 25.739 | 4779.152 | 40.8985 | 6.99 | 3.04 | 206 | 2036.8 |

# Appendix 3 (Lithological Logs)

This Appendix contains the visual lithological logs as well as the chip data taken from the deep bore at each location. “BP” stands for Broome Peninsula.

### Location A

| | |
|---|---|
| **Report Date:** 9/24/2013 | **Boring No.:** BP A |
| **Company Name:** | **Surface Elevation:** 14.80 Meters WGS 84 |
| **Site Name:** BP A | **Total Depth:** 36 Meters |
| **Location:** Broome | **Start:** |
| **Logged By:** Nicholas Wright | **Finish:** |
| **Contractor:** | **Equipment Type:** Mud and Air Rotary Drilling |
| **Conditions:** | **Sample Hammer Torque:** |
| **Comments:** | **Sampling Methods:** Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 8 | 7 | Pin | Iron oxide stained unconsolidated sand (F-VF) | | | | | |

Page 1 of 5

**Boring No.:** BP A

9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 8 | 2 | 5 | Pin | Iron oxide stained unconsolidated sand (F-VF) and significant root/organic matter | | | | | |
| | 10 | 1 | 4 | Pin+Grav | Iron oxide stained unconsolidated sand (M-VF) and Iron rich gravel 1cm max | | | | | |
| | 11 | 1 | 3 | Pin+Grav | Iron oxide stained unconsolidated sand (M-VF) and Iron rich gravel 2cm max | | | | | |
| | 12 | 1 | 2 | Pin+Grav | Iron oxide stained unconsolidated sand (M-VF) and Iron rich gravel 3cm max | | | | | |
| | 13 | 1 | 1 | Pin+Grav | Iron oxide stained unconsolidated sand (M-VF) and Iron rich gravel 3cm max | | | | | |
| | 14 | 6 | -5 | BSS | Siliceous white yellow red Broome Sandstone (F-VF) | | | | | |

Page 2 of 5

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Type | Rate | |
| | 20 | 4 | -9 | BSS | Mica rich, friable (F) | | | | | |

*LITHOLOGY DATA PRINTED ON NEXT PAGE*





| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Type | Rate | |
| | 24 | 4 | -13 | BSS | 80% white siliceous, 20% yellow (iron), mica rich, friable (F) | | | | | |
| | 28 | 8 | -21 | BSS | 60% white siliceous, 40% yellow (iron) mica rich, friable (F) | | | | | |

**Boring No.:** BP A 9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|

36 Meters T.D.

# Location B



| Report Date: 9/24/2013 | Boring No.: BP B |
|---|---|
| Company Name: | Surface Elevation: 14.80 Meters WGS 84 |
| Site Name: PB B | Total Depth: 35 Meters |
| Location: Broome | Start: |
| Logged By: Nicholas Wright | Finish: |
| Contractor: | Equipment Type: Mud and Air Roraty Drilling |
| Conditions: | Sample Hammer Torque: |
| Comments: | Sampling Methods: Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 8 | 7 | Pin | Iron oxide stained unconsolidated sand (F) | | | | | |
| | 8 | 9 | -2 | BSS | Red BSS, low mica content, friable (F) | | | | | |
| | 17 | 18 | -20 | BSS | BSS, moderate mica content, friable, white | | | | | |

**Boring No.:** BP B 9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|

35 Meters T.D.

# Location C



| | |
|---|---|
| **Report Date:** 9/24/2013 | **Boring No.:** BP C |
| **Company Name:** | **Surface Elevation:** 13.88 Meters WGS 84 |
| **Site Name:** BP C | **Total Depth:** 30 Meters |
| **Location:** Broome | **Start:** |
| **Logged By:** Nicholas Wright | **Finish:** |
| **Contractor:** | **Equipment Type:** Mud and Air Roraty Drilling |
| **Conditions:** | **Sample Hammer Torque:** |
| **Comments:** | **Sampling Methods:** Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 7 | 7 | Pin | Iron oxide stained unconsolidated sand (F) | | | | | |
| | 7 | 7 | 0 | Pin+Org | Iron oxide stained unconsolidated sand (VF-M), black organic rich sandstone (F), shel fragments | | | | | |
| | 14 | 15 | -15 | Pin+BSS | Iron oxide stained unconsolidated sand (F) + red BSS (F), | | | | | |

**Boring No.:** BP C 9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 29 | 1 | -16 | BSS | White BSS, low mica | | | | | |

30 Meters T.D.

## Location D



| | |
|---|---|
| **Report Date:** 9/24/2013 | **Boring No.:** BP D |
| **Company Name:** | **Surface Elevation:** 13.10 Meters WGS 84 |
| **Site Name:** PB D | **Total Depth:** 35 Meters |
| **Location:** Broome | **Start:** |
| **Logged By:** Nicholas Wright | **Finish:** |
| **Contractor:** | **Equipment Type:** Mud and Air Roraty Drilling |
| **Conditions:** | **Sample Hammer Torque:** |
| **Comments:** | **Sampling Methods:** Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 12 | 1 | Pin | Iron oxide stained unconsolidated sand (M-VF) | | | | | |
| | 12 | 5 | -4 | BSS+Grav | 70% BSS, friable, moderate mica content, weekly siliceous (F-VF), 30% Iron rich gravel 2cm max | | | | | |
| | 17 | 8 | -12 | BSS | 90% white 10% yellow, moderate mica content, friable | | | | | |

EasySolve Software LLC
P.O. Box 3247, Eagle, Colorado 81631
www.easysolve.com (970) 319-1591

Page 1 of 2

**Boring No.:** BP D 9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 25 | 10 | -22 | BSS | 100% white, low mica content, friable | | | | | |

35 Meters T.D.

# Location E



| | |
|---|---|
| **Report Date:** 9/24/2013 | **Boring No.:** BP E |
| **Company Name:** | **Surface Elevation:** 20.45 Meters WGS 84 |
| **Site Name:** BP E | **Total Depth:** 36 Meters |
| **Location:** Broome | **Start:** |
| **Logged By:** Nicholas Wright | **Finish:** |
| **Contractor:** | **Equipment Type:** Mud and Air Roraty Drilling |
| **Conditions:** | **Sample Hammer Torque:** |
| **Comments:** | **Sampling Methods:** Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 6 | 14 | Pin | Iron oxide stained unconsolidated sand (F) | | | | | |
| | 6 | 4 | 10 | Pin+Grav | Iron oxide stained unconsolidated sand (F) and Iron rich gravel 1cm max | | | | | |
| | 10 | 1 | 9 | Pin+Grav | Iron oxide stained unconsolidated sand (F) and Iron rich gravel 1cm max | | | | | |
| | 11 | 10 | -1 | BSS+Grav | Siltstone, white, highly siliceous (F), Iron rich gravel 0.5cm max | | | | | |

**Boring No.:** BP E 9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 21 | 5 | -6 | BSS | Dark purple, moderate mica content, highly siliceous (F) | | | | | |
| | 26 | 3 | -9 | BSS | 50% white BSS %50 yellow BSS, low mica content, friable (F) | | | | | |
| | 29 | 2 | -11 | BSS+Grav | 50% white BSS 50% yellow BSS, low mica content, friable, Iron rich gravel 2cm max | | | | | |
| | 31 | 2 | -13 | BSS+Grav | 50% white BSS 50% yellow BSS, low mica content, friable, Iron rich gravel 1cm max | | | | | |
| | 33 | 2 | -15 | BSS | 50% white BSS %50 yellow BSS, low mica content, friable | | | | | |
| 36 Meters T.D. | 35 | 1 | -16 | BSS+Grav | 50% white BSS 50% yellow BSS, low mica content, friable, Iron rich gravel 1cm max | | | | | |

## Location F



| | | |
|---|---|---|
| **Report Date:** 9/24/2013 | | **Boring No.:** BP F |
| **Company Name:** | | **Surface Elevation:** 15.37 Meters WGS 84 |
| **Site Name:** PB F | | **Total Depth:** 36 Meters |
| **Location:** Broome | | **Start:** |
| **Logged By:** Nicholas Wright | | **Finish:** |
| **Contractor:** | | **Equipment Type:** Mud and Air Roraty Drilling |
| **Conditions:** | | **Sample Hammer Torque:** |
| **Comments:** | | **Sampling Methods:** Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 11 | 4 | Pin | Iron oxide stained unconsolidated sand (F) | | | | | |
| | 11 | 2 | 2 | BSS+Pin +Grav | 50% red BSS, 50% white BSS, low mica, friable, (F), 1cm Iron disks | | | | | |
| | 13 | 18 | -16 | BSS | 60% white BSS 30% red BSS 10% yellow BSS, friable, high mica, (F) | | | | | |

**Boring No.:** BP F | 9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 31 | 5 | -21 | BSS | 60% white BSS 30% red BSS 10% yellow BSS, friable, high mica | | | | | |

36 Meters T.D.

## Location G



| | |
|---|---|
| **Report Date:** 9/24/2013 | **Boring No.:** BP G |
| **Company Name:** | **Surface Elevation:** 11.52 Meters WGS 84 |
| **Site Name:** PB G | **Total Depth:** 30 Meters |
| **Location:** Broome | **Start:** |
| **Logged By:** Nicholas Wright | **Finish:** |
| **Contractor:** | **Equipment Type:** Mud and Air Roraty Drilling |
| **Conditions:** | **Sample Hammer Torque:** |
| **Comments:** | **Sampling Methods:** Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 3 | 9 | Pin | Iron oxide stained unconsolidated sand (M-F) | | | | | |
| | 3 | 4 | 5 | Pin | Iron oxide stained unconsolidated sand (F) | | | | | |
| | 7 | 3 | 2 | Pin+Grav | Iron oxide stained unconsolidated sand (F) and Iron rich gravel 1cm max | | | | | |
| | 10 | 7 | -5 | BSS+Grav | BSS, friable, low mica content, friable, (F), Iron rich gravel 1.5cm max | | | | | |
| | 17 | 5 | -10 | BSS | BSS, friable, white, Low mica, (F), | | | | | |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 22 | 3 | -13 | Sand | lightly iron oxide stained unconsolidated sand | | | | | |
| | 25 | 5 | -18 | BSS | White, friable, low mica (F) | | | | | |

30 Meters T.D.



# Location H

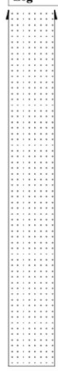
| Report Date: 9/24/2013 | Boring No.: BP H |
|---|---|
| Company Name: | Surface Elevation: 10.17 Meters WGS 84 |
| Site Name: PB H | Total Depth: 30 Meters |
| Location: Broome | Start: |
| Logged By: Nicholas Wright | Finish: |
| Contractor: | Equipment Type: Mud and Air Roraty Drilling |
| Conditions: | Sample Hammer Torque: |
| Comments: | Sampling Methods: Grab sample every meter |

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 2 | 8 | Pin | Iron oxide stained unconsolidated sand (M-VF) | | | | | |
| | 2 | 1 | 7 | Pin | Iron oxide stained unconsolidated sand (M-VF) significant root/organic matter. | | | | | |
| | 3 | 4 | 3 | Pin | Iron oxide stained unconsolidated sand (M-VF) | | | | | |
| | 7 | 4 | -1 | Pin+Grav | Iron oxide stained unconsolidated sand (M-VF) and Iron rich gravel 1cm max | | | | | |
| | 11 | 5 | -6 | BSS | Red stained, friable, low mica content (F) | | | | | |
| | 16 | 14 | -20 | BSS | 90% white 10% yellow, low mica, friable | | | | | |

**Boring No.:** BP H

9/24/2013

| Graphical Log | Top Depth (Meters) | Thick. (Meters) | Bt.Elev. (Meters) | Strata Code | Material Description | Sample No. | Sampling Method | Penetration Type | Penetration Rate | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|



30 Meters T.D.

## Appendix 4 (Water Table Heights)

This appendix contains the ground level height (AHD), location, bore depth, water depth from ground level and corrected water table height for all of the bores used within the Broome Peninsula to create the groundwater morphology model. All units are in meter, locations are in UTM WGS84

| Bore No | Easting | South | Ground Lev AHD | Bore Depth | Water Depth | Corrected WL |
|---|---|---|---|---|---|---|
| A Deep | 418214.1 | 8015047.1 | 13.42 | 35.18 | 11.32 | 2.10 |
| A Shallow | 418212.7 | 8015047.7 | 13.42 | 18.09 | 11.12 | 2.30 |
| B Deep | 418004.2 | 8014886.6 | 14.80 | 35.83 | 12.64 | 2.16 |
| B Shallow | 418003.7 | 8014886.4 | 14.80 | 18.07 | 12.55 | 2.25 |
| C Deep | 418360.9 | 8012602.3 | 13.88 | 29.83 | 12.07 | 1.81 |
| C Shallow | 418360.7 | 8012603.0 | 13.88 | 17.99 | 12.25 | 1.63 |
| D Deep | 416139.7 | 8014182.5 | 13.10 | 34.87 | 11.23 | 1.87 |
| D Shallow | 416140.1 | 8014183.6 | 13.10 | 18.08 | 11.03 | 2.07 |
| E Deep | 416634.1 | 8013797.4 | 20.45 | 35.87 | 18.43 | 2.02 |
| E Shallow | 416634.5 | 8013797.4 | 20.45 | 24.01 | 18.43 | 2.02 |
| F Deep | 416914.3 | 8012834.0 | 15.37 | 35.81 | 13.55 | 1.82 |
| F Shallow | 416914.6 | 8012834.6 | 15.37 | 17.55 | 13.53 | 1.84 |
| G Deep | 416532.5 | 8012406.3 | 11.52 | 29.87 | 9.96 | 1.56 |
| G Shallow | 416532.4 | 8012407.0 | 11.52 | 15.85 | 9.81 | 1.71 |
| H Deep | 415450.8 | 8010626.4 | 10.17 | 31.86 | 8.74 | 1.43 |
| H Shallow | 415450.3 | 8010626.2 | 10.17 | 15.28 | 8.75 | 1.42 |
| Town Beach | 418915.9 | 8013526.9 | 11.02 | 19.19 | 7.65 | 3.37 |
| Fire Station | 419077.3 | 8012976.4 | 9.17 | 19.89 | 9.01 | 0.16 |