Assessment of Coastal Groundwater and Linkages with Ningaloo Reef- Final Report February 2010

Compiled by Lindsay B. Collins and Alexandra Stevens

Applied Sedimentology and Marine Geoscience Group

Department of Applied Geology Curtin University of Technology, WA

PRODUCED FOR

Western Australian Marine Science Institution (WAMSI)

CONTENTS

PROJECT DETAILS

WAMSI project reference no: WAMSI Node 3 Project 3.10

Project title: Assessment of Coastal groundwater and Linkages with Ningaloo Reef

Node leader: Chris Simpson

Project leader: Prof Lindsay B Collins

Project personnel: Alexandra Stevens, Researcher; Deanna Wilson: MSc student.

Project duration: 2 Years, end March 2010

Due date for current milestone report: 30 December 2009

PROJECT OBJECTIVES

The aims of the project are:

1. To characterise the western coastal geological and aquifer structure
2. To characterise the hydrogeology of the western coastal plain and availability of potable water
3. To characterise the coastal seawater/freshwater interface, and its behaviour in relation to seasonal fluctuations, tidal and episodic events (e.g. cyclones)
4. To determine the physico-chemical structure of the freshwater/saltwater system
5. To determine the pathways of groundwater discharge to the Ningaloo Reef lagoon, and physical and/or benthic 'signals' of discharge, by remote sensing and ground truth studies

EXECUTIVE SUMMARY

1. Introduction

This report outlines the final report of WAMSI Project 3.10. The project was achieved in parallel with a number of other WAMSI projects which have independent outputs but will assist remote sensing in this study by providing information on the Ningaloo reef system, particularly with respect to biophysical variables, habitats and key ecological processes, seabed geomorphology, biodiversity and storm surge and tsunami impacts. These research topics are being addressed through interactive research in progress as part of WAMSI node 3.

Little is known about the groundwater system and its connectivity with Ningaloo reef but there is sufficient information to indicate that groundwater discharge from the hinterland to the reef system is a significant process which probably has linkages to issues such as stygofauna habitat, water chemistry and biodiversity patterns within the reef lagoon. Groundwater influx is expected to be responsive to recharge and runoff events, tidal oscillations, seasonal variations and storm events. Groundwater discharge has been shown to be significant within the lagoon of the Great Barrier Reef, for example by delivering nutrients to the reef system, and analogies are to be expected with Ningaloo Reef due to the presence of a karst hinterland and distinctive palaeochannel systems encroaching into the reef lagoon.

Project findings have been that spatial patterns do exist in the groundwater data for the Ningaloo Reef Marine Park and it is possible to predict areas where groundwater discharge is likely using a combination of fresh groundwater indicators such as well locations, karst, Ficus distribution and stream discharge. Predictive analysis has highlighted a number of ‘likely areas’ for groundwater discharge and will focus future groundtruth studies and area to be covered by these studies. A map of the groundwater system has also been composed based on the predictive analysis. Further, work has been undertaken on hyperspectral data analysis in the predicted areas to determine if a particular spectral signature exists for groundwater discharge in a marine setting and to further refine the study sites. It is unlikely that a ‘pure’ spectral signature exists for SGD, rather there is a combination of signals relating to the benthic cover at and around the discharge point which will be dependant on the nature of the groundwater and extent of the discharge. Table 1.1 summarises the findings of the predictive analysis for probable groundwater discharge areas identified by this study.

Area	Location	Groundwater Indicators	Terrain/ Geology	Mechanism
1	West of Bundera sinkhole	Anecdotal evidence of 'bubbling' groundwater in lagoon; karst: Bundera sinkhole	Limestone coastal plain and sandy beach ridges	Tidal oscillation within sinkhole suggesting a karst conduit.
2	Yardie Creek	Ficus along creek and at coast, marine channel, well, permanent water	Dissected limestone plain and coastal barrier	Freshwater input from adjacent creek and through permeable barrier, rockhole:karst
3	Mandu Mandu Creek	Ficus, drainage discharge points, well, offshore alluvial fans	Limestone plain and coastal alluvial fan complex	Freshwater input from adjacent creek and porous alluvial fans, karst
4	Turquoise Bay	Marine channel, drainage discharge points, karst, abandoned well and Ficus	Sand cusp backed by limestone plain	Discharge through sandy beach ridges
5	Lakeside	Marine channel, drainage discharge points, karst conduit with south to north waterflow and well	Limestone plain, alluvial fan complex, sand cusp and sandy beach ridges	Marine features, karst conduit with south to north water flow in coastal plain, surveyed length ~450m, porous alluvial fan
6	Mangrove Bay	Well, drainage discharge points, mangroves likely influenced by freshwater	Limestone plain, alluvial fan, embayments with mangroves and sand barriers	Cluster of springs, porous alluvial fan

Table 1.1 Summary of remote sensing findings. Areas of high probability of groundwater discharge described by groundwater indicators, terrain and likely discharge mechanism.

Given that there is a high probability of significant groundwater input to the reef system, in addition to surface flows during wet periods, care needs to be taken if any future coastal plain tourism or other developments occur to ensure that nutrient inputs to the hydrological system (and thereby the reef ecosystem) are minimised. In addition, any groundwater usage proposals on or near the coastal plain will require careful evaluation in view of supply limitations and the fragile nature of the coastal groundwater system.

This study has evolved through the following stages:
Initially Node 3 planners wished to link groundwater research to concurrent work on the stygofauna, but this proposal foundered before implementation in the initial stages of Node 3 activities. The research plan included establishment of western coastal plain monitoring boreholes.

A Curtin seminar and review of groundwater issues was held jointly with Government hydrogeologists and CSIRO cluster researchers, during 2007, in an attempt to promote groundwater research.

WAMSI Project 3.10 was established in mid 2008 as a remote sensing study of the groundwater system, and final results are described in this report. The remote sensing outcomes essentially relate to objective 5 and conclude this part of the project.

Through a separately funded Curtin study of the Exmouth borefield (Lee, 2008) a hydrogeological model prepared for the eastern coastal plain provided, in the absence of western borehole information, a useful model for the western coastal plain, since the geology and stratigraphy are similar on either side of the Cape Range anticline. These findings (summarised in this report) are applicable to objectives 1-2 of WAMSI project 3.10.

Working in the offshore region during AIMS seabed surveys, researchers in Projects 3.1.1 and 3.4 discovered seafloor mounds which are likely submarine groundwater discharge points. These features are close to the Last Glacial Maximum shoreline (SL-120m/18ka BP; Fig 4.7) and may represent termination points of lowstand karst features which would be expected to have developed along this palaeoshoreline. The controls exerted by oscillating sea levels and groundwater interfaces operating at geological timescales are important for processes such as karst development, submarine groundwater discharge and stygofauna evolution.

Discussions of research progress during the second half of 2009 led to formulation of a partnership between project 3.10 and the Bundera Project led by Dr Bill Humphreys of WAM, in which it is proposed to drill and instrument a borehole transect at Bundera for stygofauna and groundwater monitoring within the western coastal plain at Bundera, a known stygofauna and karst conduit site.

This proposal (extending beyond the effective life of project 3.10) has been agreed to by the Node 3 leader and WAMSI, and is summarised in Appendix 4. It will produce data on objectives 3-5 of project 3.10 during 2010 and potentially beyond, re-establish the planned link between groundwater and stygofauna research, pool scarce resources for expensive drilling, and is a logical continuation of groundwater related research at Ningaloo Reef.

2. Project timescale, funding and milestones

The project was designed as a 2 year study. Funding approval was received in February 2008 and the project commenced on 1 April, 2008. The project was funded as a remote sensing study which grew out of an original more ambitious request to use boreholes to monitor coastal plain groundwater. This progress report constitutes the final project milestone.

3. Project Progress

Briefly the progress of the project is as follows

- Initial startup of the project was undertaken in the first half of 2008and included completion of a literature review, acquisition of georeferenced karst and Ficus locations as indicators of shallow groundwater, acquisition of imagery and incorporation of GIS information from previous research projects.
- In July 2008 a Masters student, Deanna Wilson, joined the project to work on the remote sensing aspects of the study using -GIS and remote sensing software. Section 4 outlines her work
- GIS work continued in 2009 including characterisation of the geology of the Cape Range and, particularly, the western coastal plain and bathymetry analysis.
- Negotiations with the WA Museum during the second half of 2009 led to a plan to link ongoing research on groundwater monitoring with downhole stygofauna monitoring in a new drilling transect at Bundera, initially scheduled to commence in late 2009, but now rescheduled for 2010
- While it was not possible to carry out borehole drilling on the western coastal plain, the results of a Curtin PhD study of the hydrogeology of the Exmouth borefield produced

results for the eastern coastal plain which are applicable to the western coastal groundwater system and Project 3.10.

4. Remote Sensing and GIS Analysis of Groundwater Occurrence in Ningaloo Reef Marine Park, Western Australia.

4.1 Introduction

The area covered in this study is the western extent of the Cape Range peninsula and adjacent Ningaloo Reef Marine Park. The aim of this study was to help reduce the threat of pollution through better coastal and groundwater management. Fuel and oil, sewage and other wastes from vessels or contaminants from coastal developments can affect water quality. This study focused on predicting the occurrence of fresh groundwater discharge from the terrestrial environment to the adjacent marine environment. There is currently only one confirmed fresh groundwater discharge point recorded within the study area.

Groundtruth studies can be time consuming, expensive and impinge on the natural ecosystem. Reducing the duration of groundtruth studies and the area covered, but at the same time increasing the chance of locating fresh groundwater discharge, is cost effective and aids environment conservation. Spatial analysis was used to investigate different techniques for predicting fresh groundwater occurrence. Preliminary analysis included correlation between data and visual placement of data with more developed analysis including hydrology studies of drainage patterns and density of fresh water indicators. Hyperspectral interpretation aimed to minimise predicted results for follow-up research.

Previous research in the area includes monitoring coral reef growth, substrate mapping of sanctuary zones, GIS risk assessment, terrestrial park mapping, borehole studies and hyperspectral data processing.

The aims for this Ningaloo study were:

- To develop a groundwater geodatabase
- GIS interpretation of the local groundwater system
- To predict groundwater discharge into the marine setting
- To interpret hyperspectral datasets

- To synthesise information for project results.

4.2 Background

4.2.1 Project Area

Ningaloo Reef Marine Park (NRMP) is located along the coast of Western Australia stretching northwards to just below the Tropic of Capricorn. It was declared a marine park in May 1987 and includes both State and Commonwealth waters covering a total area of 5076km² (Commonwealth of Australia, 2006).

Ningaloo Reef is one of the longest fringing barrier reefs in the world and the only fringing reef located on the western side of a continent (Taylor and Pearce, 1999). In comparison with other reefs around the world, Ningaloo is still pristine due to clear oceanic waters and low levels of land-based pollution. A rapid 100m drop-off of seafloor depth in the Park's north lies within 6km of the coastline where oceanic species such as migrating whales can be found close to shore.

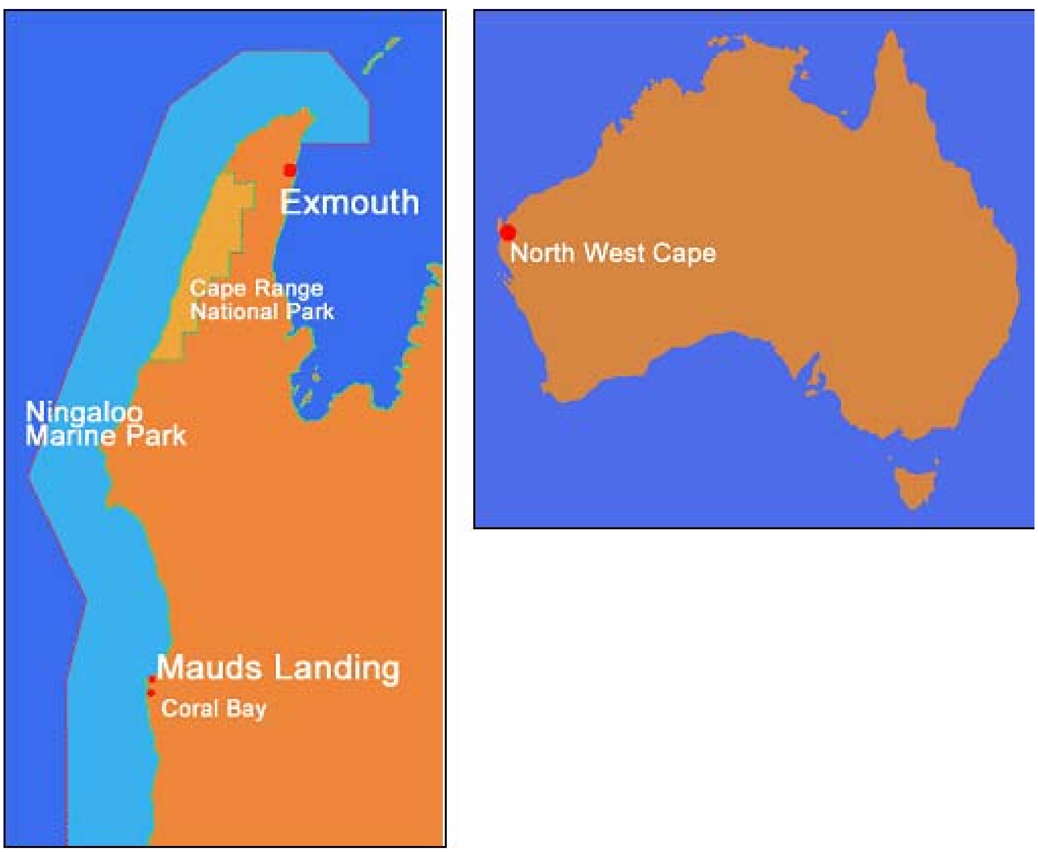


Figure 4.1 - Cape Range and Ningaloo Reef Marine Park Location Map (Australian Marine Conservation Society, 2007).

The NRMP hosts diverse habitats including Open Ocean, continental slope and shelf, coral reef, lagoons and intertidal coastal zones. These habitats support many flora and fauna including over 200 species of coral, 600 species of mollusc and 500 species of fish including sharks, manta rays and migratory fish (Commonwealth of Australia, 2006). The park is also an important habitat for mammals such as dugongs, dolphins and whales. "Migrating birds also frequent the area along with turtles that feed on the Park's waters and nest in the many Cape Range peninsula beaches" (Commonwealth of Australia, 2006).

4.2.2 Climate and Physiography

The climate of the Cape Range peninsula in general is hot and arid with the annual average minimum and maximum temperatures being 19.1ºC and 30.8ºC (The Weather Co., 2008).

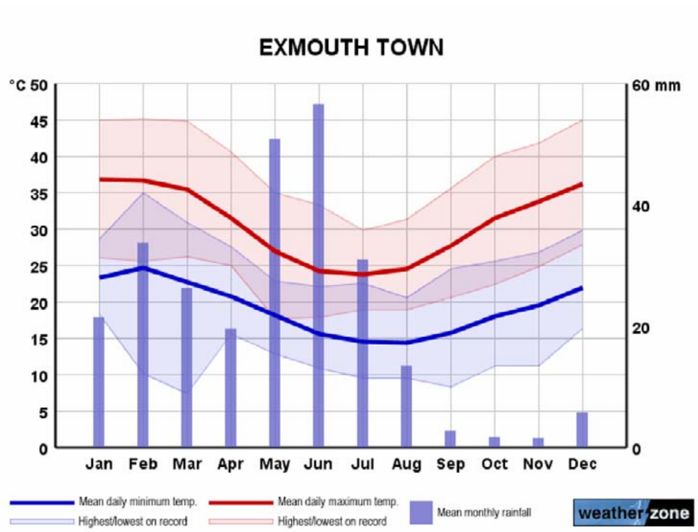


Figure 4.2 – Exmouth Town Annual Temperatures and Rainfall (The Weather Co. 2008)

Cyclones occur in the area approximately every 3-5 years and mid-latitude depressions cause peaks and falls in climate in both summer and winter (Collins, et al., 2006). Sea surface temperature ranges from a high of 28ºC to a low of 22ºC with a tidal range in the northern part of the reef up to 1.7m. The mean annual wind speed at Carnarvon, just south of the reef is 6.1m/s with a mean wind direction of 184º. The regional oceanography is dominated by the Leeuwin Current, a warm low salinity current that flows southward along the adjacent shelf in autumn and winter, close to reef and coast. The current is an important control on larval delivery and probably suppresses upwelling, which, though little recorded, most likely influences primary productivity off Ningaloo Reef (D'Adamo & Simpson, 2001). The northward Ningaloo Current is active in spring and summer (Taylor & Pearce, 1999) and local shelf-scale hydrodynamic processes probably influence key ecological processes in the region.

The Cape Range peninsula and Exmouth Gulf are part of the southern, primarily onshore section of the Carnarvon Basin known as the Southern Carnarvon Basin. The basin contains geological sequences from the Silurian, Devonian, Early Carboniferous and Upper Carboniferous – Permian time periods (EPA, 1999).

The entire province is underlain by about 10km of sedimentary rocks with those forming the peninsula itself predominately carbonate sediments. Shallow water marine, alluvial, littoral and aeolian sediments of recent age form coastal plains on each side of the peninsula. The area is tectonically complex with the Cape Range Anticline forming a spine running approximately north-south which has been rising intermittently since the late Cretaceous.

It is the upper units (Tulki and Trealla Limestones) of the calcareous sedimentary rocks which have karstified and extensively eroded. These are approximately 100m thick (EPA, 1999).

4.2.3 Topography and Drainage

The topography and drainage of the Cape Range has developed in response to the local geology and geological events. The crest of the range is gently undulating and rises to approximately 100m above sea level at Mt Hollister. It has gently sloping flanks that broaden down to relatively flat coastal plains. Preserved along the crest of the range are remains of a pre-existing plateau where sinkholes and areas of internal drainage are identified (Allen, 1993). Murphy & Nance (1999) modelled the present day drainage system. The crest of the range provides a regional drainage divide with drainage systems to the east and west. In the northern two thirds of the range the drainage system is deeply incised whilst in southern regions drainage is less incised and partly covered by sand sheets. The drainage pattern on the northeastern side of the range is dendritic whereas in the northwest it is trellised. In the south the drainage is predominately dendritic with some long, fault controlled reaches such as Yardie Creek (Allen, 1993).

4.3 Geological Setting

About one third of the Cape Range peninsula is included in the Cape Range National Park which abuts the Ningaloo Reef Marine Park (NRMP) on the west coast. The peninsula is predominately Tertiary to Quaternary limestones that are richly fossiliferous.

Interpretation of geological structure is based on seismic and oil well data that show the area is tectonically complex. The Cape Range Anticline has resulted from inversion of fault movement along the Learmonth Fault. Cape Range is a gentle, slightly asymmetric anticline with steeper flanks on the eastern side (Allen, 1993).

Over 300 caves are known on the Cape Range with many more possibly undiscovered. The entrance to some caves is given on existing topographic maps, whilst the sites of many others are recorded but not published (W.F. Humphreys, per. comm. cited in Allen, 1993). Along the crest of the range, caves are developed on the regional divide between main drainage lines. Many entrances to caves are marked by Ficus trees which have sub-aerial roots extending vertically for a considerable distance. The caves that have been explored are generally dry with poor cave ornamentation. Slow flowing stream and minor seepages of water have been seen after heavy rainfall in the larger known cave systems (Allen, 1993).

On the coastal plain the cave system in the sediments and underlying Tulki Limestone is partially or totally filled with water that may extend for some distance below sea level and offshore (Allen, 1993).

4.3.1 Cave Systems

A variety of terrestrial karst landforms are found at Cape Range., the most common being solution dolines and to lesser extent, some collapse sinkholes. Sinkholes are frequently observed on the western coastal plain. To the north and south of the Exmouth Marina site, SCUBA divers have discovered caves at depth (Humphreys, 1994). They represent the outlets for either the Tertiary or Quaternary aquifers and are common in other carbonate-island or coastal type settings, where groundwater discharges close to shorelines.

The caves developed on the peninsula are the result of geological, climate and sea level changes. The main predisposing geological factor towards karst development in the area is the presence of the Trealla and Tulki Limestones (Allen, 1993). Both limestones are relatively pure and permeable bounded by the underlying relatively impermeable Mandu Limestone and local jointing and faulting enables solution and development of piping and flow paths within the limestone. Karstification and initiation of the cave systems possibly commenced in the Late Miocene – Early Pliocene around 5.3 million years ago (Murphy & Nance, 1999), when the range emerged as an island. At this time a Ghyben-Herzberg (island aquifer) type groundwater flow system would have been established. As the range continued to rise due to movement along faults, a cave system developed and extended laterally towards the coast and offshore during the low stand of sea level in the Pleistocene (around 1.6 million years ago). The Pleistocene Epoch began the most recent geological period, the Quaternary, which continues to the present day. At this time, the climate changed to similar conditions to those of the present day (Wyrwoll, 1993); with cooler air and water temperature and less precipitation. This resulted in the destruction of the integrated cave system on the crest of the range, except for the plateau remnant and preservation of the system beneath the coastal plain and offshore. A cave system has also developed in the coarse grained alluvials of the coastal plain that is possibly related to collapse features in the underlying system or as the result of a new system in response to changes in hydrogeological conditions (Allen, 1993).

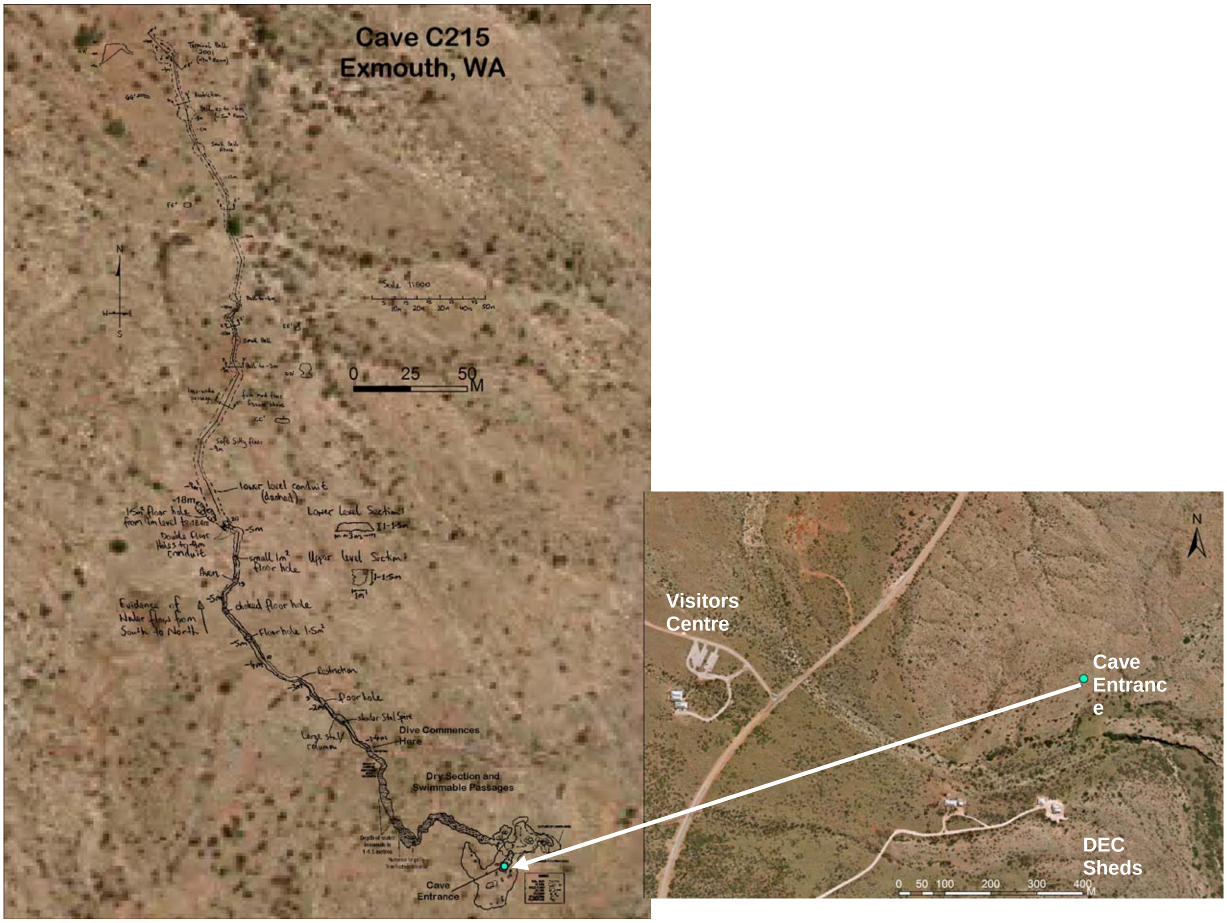


Figure 4.3 Cave C215 east of the Visitors centre. The cave is the longest surveyed cave on the west coast and surveys have found south to north water flow.

The cave system is situated above the water table and contains numerous pools and streams, which represent perched groundwater in the unsaturated (vadose) zone. Cave C - 414 known as the Wobiri rockhole can only be traversed at low tide indicating a tidal connection/influence. Karst characteristics such as rock breaks, sink holes and depressions – when recognised, can be used by site planners as part of a stormwater management plan (Laughland, 1999 cited in EPA, 1999).

Understanding the presence, concentrations, duration and timing of contaminant fluxes to karst springs is essential to being able to predict when contaminants are likely to be discharged (Vesper, 1999 cited in EPA, 1999). Many karst springs are known to vary significantly following precipitation or storm surges (Shuster & White, 1971). Springs, because they are discharge points, must be considered when evaluating potential human health and ecological risks in karst systems.

4.3.2 Alluvial Fans

A direct response to uplift is the development of alluvial fans associated with many of the canyons. The fans cover a large part of the coastal plain and occur beneath Holocene reef offshore (Fig. 4.4). The size of the alluvial fan is directly related to the size of the catchment area of the associated stream (Bull, 1962; Leece, 1991 cited in Wyrwoll et al,1993).

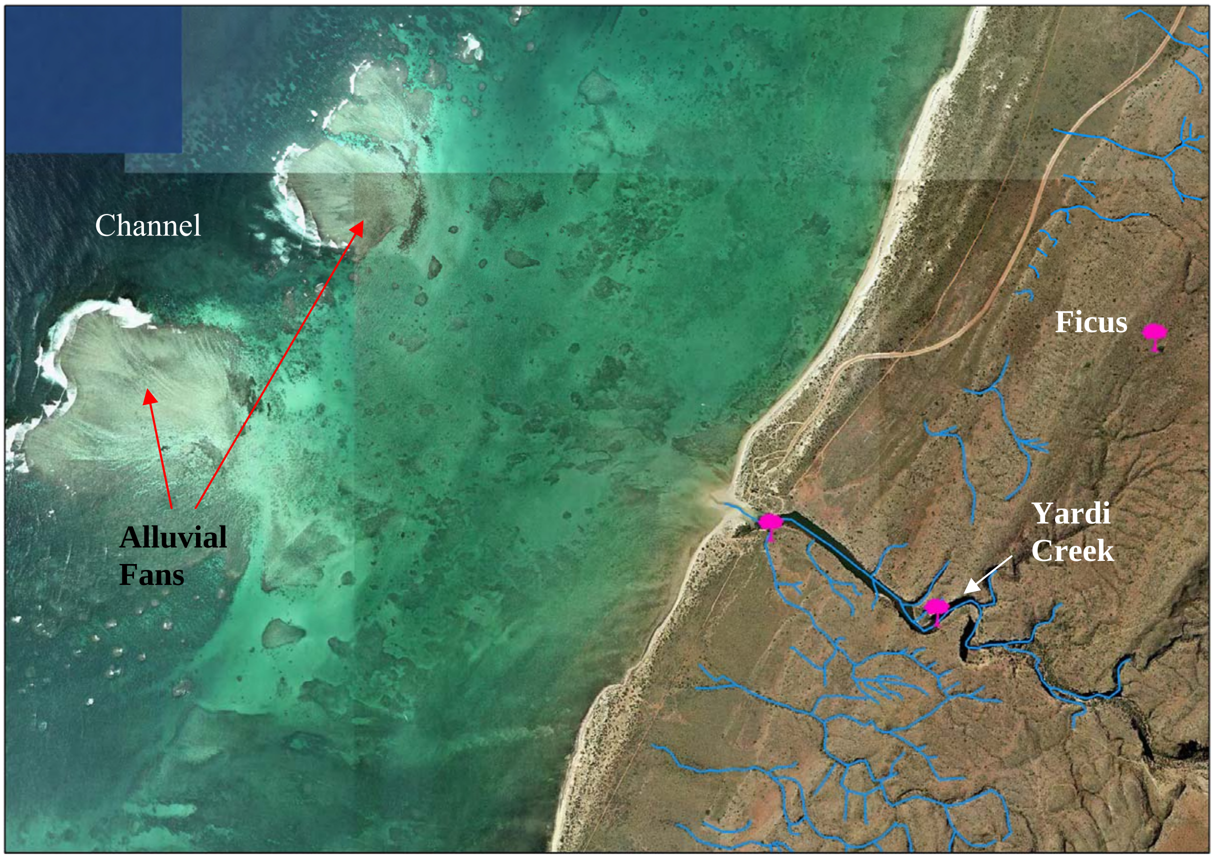


Figure 4.4 – Location of Ficus trees marking cave entrances and marine alluvial fans.

On the western side of the range, the fans take on a more linear form, with some being relatively irregular. These fans exhibit simple channel networks, essentially consisting of one main channel which has been bifurcated. Small scale fan-delta complexes can also be found. It is expected that similar alluvial fan complexes can be found in the adjacent marine environment with associated channel networks and catchments where terrestrial drainage leaves Cape Range.

4.3.3 Hydrogeology

The regional hydrogeology of Cape Range is strongly controlled by the folded Tertiary limestone units, flanked by coastal plain aquifers on both sides of the range. Groundwater predominantly flows from the centre of Cape Range towards Ningaloo Reef and Exmouth Gulf. The water table formlines indicate that relatively steep groundwater gradients occur near the crest of the range with relatively flat gradients on the coastal plain. According to Allen (1993) "local perched groundwater is also believed to occur in pools in some caves although these are likely to be small or transient".

The regional groundwater system occurs within a non-homogeneous karstic aquifer system formed by the Mandu Limestone on the crest of the range, the Tulki Limestone on the flanks of the range and the Pliocene-Recent sediments and/or the Tulki Limestone on the coastal plain. All of which are in hydraulic continuity (Allen, 1993).

The aquifer that exists below the Cape Range Peninsula consists of four main elements:

- Vadose (free-draining) waters above the water table;
- A freshwater lens floating on, and grading into;
- Brackish water that in turn rests upon;
- The seawater wedge beneath (Hamilton – Smith et al, 1998 cited in EPA, 1999).

The aquifer resembles that found on many islands, with a relatively thin freshwater layer, diffusion zone about 20-30m thick where mixing of saline and fresh water occurs, and a low hydraulic gradient (Martin, 1990 cited in Allen, 1993).

A cross-section (Figure 4.5) of the hydrogeology for the Cape Range peninsula and adjacent Ningaloo Reef identifies the main four elements of the aquifer. The cross-section identifies the geological units and also man-made wells on the eastern side of the peninsula that have tapped into the fresh groundwater. The groundwater model proposed by Lee (2008) for the eastern side of the Cape Range (Figure 4.6) can be considered applicable to the west coast and shows the aquifer zones and the position of the saltwater wedge.

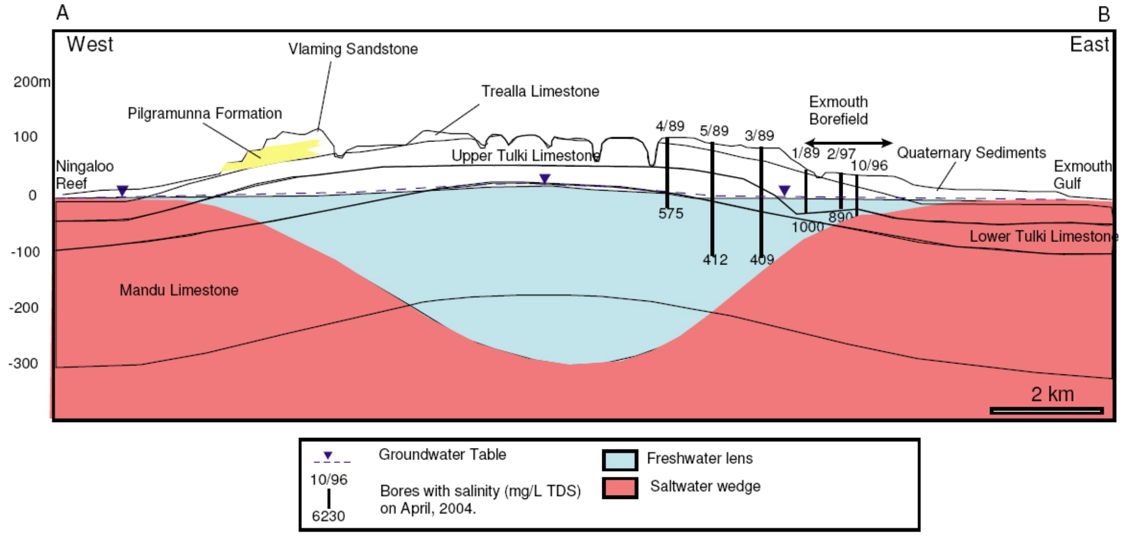


Figure 4.5 - Cross section of the regional hydrogeological units of Cape Range (Modified after Allen, 1993). Shows bores with salinity data from April, 2004 field sampling.

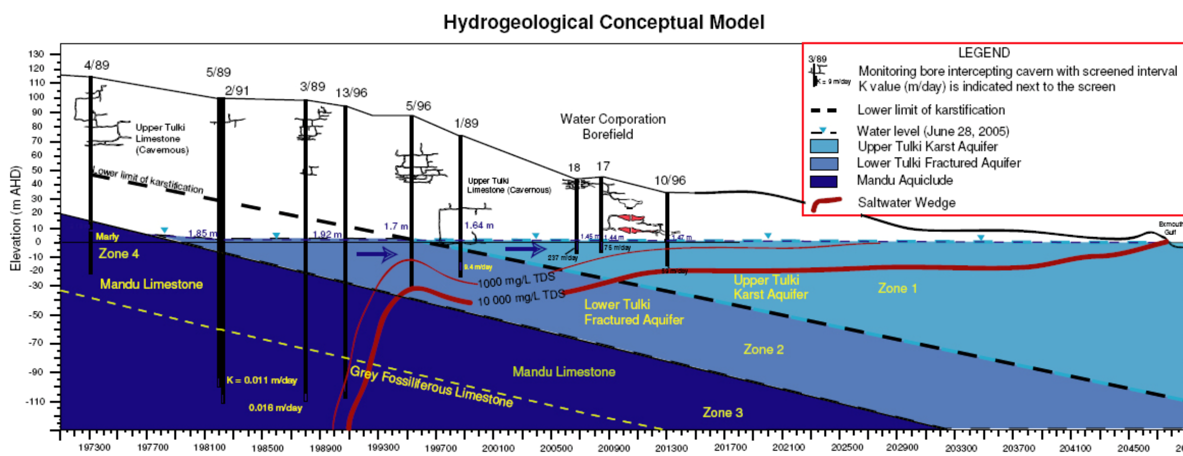


Figure 4.6 West-East cross section showing the limestone units, lower limit of karstification and seawater wedge for the eastern side of Cape Range. Note groundwater and salt water distribution beneath coastal plain. This model is applicable to the west coast (From Lee 2008)

The water table is located a couple of metres above present day sea level near the coast and rises to 15m altitude towards the inland part of the Water Corporation wellfield (Refer to Appendix 1). The aquifer is recharged both directly by rainfall and indirectly through beds of ephemeral streams which carry storm runoff from the peninsula. However, limited recharge results in the thinness of the freshwater lens. Lee (2008) observed that the thickness of the lens on the east coast is about 30% of the hypothetical thickness according to the Ghyben-Herzberg relationship, indicating a significantly thinned freshwater lens which he attributed to factors such as tidal oscillations and groundwater abstraction. The upper part of the aquifer is karst and has high permeability (Water Corporation, 1996 cited in EPA, 1999).

Various bores and wells were established for pastoral water supplies, for defense facilities and for the fishing industry prior to 1950. The first known observation of groundwater availability was by Sofoulis (1951) cited in Allen (1993) who undertook regional mapping for petroleum exploration. Later when Exmouth was being established, O'Driscoll (1965) cited in Allen (1993) recommended the location of the Exmouth wellfield. He recognised that a thin layer of fresh groundwater overlying brackish groundwater existed and cautioned against overpumping the supply. The performance of the wellfield was subsequently reviewed by Bestow (1966) cited in Allen (1993) and Forth (1972, 1973) who estimated that the groundwater occurred in a wedge that tapered seawards on impermeable marl. Following further exploratory drilling by the Water Authority, Martin (1990), has provided the most detailed information on the Cape Range groundwater occurrence adjacent to the wellfield. He showed that inland from the coastal plain fresh groundwater extends to more than 100m below sea level in rocks previously thought to be impermeable (Allen, 1993).

A recently prepared coastal groundwater model for eastern Cape Range (Lee, 2008 PhD thesis) was investigated for its applicability to groundwater systems of the western Cape Range. This model will assist planning for borehole instrumentation and its feasibility. This section summarises his findings.

The study of carbonate aquifers is challenging and deserves much attention owing to their dynamic behaviour under stressed and natural conditions. Broad to deeply incised drainage channels are prevalent on Cape Range. Towards the coast, the drainage channels widen to broad alluvial fans composed of sand, gravel and large sub rounded cobbles and boulders. The broad drainage channels and associated creek beds are dry except during extreme recharge events when surface water flows intermittently, with flooding in the lower lying areas.

The climate of Cape Range is arid with an annual mean rainfall of approximately 260 mm and pan evaporation between 1700-3050 mm (Bureau of Meteorology data between 1968 and 2006). The monthly average rainfall in Exmouth is highest during the months of May and June. Much of the high intensity rainfall on Cape Range is episodic and derived from mid-latitude depressions, which cause peak falls in summer and winter, and also from tropical cyclones every 3 to 5 years (Collins et al. 1999).

Isolated fig trees are typically found in dolines where the roots extend deeply into the cavernous limestone. The coastal plain vegetation is typically grasslands, coastal strand, low shrublands and mangrove low forest and the sandplain by heath over *Triodia* (Keighery & Gibson, 1993). Significant species of rare stygofauna exists within the cavernous limestone below ground, for example Bundera Cenote (Humphreys, 1994).

The limestone aquifers of Cape Range are in a highly dynamic and fragile state due to the highly permeable fractured and karst limestone set in an arid coastal setting. The fresh groundwater occurs as a thin lens shaped aquifer and overlies a saltwater wedge that extends up to 5 km inland. A thick brackish zone is present due to mixing between the freshwater and saltwater from tidal oscillations and groundwater abstraction and is the major habitat of the stygofauna.

Groundwater recharge preferentially occurs within broad drainage channels after heavy rainfall events. Direct recharge is the result of incident rainfall infiltration through the vadose zone regardless of residence time. Incidence recharge occurs when rainfall intensity exceeds infiltration and overland flow is generated (Jocson *et al.* 2002). Recharge along ephemeral channels can be large and play an important role in groundwater/surface water dynamics in arid and semi-arid regions. Infiltrated rainwater is initially stored in the unsaturated zone and then released to the aquifer at different rates. Allen (1993) suggested that groundwater recharge occurs after heavy rainfall events by direct surface infiltration through permeable beds, bedding plain partings and joints and by infiltration of run-off along alluvial channels Groundwater is then discharged by abstraction and via submarine groundwater discharge along the coast of Exmouth Gulf.

The aquifer responds to neap and spring tides, below average rainfall and heavy rainfall events with the highly transmissive nature of the karst features allowing groundwater levels to be influenced by tides up to at least 3.5km from the coast on the eastern side of the range. Groundwater levels are influenced by tides due to the transmissive nature of karst aquifer and proximity to the coastline (Forth, 1973). On the western coastal plain, tidal influences are known to extend to at least 1.6 km inland, as observed in Bundera Sinkhole (Humphreys, 1994). The aquifer response to tide indicates the transmissive nature of the Cape Range limestone aquifers and suggests a direct hydraulic connection between the Quaternary coastal plain aquifer and the Tertiary fractured and karst aquifers.

Recharge from low to high rainfall events may not result in an immediate aquifer response, particularly if it is dry, but their cumulative effect over a time period can lead to significant storage in the unsaturated zone and providing a large source of recharge within the karst system. Delays of about 3 to 4 months have been observed in other karst aquifers after significant rainfall events (Bredenkamp *et al.* 1995)

4.3.3.1 Nature of the System

The hydrogeological setting of Cape Range is similar to that of a carbonate island setting with conduits mostly developed in the upper karst terrain due to uplifting and a wetter climate at Cape Range during the Tertiary when the limestone formations were deposited. A Carbonate Island karst aquifer commonly includes a body of brackish water between the overlying freshwater and underlying saltwater (Mylroie, 2001). In the Cape Range acquifer a broad brackish zone (i.e. zone of diffusion with tidal influences) 10-20m thick is present between the freshwater and underlying seawater wedge and is the major habitat of the stygofauna (Muir Environmental, 1995). Martin (1990) suggested that karst features control the inland limit of the seawater interface in Cape Range. At distances greater than 5 km inland, in non-karstic aquifer, the freshwater lens thickens considerably toward the centre of the range due to increasing topographic elevation. Groundwater flow in karst aquifers is controlled by regional hydraulic gradients, but actual flow routes are controlled by its local geological structure (e.g. bedding plane orientation) and organized patterns of drainage conduits that develop over time (Smart and Ford, 1986).

The regional geometry of the freshwater lens in carbonate islands is asymmetric due to the aquifers commonly being thicker on the lagoon side than on the reef side (Rowe, 1984) (see Figure 4.5) The thickness variation is caused by differences in the permeability, which is dependent on the size of sediment grains. The eastern side of the freshwater lens is also thicker than the western side of the lens. This overall asymmetrical lens shape is probably due to finer grained sediments on the Exmouth Gulf side, compared to the coarser grained sediments on the Ningaloo Reef side, which is more susceptible to seawater intrusion as also pointed out by Peterson (1997)

Another common feature of carbonate islands and their coastal setting is submarine groundwater discharge zones (SGWD), where groundwater discharges close to shorelines. The location of the seepage zones depends on the coastal configuration (Urish and Gomez, 2001), preferentially where an aquifer is connected hydraulically with the sea and the groundwater head is above sea level (Uchiyama et al. 2000). In places where highly permeable strata (i.e. cavernous limestone) underlie coastal regions, SGWD may exceed the discharge from adjacent rivers (Younger, 1996) and SGWD near the coastline is the greatest source of discharge on Cape Range. The high submarine groundwater discharge rate can be attributed to the karstic nature of the Cape Range limestone aquifers. The presence of offshore conduit systems is indicated by the possible existence of submarine springs and the incursion of seawater beneath the coastal plains, which in some cases shows tidal fluctuations (Hamilton-Smith, 1998). Possible groundwater mounds have been observed offshore by AIMS in conjunction with projects 3.1.1 and 3.4. These features are close to the Last Glacial Maximum shoreline (SL-120m/18ka BP; Fig 4.7) and may represent termination points of lowstand karst features which would be expected to have developed along this palaeoshoreline.

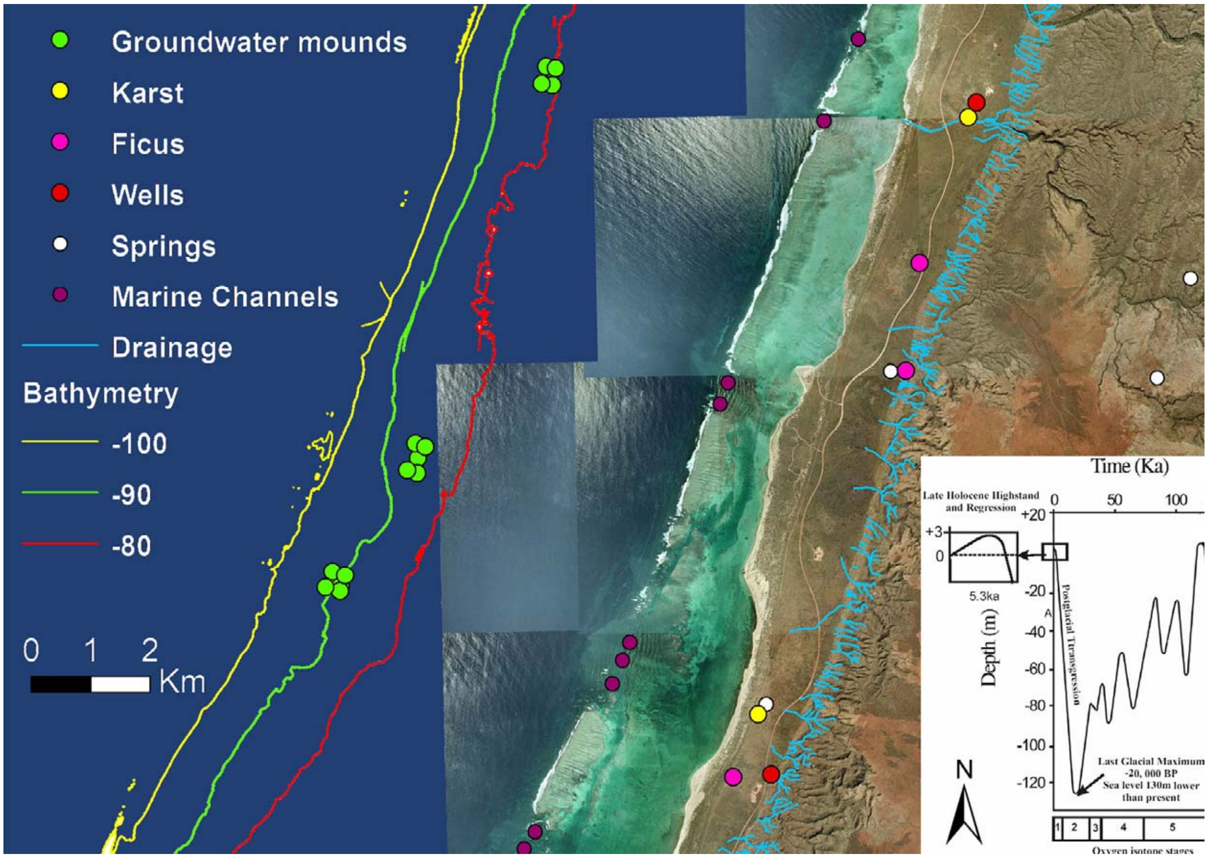


Figure 4.7. The location of possible submarine groundwater discharge mounds in relation to onshore groundwater indicators. Note proximity to the LGM (~20ka BP) shoreline at ca. -120m. Data on mounds (depth 80-90m) supplied by project 3,1,1.

The groundwater discharge on fringing reefs is commonly observed at low tide, from caves at the inland edge of coastal terraces (Jacobson et al. 1997). In many cases, dead shellfish, terrestrial and marine debris covers caves or conduit vents, so that they are invisible unless specific measurements are taken. Mueller (1991) observed that areas near submarine springs were devoid of marine life and showed anomalously low salinity measurements. They also suggested that blocking of vents with debris hinders the outflow of groundwater. In Cape Range, SGWD zones are known to exist along the Exmouth Gulf due to hydraulic connection with the Tulki karst aquifer.

4.4 Data Sources

Personal geodatabases were created in ESRI's ArcCatalog to store working data required for this project. A geodatabase was created for Ningaloo data acquired from the Geology Department at Curtin University of Technology and for Topographic data acquired from

Landgate, Western Australia. The geodatabases consist of point, line and polygon feature class files, raster datasets and tables. All metadata has been appropriately maintained with information clearly stating the contents and purpose.

For this study most of the data uses the same geodetic datum (Appendix 2). The common datum is the Geocentric Datum of Australia (GDA94) with the GRS80 reference ellipsoid. GDA94 coordinates are based on the International Terrestrial Reference Frame (ITRF92 (epoch 94.0)) coordinates of 8 accurately known stations around Australia. These stations are also referred the Australian Fiducial Network (AFN) (Kirby, 2007). A few datasets do however use WGS84 that is maintained by the US military and primarily used as the reference ellipsoid for the Global Positioning System (GPS). WGS84 is both an ellipsoid and a datum. Although there are some differences with WGS84 and GDA94 for this study the differences are negligible.

The Cape Range peninsula lies on the cusp of two Universal Transverse Mercator (UTM) zones – zone 49 and zone 50. UTM zones are 6º wide with half degree overlaps. The zones were created to minimise distortion although areas that lie on edges of the zones and within this overlap have the highest distortion (furthest from the central meridian). To overcome this distortion, data can be projected into a Local Transverse Mercator (LTM) grid with different parameters for the central meridian longitude, central scale factor and origin. A local grid does exist for Exmouth that encompasses Cape Range peninsula although for this study projecting all data into zone 49 provided sufficient accuracy.

The area has been extensively surveyed by government, commercial and independent constituents. Australian government survey data for the Cape Range peninsula include a topographic dataset with terrestrial elevations, drainage patterns, contours and infrastructure. The topographic dataset was acquired from Landgate, Western Australia.

An initial Digital Elevation Model (DEM) was acquired through the United States Geological Survey (USGS) from the Shuttle Radar Topography Mission (SRTM) in a 3 arc second SRTM Format. Australia and New Zealand are classed as Area 13.

Hyperspectral Data were obtained from the Geology Department at Curtin University of Technology. Preliminary processing of the hyperspectral data was performed by Wojciech

Klonowski and colleagues in the Physics Department at Curtin that includes atmospheric and tide correction. The flightlines were compiled to form mosaic blocks *a* to *j*. The blocks used in this study are *g*, *h* and *i* that cover the west coast of Cape Range peninsula and the adjacent Ningaloo Reef. The Physics Department processing of the data produced three individual datasets used in this Ningaloo study. From the hyperspectral data – bathymetry that consists of a single band for elevation was acquired and stored in ENVI (hdr.) format. The second dataset contains the benthic habitat signatures that were developed by fellow Ningaloo researchers both at Curtin and Murdoch Universities in Perth, Western Australia. The benthic dataset was obtained in a Portable Network Graphics (PNG) format. And thirdly, a spectral reflectance dataset was developed that displays bands 1 to 21 stored in ENVI (hdr.) format.

The aerial photography was acquired from the Geology Department at Curtin University of Technology. Aerial photography is a common and widely used form of Earth Observation by remote sensing. Many aerial photographs are captured via digital cameras that are compatible with computer processing. These digital cameras have a two-dimensional array of charge-coupled devices (CCDs) that are used to detect a small area of the Earth's surface along a flight line (Mather, 2004). The amount of light that impinges on the CCD array is recorded as a number between 0 (no light) and 255 (light saturation). A single set of CCDs produces a greyscale image, whilst three sets of CCDs are used for colour imagery. The three sets of CCDs measure the amount of red, green and blue light that reaches the camera (Mather, 2004). Aerial photographs provide an important role in GIS acquisition and visualisation. They are suitable for putting spatial concepts into perspective and also provide a basis for collecting spatial information for topography such as drainage, landmarks and roads. Before this information is able to be collected, the aerial photographs need to be prepared in a way that removes distortion. This process is known as orthorectification. Without this process the images could not be used for such functions as accurately measuring distances, angles, positions and areas.
(http://www.satimagingcorp.com/svc/orthorectification.html)

Two 1:250,000 scale geology map sheets were acquired from the Department of Industry and Resources (DoIR), Western Australia, scanned and rectified to aid analysis.

Vector data was acquired from the Geology Department of Curtin University of Technology that includes – karst locations, Ficus locations, well locations and geology polygons (field mapped lithology - geological units). The vector data consists of point, line and polygon shapefiles with locations and boundaries created from a variety of sources including hyperspectral spectral signature interpretation, GPS ground point coordinates and digitised points.

4.5 Literature Review

There have been numerous studies conducted worldwide that look at marine groundwater discharge. The two locations examined for this Ningaloo study were Manila Bay in the Philippines and Florida Bay in the United States (Refer to Appendix 3). These locations were chosen for similarities with location (Manila Bay) and geological units (Florida Bay). Groundwater is commonly contained in confined aquifers in permeable and porous rocks. The permeable and porous rock types are generally sedimentary facies and in the Ningaloo area are dominated by carbonates.

Literature on an inductive predictive model was chosen to emphasise techniques that can be used when known site locations are provided. Methods used in this study were adopted for Ningaloo although modifications were made for the limited known fresh groundwater sites.

The hyperspectral literature study investigates coral reef benthic communities of the Great Barrier Reef, Australia. This study provided comparative information for hyperspectral data usage for another Australian reef system. Remotely sensed data acquisition and technique were also covered in this study.

4.6 Methodology and Results

Three stages of spatial analysis were used in the methodology for this study; the methods were visualisation, exploratory and confirmatory data analysis. The stages of the methods used are outlined in the following structure chart.

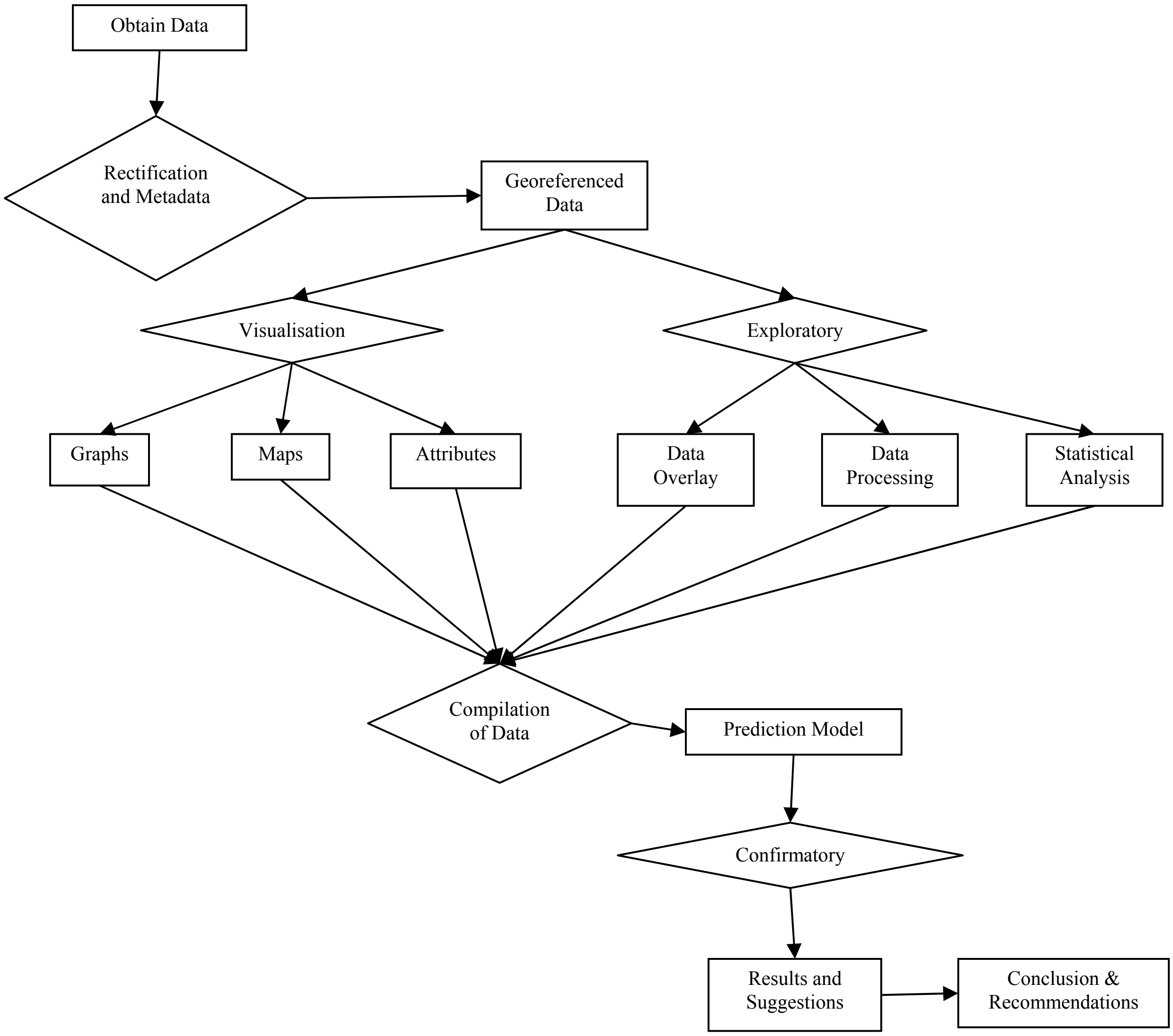


Figure 4.8 - Methodology Structure Chart

The three main GIS software packages used for spatial analysis in the study were ESRI ArcGIS (www.esri.com/index.html), ER Mapper (www.ermapper.com/) and ERDAS (www.erdas.com/).

The assumptions made during spatial analysis were that the data were from reliable sources, there is no measurement or representation error and there are no propagation errors in the software – ArcGIS, ER Mapper and ERDAS.

The hypotheses were:

Original Hypothesis (Ho): A predictive model can be used to help identify groundwater discharge into a marine environment and therefore spatial patterns exist.

Alternative Hypothesis (Ha): Spatial patterns can not be used to predict groundwater occurrence in a marine environment.

Visualisation analysis included graphs, charts and maps. The purpose of visualisation in data analysis is to create graphical images directly from the data (Carr, 2002). It is often necessary to apply mathematical algorithms to enhance data analysis although without initial visualisation investigation of raw data the outcomes commonly cannot be fully appreciated. Visualisation aids understanding the magnitude (value), variability (differences between data values), and distribution (proportion of different data values) of the data to adequately recognise analytical procedures that may be required for further data analysis.

An example of visual analysis can be seen in Figure 4.9 which shows the distribution of freshwater indicators – Ficus, man-made wells and karst features.

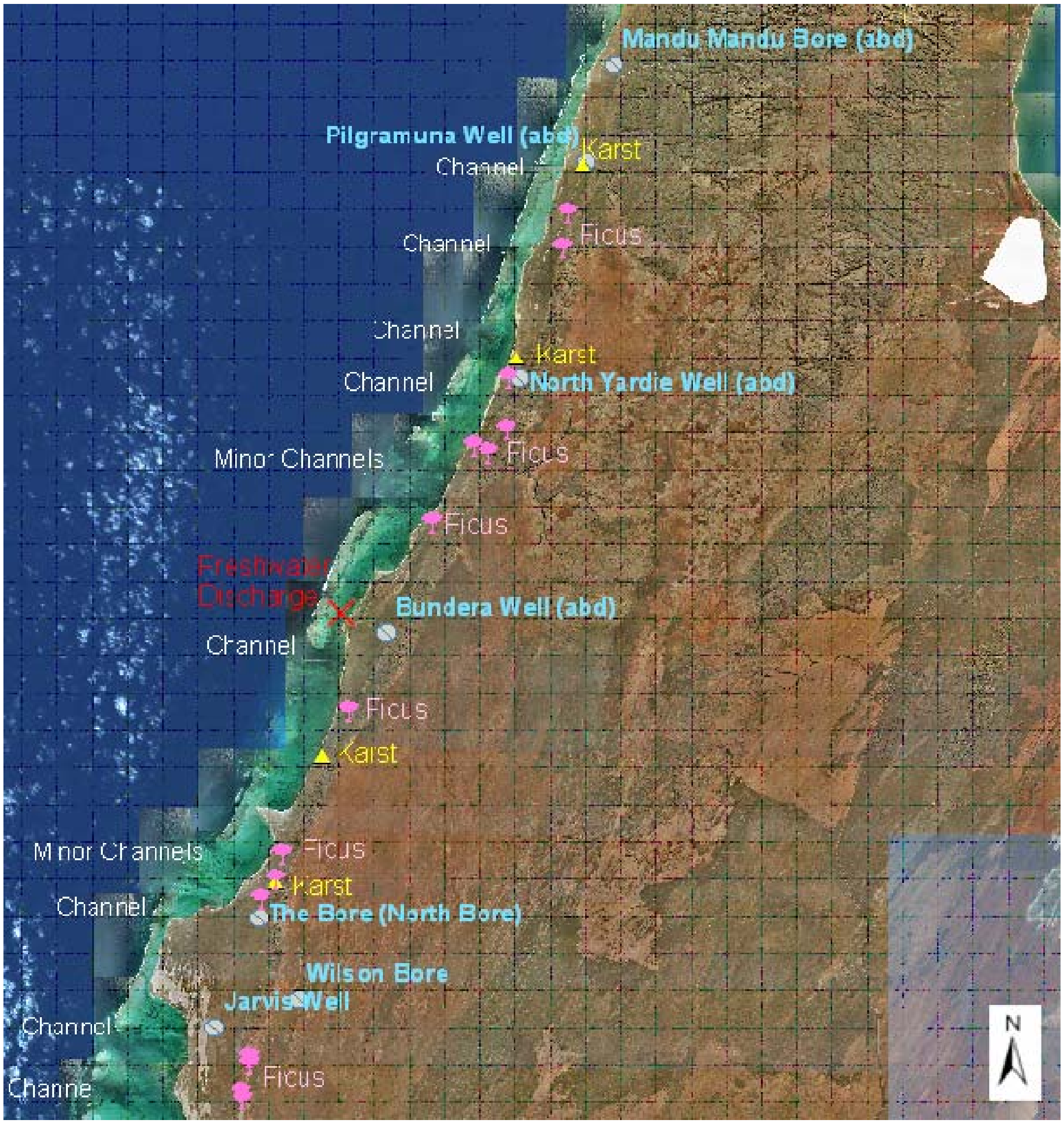


Figure 4.9 – Distribution of freshwater indicators.

The method for exploratory analysis was derived from conventional descriptive statistics emphasising data presented as graphic form observed in visualisation analysis. Exploratory analysis looked at vector data points and their involvement in a spatial prediction model. Additional data points were created for known drainage outlets, springs and marine channels. Kernel density estimation (KDE) was then performed using these data points with a search radius of 10m. Kernel density estimation finds the density of points at a location. The density at the location is determined by the search radius, the weight of the point (knowledge based) and the distance to another point location. Results were produced for individual point variables. These individual results were then combined and overlain with original data points to identify hotspot areas (Figure 4.10).

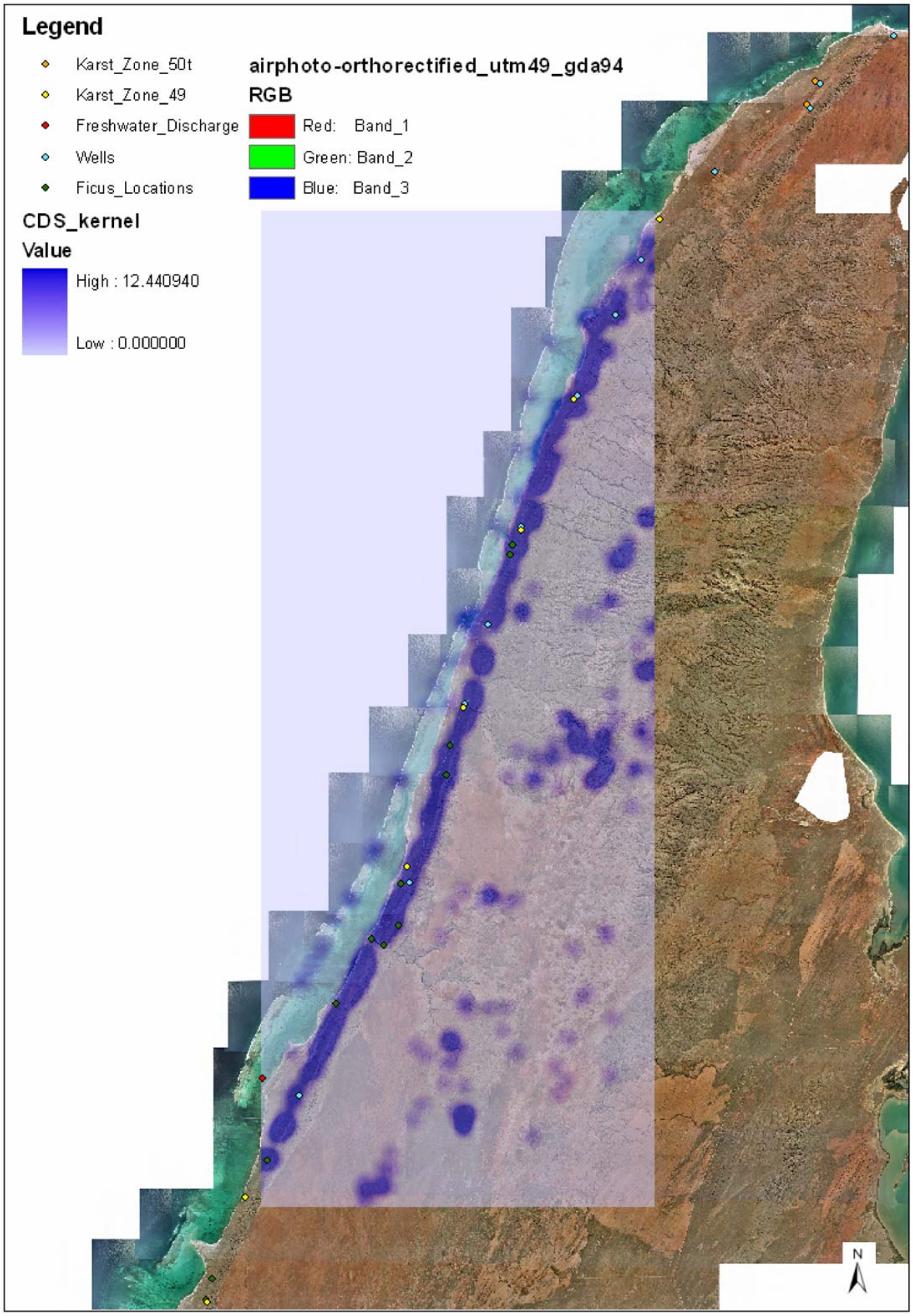


Figure 4.10 - Kernel density estimation map for channels, drainage outlets and springs, includes original water feature points.

Exploratory analysis included a study of drainage patterns using both a digital elevation model (DEM) and bathymetry. With both sets of data, hydrology analysis was achieved using ArcMap tools. Hydrology analysis proved useful to create an estimate for drainage patterns when compared with the topographic data. The drainage patterns for the DEM were noted as more successful in comparisons with the bathymetry due to greater variation and more accurate acquisition in height/depth measurements.

The results from the bathymetry analysis provided little insight into fresh groundwater indicators. The depth information obtained through the hyperspectral data was limited to the depth in which the light source (in this case, sunlight) can penetrate the water. Some of the light is absorbed, refracted and scattered. The maximum depth of light penetration for this hyperspectral obtained bathymetry data was approximately 20m. This limitation for the bathymetry depth values also limits the depressions and elevations that can be identified. The bathymetry watershed has a significant amount of fine detail and the limitations of depth therefore made it more difficult to determine likely drainage patterns. Drainage patterns are more distinguishable in the DEM as seen in Figure 4.11.

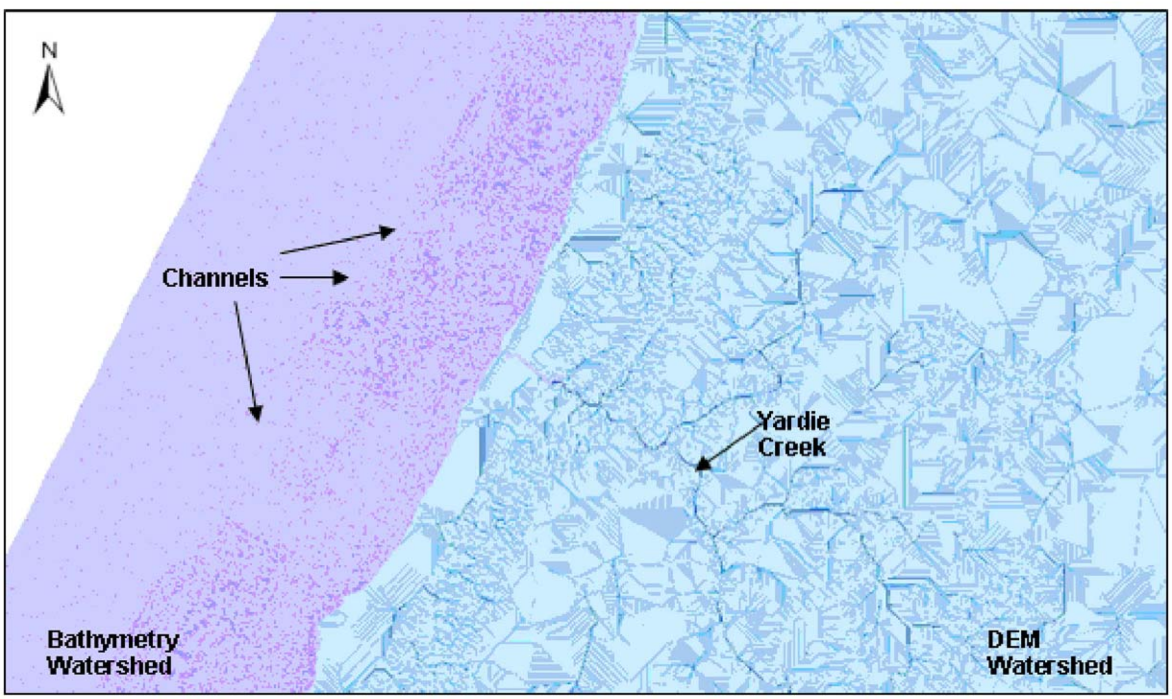


Figure 4.11 - Continuation of drainage from terrestrial to marine environment.

Confirmatory analysis provided a means of testing the hypotheses and determining the extent or form of a data relationship (confirming patterns and data structure). Confirmatory analysis involved analysing the KDE predicted areas using hyperspectral data. Two methods of confirmatory analysis were conducted to prove that the six predicted areas have some likelihood of displaying fresh groundwater occurrence. The predicted fresh groundwater areas are seen in Figure 4.12.

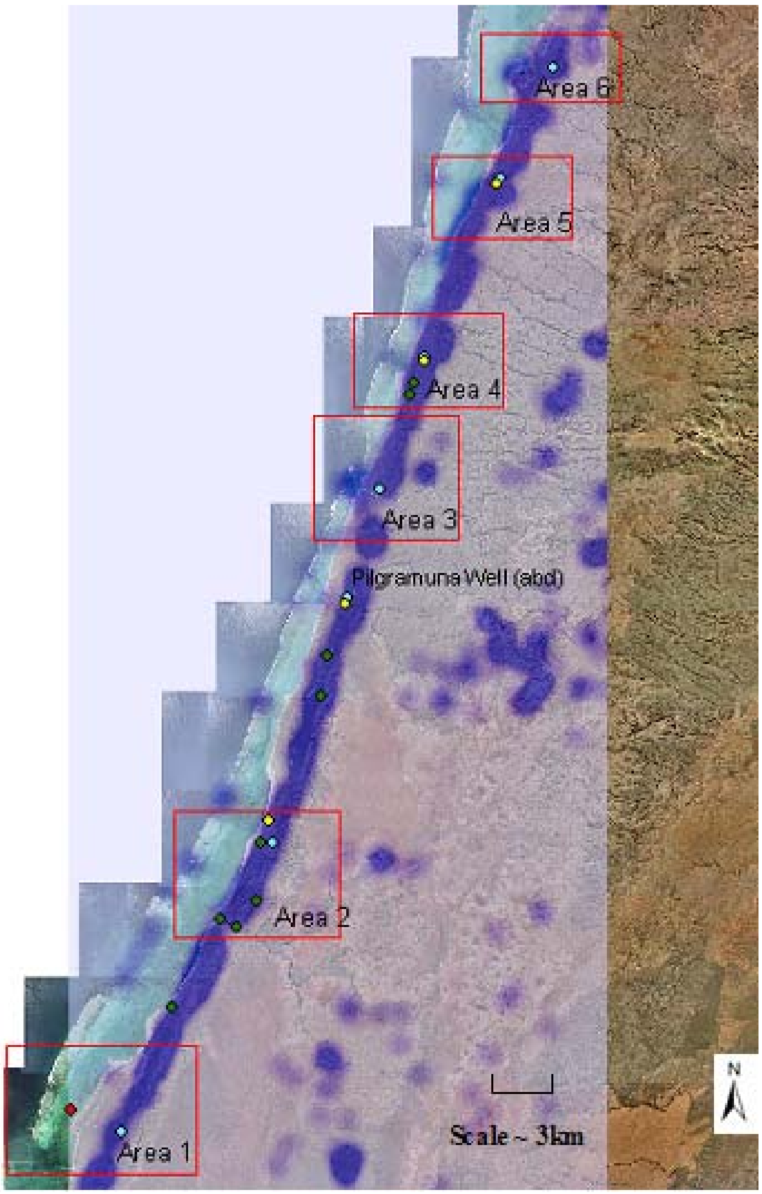


Figure 4.12 – High probability areas of fresh groundwater occurrence in the marine environment.

Area 1 is located in the vicinity of Bundera and identifies an area where known freshwater discharge, the Bundera well and Bundera sinkhole are located. Area 2 is located in the vicinity of Yardie Creek situated in the Osprey Sanctuary Zone and displays a large number of freshwater indicators including four Ficus tree locations, a man-made well, a karst and semi-permanent drainage (Yardie Creek). Area 3 is located in the vicinity of Mandu Mandu Creek situated within the Mandu Sanctuary Zone. Analysis at Area 3 focused on the Mandu Mandu Creek mouth, it highlights a hotspot area identified by kernel density estimation. There is one man-made well location in Area 3. Area 4, 5 and 6 are located in the vicinity of Turquoise Bay (Mandu Sanctuary Zone), Lakeside (Lakeside Sanctuary Zone) and Mangrove Bay (Mangrove Bay Sanctuary Zone) respectively. These areas were selected due to an increase of freshwater indicators (Ficus, man-made wells and karst locations) and hotspots identified by kernel density estimation.

4.6.1 Benthic Habitats

Hyperspectral benthic data were presented as non-georeferenced PNG images. The importance of the benthic images was to interpret whether benthic habitats/substrate were associated with fresh groundwater occurrence in the reef marine environment. The benthic habitats have been categorised according to colour to represent the amount of energy reflected back to the sensors in the visible spectrum. The colours of the benthic images are associated with substrate vegetation, rock and sediment cover and are identified in the following table:

Colour	**Substrate**
Blue	Sand
Green	Vegetation (sargassum or green algae)
Red	Coral (acoropora sp.)
Aqua	Limestone/brown algae
Yellow	Limestone/coral
Orange	Sand/coral
Khaki	Coral/Vegetation mix

Table 4.1 – Colour representation of benthic substrate in Ningaloo Reef Marine Park.

Using the coordinates of the known freshwater discharge point the benthic habitat was investigated for patterns in both benthic type and unique shapes. The known site as seen in Figure 4.13 identifies a mixture of colours as a circular feature.

The central part of the feature is interpreted as mostly limestone/brown algae with minor sand and limestone/coral with the outer part (or rim of the circle) more mixed with minor coral, limestone/coral, sand/coral and vegetation. The most distinguishing feature of the known freshwater discharge point is the circular feature in which it's found.

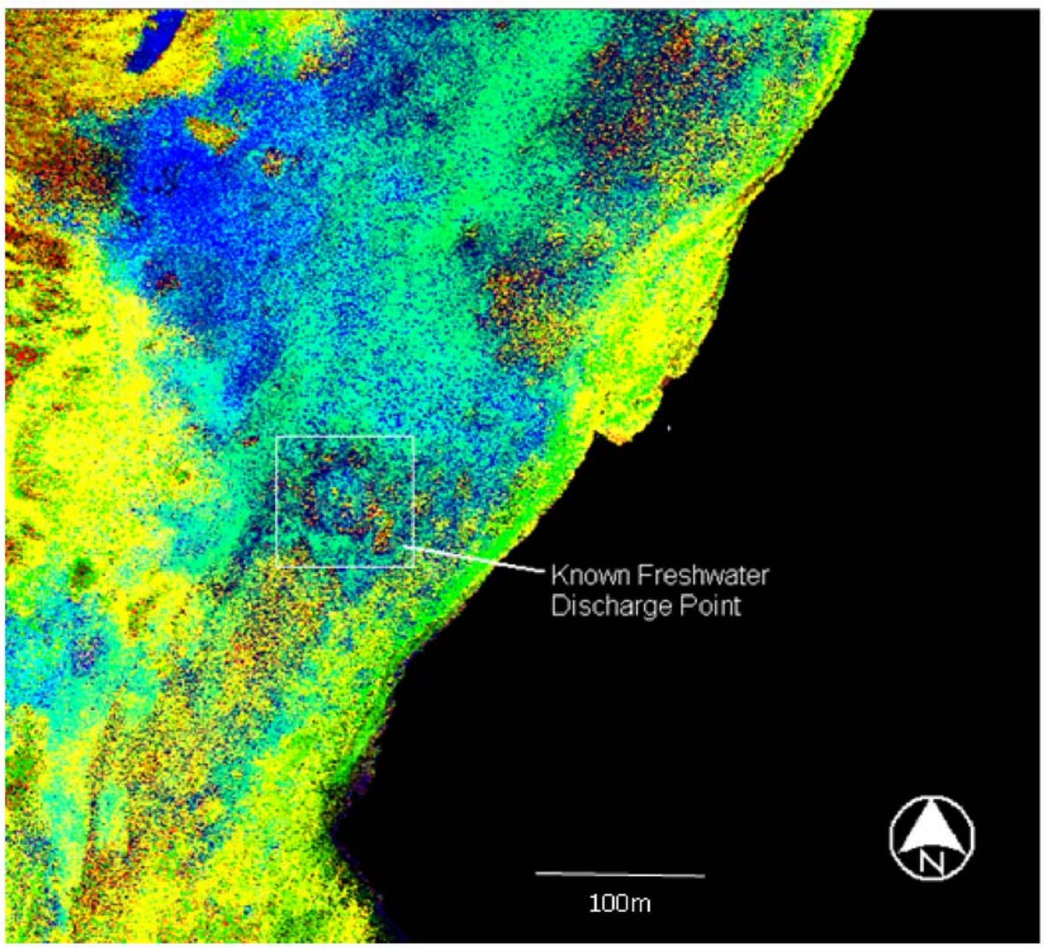


Figure 4.13 - Benthic habitat of Known Freshwater Discharge Point at Bundera (Area 1).

The benthic habitat of the known freshwater site was then compared with Areas 1 to 6 for similar circular features and possibly similar substrate types. Area 2 seen in Figure 4.11 is the marine area directly adjacent to Yardie Creek. Circular features can be seen in the marine area directly adjacent to the Yardie Creek mouth.

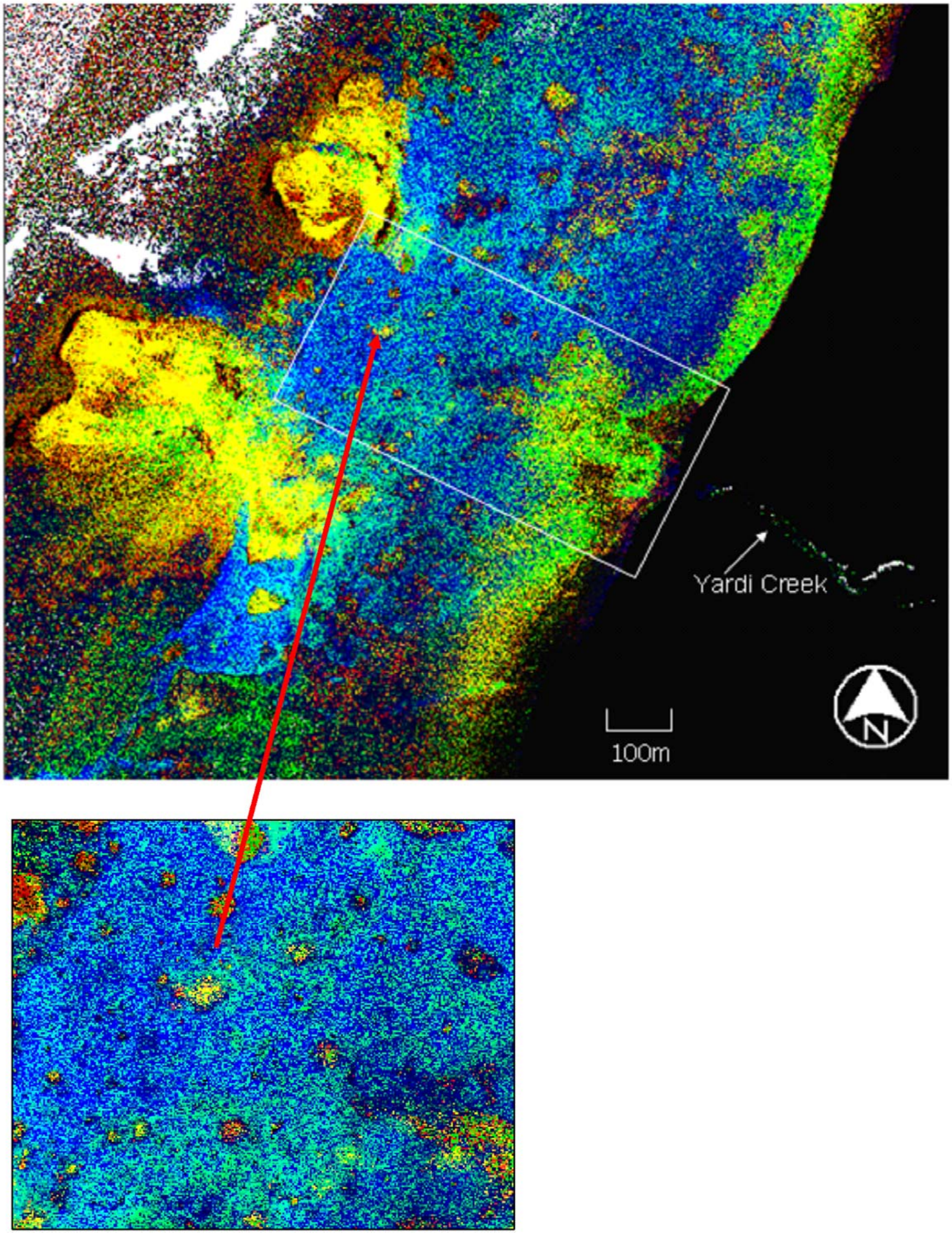


Figure 4.14 - Benthic habitat of marine environment adjacent to Yardie Creek (Area 2).

The enlarged image shows the circular features seen adjacent to Yardie Creek. The features are mostly solid circular features of coral and limestone/coral with minor vegetation on the outskirts. These features are possibly reef formations more commonly known as coral “bombies”.

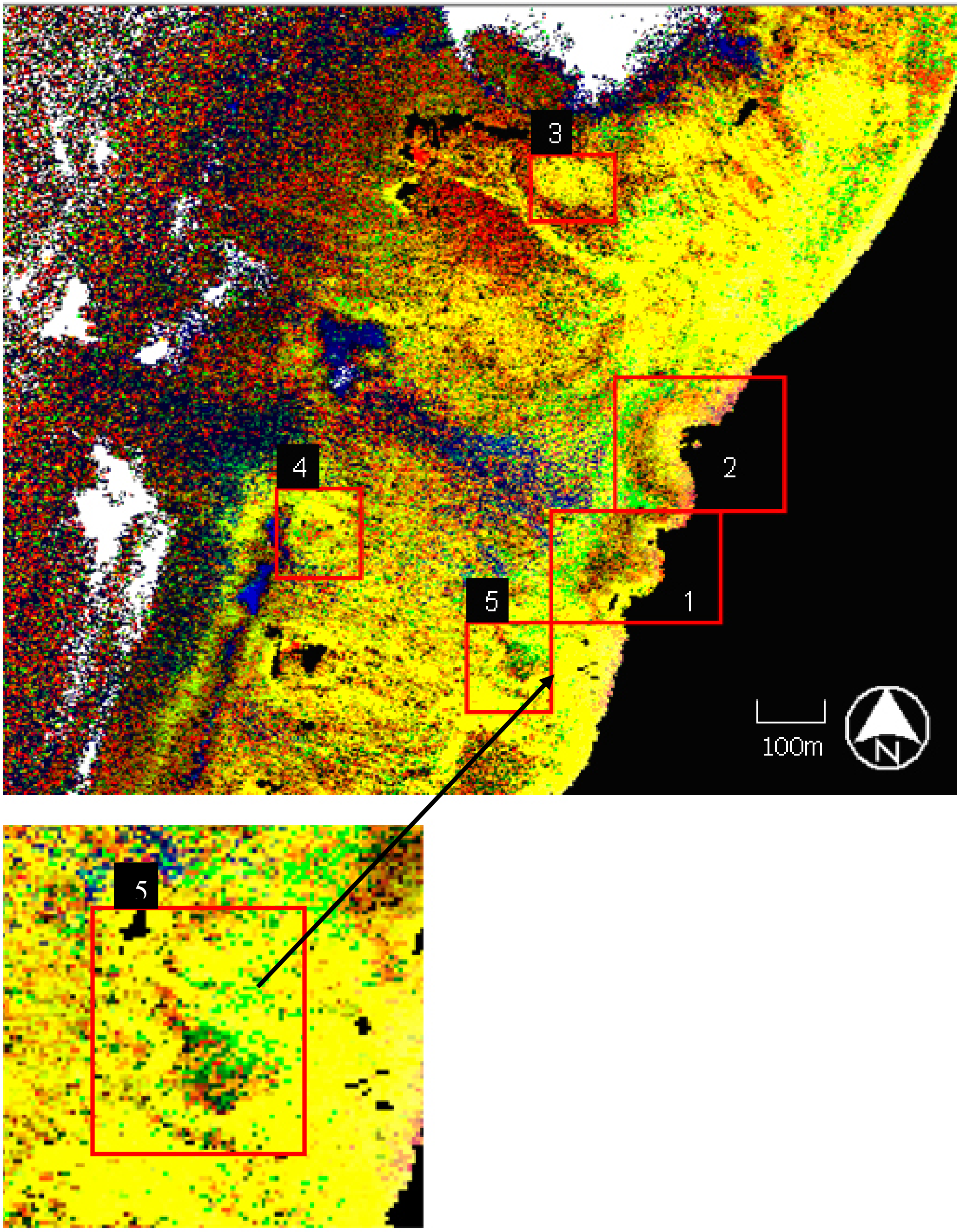


Figure 4.15 – Benthic habitat near Mandu Mandu Creek (Area 3).

The benthic habitat of Area 3 identifies some circular features in a mostly coral and limestone/coral dominated part of the reef. The circular features 1 to 4 are dominated by a limestone/coral core and coral outer rim. Circular feature 5 however has a slightly more mixed benthic signature that suggests the substrate consists of mostly vegetation, sand/coral and coral.

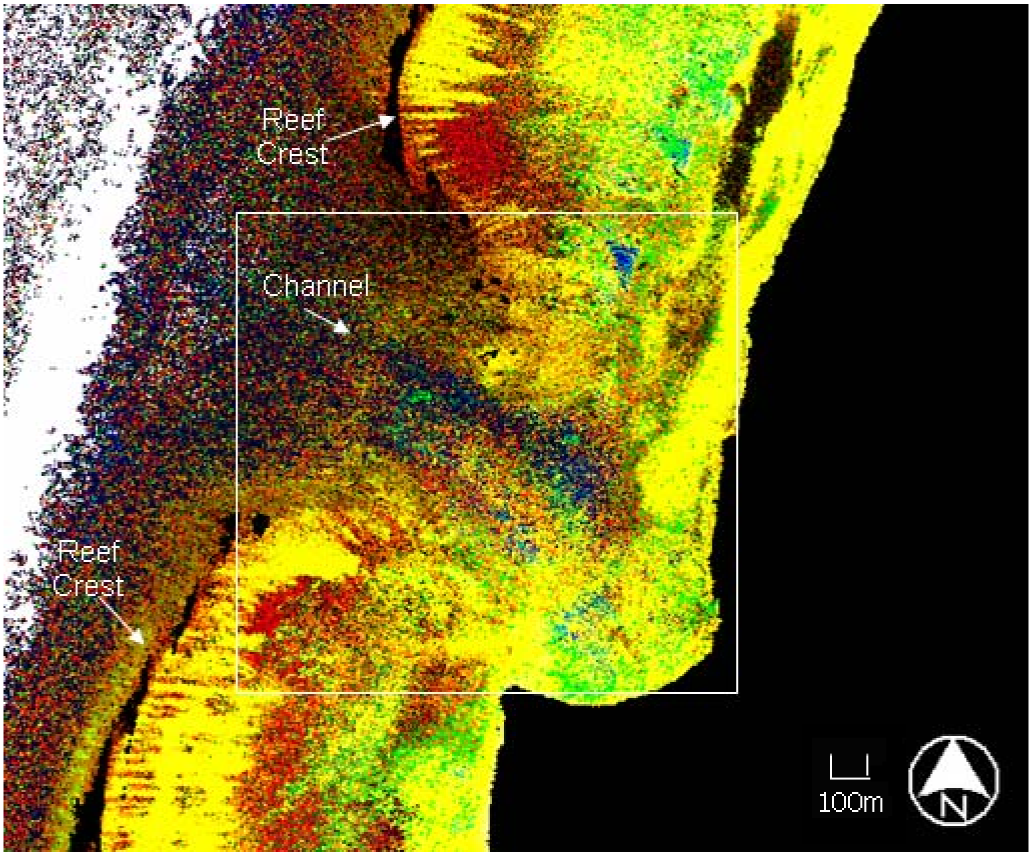


Figure 4.16 – Benthic habitat for a channel area at Turquoise Bay (Area 4).

The benthic habitat in Area 4 was investigated because of the relatively high amount of water features found in the area including Tulki Well (abandoned), Ficus trees, karst formation, coastal drainage outlets, a major marine channel and inland springs. The benthic signature suggests that the reef crest either side of the channel are predominately coral (red) and limestone/coral (yellow), the inner/lagoon reef is coral, limestone/coral and vegetation (green) with the channel (possibly due to tidal currents) a mixture of vegetation, coral, coral/sand (orange) and limestone/coral.

Area 4 in contrast to Area 5 (Figure 4.17) identifies another marine channel setting. The main difference between the two areas is that the channel in Area 5 is a lot smaller and therefore the inner/lagoon reef are more protected from tidal currents and wave fronts. Area

5 is dominated by limestone/coral (yellow), vegetation (green), sand (blue) and coral (red) on the reef crest.

There are two features of interest that are highlighted in Figure 4.17. The features are circular and display unique signals compared with their surrounding environment.

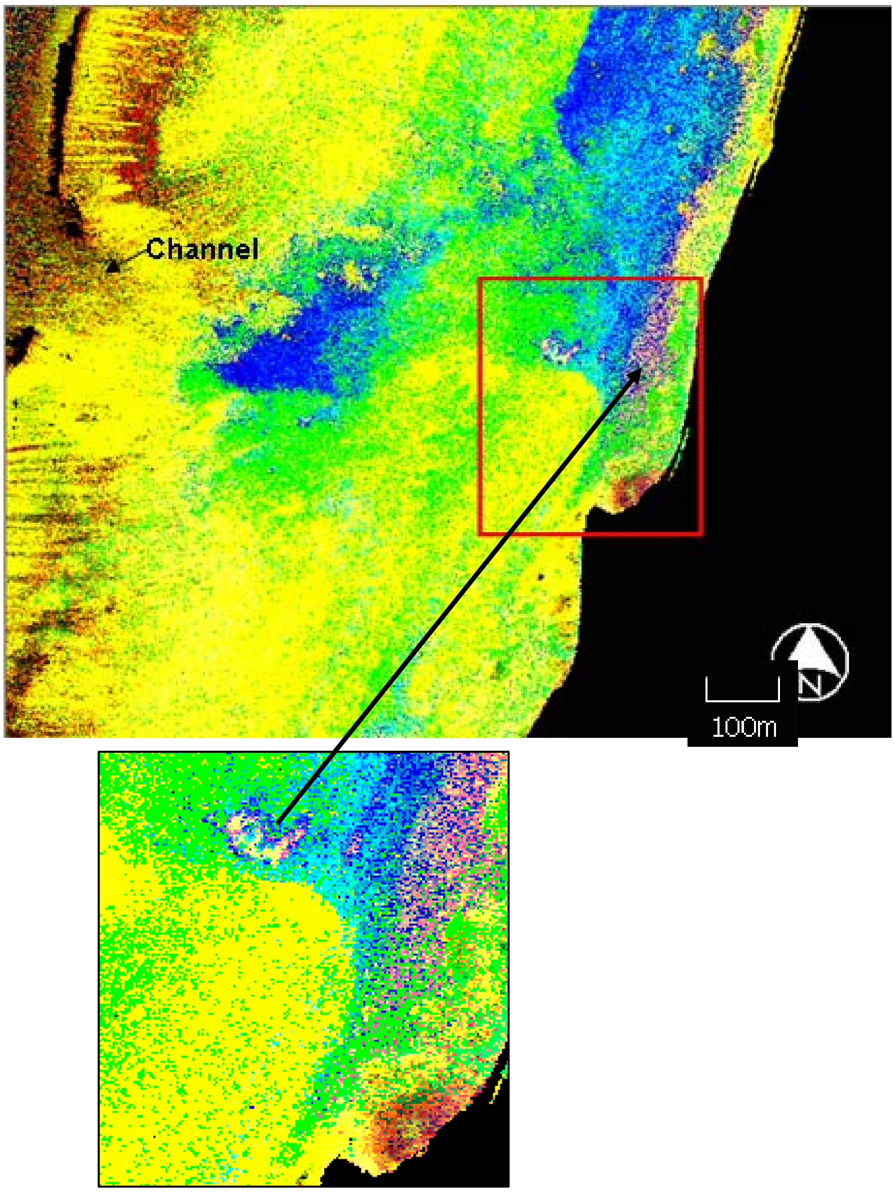


Figure 4.17 – Benthic habitat at Lakeside (Area 5) identifying two circular features.

The enlarged section identifies that the circular feature in the lower right corner (zone 2) is dominated by coral and coral/sand whilst the circular feature in the upper left area (zone 1) has a limestone/coral (yellow) core with a sand (blue) rim and minor limestone/brown algae (aqua).

The last area that was investigated was Area 6 that displays interesting benthic features in the shoreline lagoon area highlighted in Figure 4.18 below:

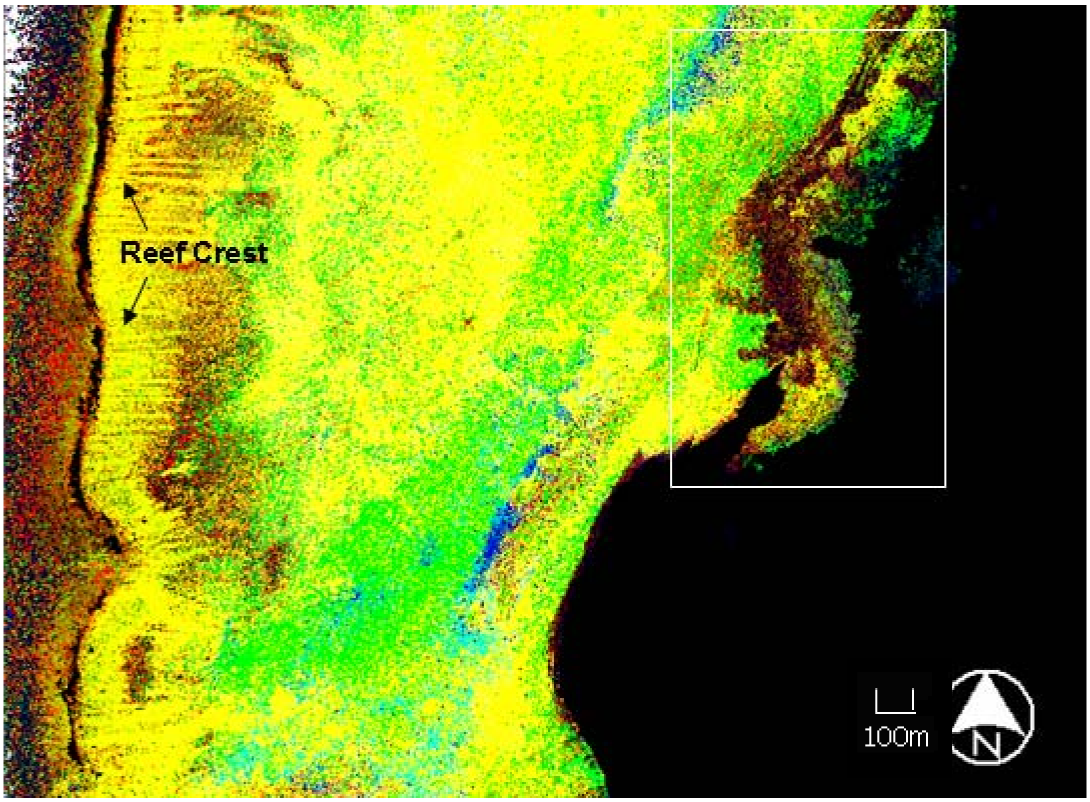


Figure 4.18 – Benthic habitat of the lagoon shoreline environment at Mangrove Bay (Area 6).

The benthic colours suggest the area is mostly vegetation (green), coral/vegetation mix (khaki) and sand/coral (orange). The area on a whole is dominated by limestone/coral (yellow) and is sheltered in a lagoon setting by the almost continuous reef crest.

The summarised results for the benthic habitat study are presented in Table 4.2. The results show similarities and differences between predicted fresh groundwater sites and the known site.

			Benthic Habitats						
Areas	**Features**	**Sub-Features**	**Sand**	**Vegetation**	**Coral**	**Limestone/Brown algae**	**Limestone/Coral**	**Sand/Coral**	**Coral/Vegetation**
1	known freshwater	inner circle	▫			▪	▫		
	discharge	outer circle		▫	▫		▫	▫	
2				▫	▪		▪		
3	zones 1 to 4	inner circle					▪		
		outer circle			▪				
	zone 5			▪	▪			▪	
4	reef crest				▪		▪		
	inner reef			▪	▪		▪		
	channel			▫	▫		▫	▫	
5	zone 1		▪			▫	▪		
	zone 2				▪			▪	
6				▪				▪	▪

*Note: Black dots ▪ major component and red dots ▫ minor component.

Table 4.2 – Benthic habitats for predicted sites of fresh groundwater occurrence.

The most interesting and encouraging results were found in the circular feature of the known groundwater discharge site. The substrate consists of limestone/brown algae with minor sand and limestone/coral for the central part of this feature. The central part of this feature is the most indicative feature of fresh groundwater occurrence because this is possibly the area where water upwells/discharges from the land. Darker features for this area were identified using aerial photographs, the bathymetry, benthic images and surface reflectance data. The darker features are likely to indicate subsidence caused by karst.

The six predicted areas were dominated by coral, limestone/coral and vegetation with minor sand/coral. There were some areas observed with sand and coral/vegetation. The area with the closest benthic habitat signature to the known site is Area 5 (zone 1). To aid benthic habitat recognition, spectral signatures were used to observe similarities and differences with the known site.

4.6.2 Spectral Signatures

Different material (vegetation, minerals etc.) assemblages generally have different spectral profiles. The different profiles allow different material types to be mapped. The focus of this study was to identify different substrate types that encourage occurrence of fresh groundwater discharge. The limitations of this study were that only one known freshwater site exists. It is hard to say whether spectral and spatial features of the known site are unique or common for freshwater discharge points. To aid positions for spectral profiles, the benthic signatures have been used.

The spectral bands used in this study are bands 1 to 21 that lie in the visual region of the electromagnetic spectrum. Three bands were chosen that best represent true colours red, green and blue; band 15, band 7 and band 4 respectively. Each band displays a different wavelength.

The first area investigated was Area 1 at Bundera (Figure 4.19) that includes the site of known fresh groundwater occurrence (profile 1).

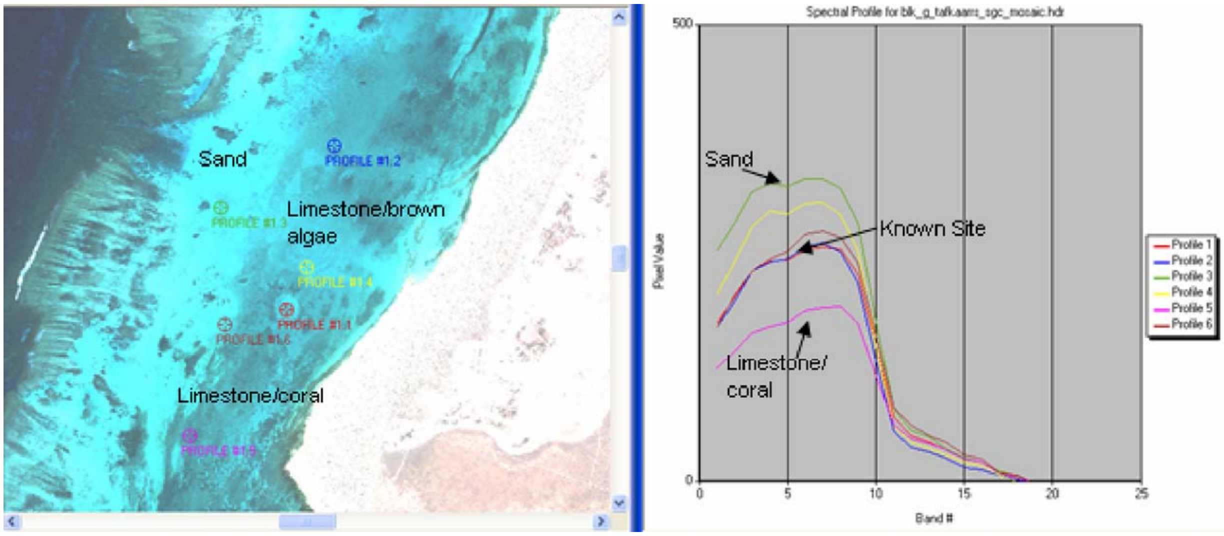


Figure 4.19 – Bundera area spectral analysis – zoomed out (Area 1).

These spectral profiles compare the known freshwater site (profile 1) with the surrounding environment. The spectral view window was set to show all bands within pixel brightness values 0 to 500.

Using the benthic signatures, corresponding substrate types were determined. Area 1 is dominated by sand, limestone/coral and limestone/brown algae with minor vegetation. Sand substrate types (profile 3, 4 & 6) display higher pixel values compared with other substrate types. This identifies more light is reflected back to the sensor. In comparison are limestone/coral substrates (profile 5) that appear darker due a greater absorption of light or indicative of deeper water. The known fresh groundwater site produced a similar signature to sand substrate although with slightly lower pixel values. Beyond band 10 (increased wavelength) the signatures are similar because much of this component of visible light has been absorbed. “At a depth of 20m only visible light (mainly the blue region) is present” (Mather, 2004). The maximum depth of natural light penetration received back to the aircraft HyMap sensor in this study was approximately 20m.

A close-up study was made for the known fresh groundwater site focusing on the circular feature. Spectral profiles were taken for the circumference of the circular feature and from selected places within the feature.

The results produced almost homogeneous signatures suggesting similarities of substrate and/or features. According to the benthic study, the circular feature is predominately limestone/brown algae with minor sand and limestone/coral in the center and mixture of minor coral, limestone/coral, sand/coral and vegetation on the outer rim.

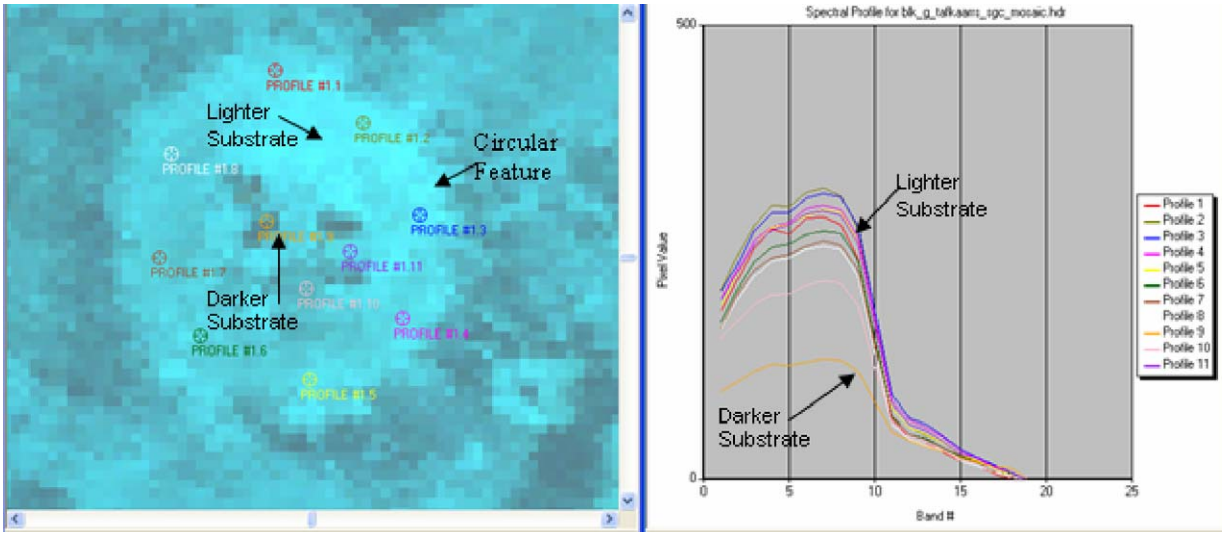


Figure 4.20 - Known freshwater site spectral analysis (Bundera) – zoomed in (Area 1).

Figure 4.20 identifies that profiles in the centre are more likely to be associated with darker substrate with more light absorbed. Values on the rim of the feature have higher more consistent pixel values that vary depending on the light intensity of the substrate and possibly due to the mixture of substrate types. Another possible reason for the darker features within the centre of the circular feature is that it is an area of subsidence where karsts or a sinkhole might exist. These karsts could possibly be at a depth greater than 20m that is undifferentiated using the hyperspectral data in this study. A hydrographic marine survey for the Ningaloo area could be one solution to this problem. It would allow more accurate and precise information about the depths of the seafloor. This would confirm karst/sinkhole feature locations.

The spectral profiles of the other predicted areas (Figure 4.21) were studied for spectral signatures to assess similarities with the known fresh groundwater site.

Area 2 is located in the vicinity of Yardie Creek and a well defined marine channel bounded by two ancient marine alluvial fans.

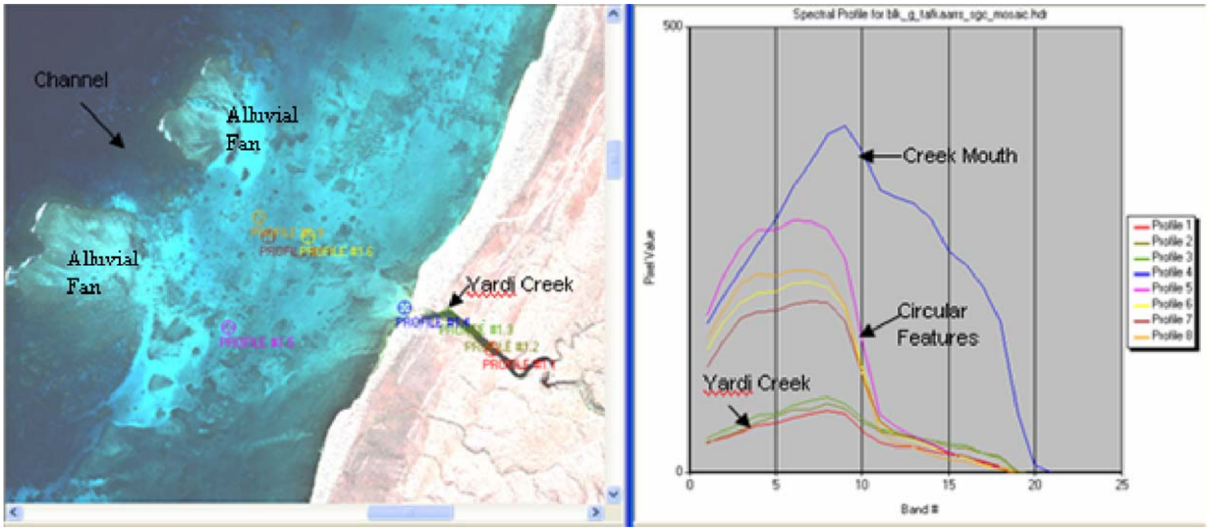


Figure 4.21 - Yardie Creek spectral analysis (Area 2).

Spectral profiles for this area displayed some distinguishing features. Yardie Creek displayed the lowest pixel values, with three profiles sampled for the creek (profile 1, 2 & 3). The creek is likely to be shallow compared with the other water profiles for this area. The water is also darker in the creek when viewed in the orthorectified aerial photographs. The creek mouth (profile 4) identifies the highest pixel values most likely corresponding to the high reflectance substrate; sand. A reason that the creek mouth and creek have different signatures is most likely because of the substrate type or depth of the water.

Areas directly adjacent to Yardie Creek were the main focus in this spectral study. This was determined through kernel density estimation maps for predicted sites and benthic circular feature indicators ('bombies').

Spectral profiles were then studied for Area 3 in the Mandu Mandu Creek vicinity. In contrast to the semi-permanent Yardie Creek, Mandu Mandu Creek is intermittent and at the time of data acquisition, Mandu Mandu Creek was dry. The spectral signatures therefore differ for both creeks as seen in the spectral profile for Mandu Mandu Creek as profile 1. Mandu Mandu Creek displays a high reflectance surface with very little interference from its surroundings. There appears to be very little to no vegetation or water within the Mandu Mandu Creek.

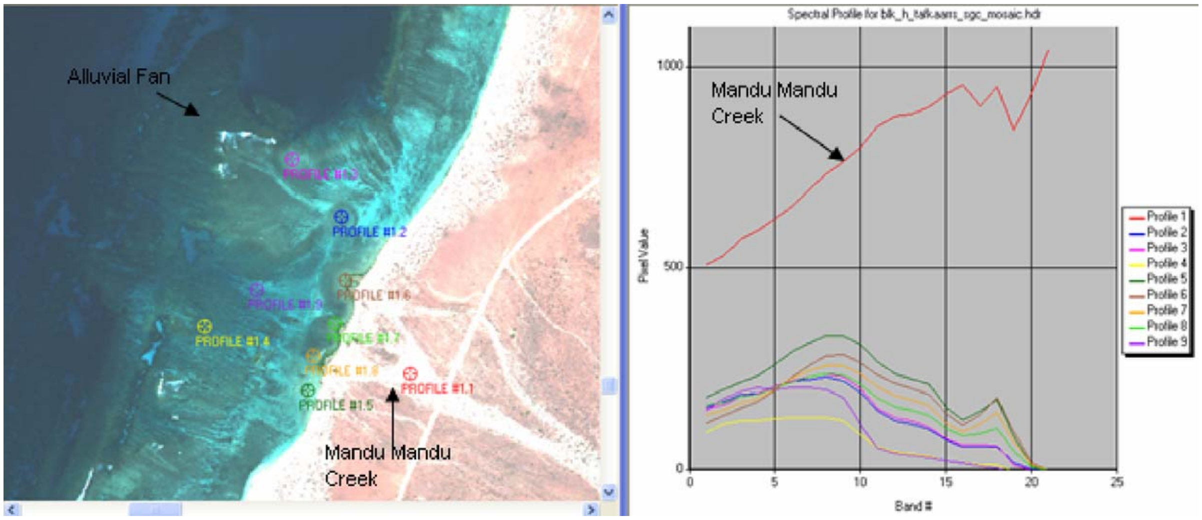


Figure 4.22 - Mandu Mandu Creek spectral analysis (Area 3).

The spectral profiles for this marine environment have different signatures to Areas 1 and 2. The difference is possibly best explained by the benthic habitat signatures that suggest the area is mostly coral and limestone/coral substrate. There are small patches of sand and vegetation identified by profile 3 and profile 9. Spectral signatures for Area 3 show small similarities with the known fresh groundwater site.

Some signatures for the spectral profiles of Area 3 display a peak between bands 5 and 10 and a gradual decline to band 21. Profiles 6 to 8 display another peak at approximately band 18. This peak identifies an increase in reflectance for the red part (*red edge point*) of the electromagnetic spectrum suggesting vegetation.

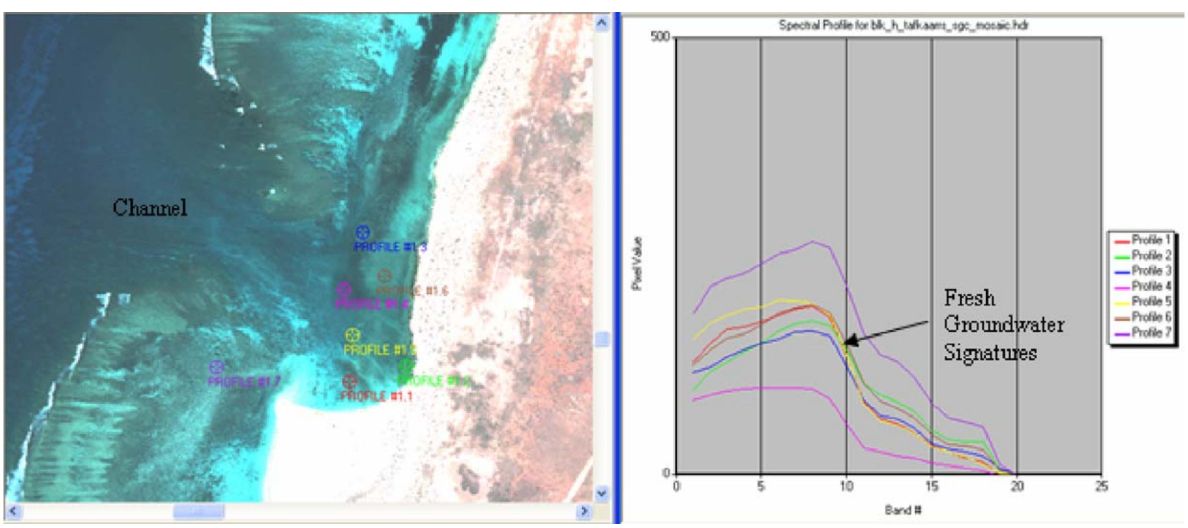


Figure 4.23 – Turquoise Bay spectral analysis (Area 4).

Area 4 identifies an area dominated by coral and limestone/coral substrate. Compared with Area 3, that displays similar benthic habitat signatures, more vegetation is associated with this area. There is a gradual peak in the signatures between band 5 and 10 and a steady decline to band 21. These signatures are relatively consistent with profiles from Areas 1 and 2. There is a small peak around band 18 supporting the increase in vegetation. Area 4 was chosen using kernel density estimation maps and profiles were selected using substrate and features from the benthic habitat signatures.

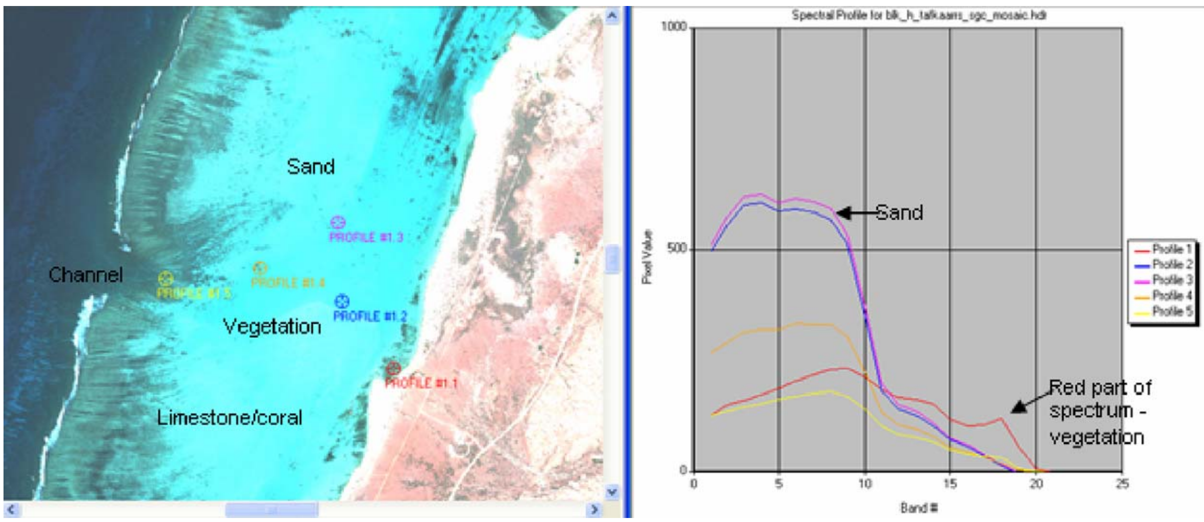


Figure 4.24 - Lakeside spectral analysis (Area 5).

In Area 5 two circular features were identified within the benthic habitat study. The circular features are represented as profile 1 and profile 2. Both circular features displayed different benthic signatures – profile 1 is dominated by coral and coral/sand whilst profile 2 has a limestone/coral core with a sand rim and minor limestone/brown algae. It was thought profile 2 would display a similar spectral signature to the known site due to similarities of the substrate.

The spectral profiles confirm that different signatures exist for both circular features. Neither profile 1 nor profile 2 displays a similar spectral signature to the known fresh groundwater site. Profile 4 spectral signature does however have similarities with the known site (Figure 4.20). This profile was sampled within the channel adjacent to the circular features.

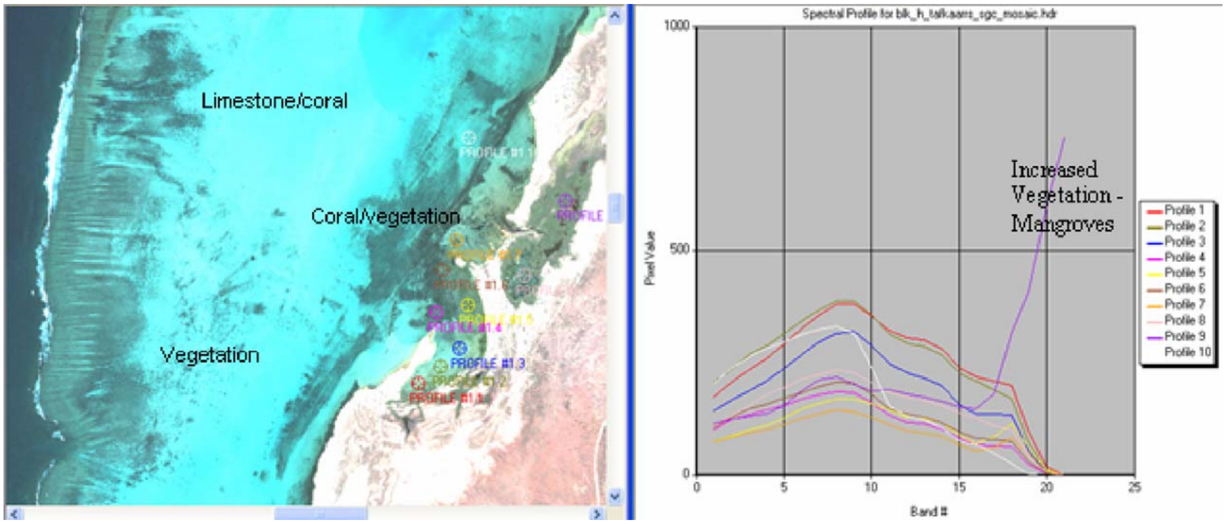


Figure 4.25 – Mangrove Bay spectral analysis (Area 6).

Area 6 displays spectral signatures that suggest the substrate type and features for this area are slightly different to the other five areas with one major difference. Most of the profiles peak in pixel values between bands 5 and 10 and decline in values towards band 21. This decline toward band 21 is a lot more gradual compared with the other five areas. This area has a large colony of Mangrove vegetation and is commonly known as Mangrove Cove. There is a peak at approximately band 18 identifying an increase in the light reflected back from the red part (*red edge point*) of the electromagnetic spectrum suggesting vegetation. The benthic habitats signatures for this area identify vegetation as a main substrate type.

Profile 9 has a peak in spectral signatures from approximately bands 17 to band 21 suggesting an increase in vegetation for this area. If infrared bands were available in this hyperspectral study you would expect to see a peak in that part of the electromagnetic spectrum for profile 9.

The spectral signatures for the predicted areas have been supported by benthic habitat signatures. The findings show that some similarities do exist in the Ningaloo Reef Marine Park with the one known fresh groundwater site. These findings would be better supported using a standard signature or a diffuse attenuation coefficient. The attenuation (gradual loss of intensity) of light with water depth is an exponential function (using a homogeneous water column) (Corner, 1993).

A number of researchers have conducted measurements for the diffuse attenuation coefficient of various water types. If the diffuse attenuation coefficient for the water type that best suits fresh groundwater in a shallow marine environment exists then this can be used for further comparative studies as a standard signature.

The results from this preliminary spectral analysis identified areas that have similar spectral signatures to the known fresh groundwater site. These three main areas are; Area 1 in the vicinity of Bundera, Area 2 in the vicinity of Yardie Creek and Area 4 in the vicinity of Turquoise Bay.

4.7 Findings of Remote Sensing Study

This study predicted the occurrence of fresh groundwater discharge from the terrestrial Cape Range peninsula to the adjacent Ningaloo Reef Marine Park. The study developed groundwater geodatabases, GIS interpretation of datasets for the local groundwater system, a predictive model for groundwater discharge into the marine setting, interpretation of hyperspectral datasets and correlation of information for results. The data used in this study are from a variety of sources that cover both the Cape Range peninsula and Ningaloo Reef Marine Park. The main datum used was GDA94 projected into UTM zone 49.

There was only one 'groundtruth' confirmed fresh groundwater discharge point recorded within the Ningaloo reef community. This one known site limited the prediction model to using fresh groundwater indicators. These indicators could only produce an estimate of sites for where fresh groundwater might occur in the reef environment. Because these predicted sites are only estimates further analysis was conducted with caution. Estimations create an element of uncertainty in the data. Six predicted sites were identified and used in confirmatory analysis for results.

Four areas were identified as the most likely positions where fresh groundwater occurs. These areas are Area 1, Area 2, Area 4 and Area 5. Area 1 contains the known fresh groundwater site that has been described to display "bubbling" water. Area 2 displays benthic circular features (similar to the known site) adjacent to the semi-permanent Yardie Creek. Area 2 also displays similar spectral signatures to Area 1. Area 4, in the vicinity of Turquoise Bay, displays similar spectral signatures and benthic circular features to the known site (Area 1). Area 5 has similar benthic habitat signatures to the known fresh groundwater site (Area 1).

The four areas are identified by fresh groundwater indicators. The indicators for Area 1 (Bundera) include the site of fresh bubbling groundwater likely upwelling during times of increased rainfall (seasonal and cyclonic) flowing through the limestone karstic system. The circular feature indentified in this area is possibly a sinkhole formed through subsidence of the karstic system. Other indicators for Area 1 include the Bundera man-made well, inland springs and drainage discharge points. There are no main marine channels in Area 1. No marine channel suggests terrestrial drainage in this area has been dominated by underground water systems, possibly due to the decrease in adjacent topography. Area 2 (Yardie Creek) freshwater indicators are dominated by the semi-permanent Yardie Creek. Yardie Creek is a semi-permanent flowing creek although contains a permanent source of water. Yardie Creek discharges into the marine environment seen in the benthic images as an increase in vegetation around the creek mouth. Other indicators for Area 2 are Ficus trees suggesting cave systems within the karstic limestone, prominent marine channels likely formed by ancient terrestrial drainage discharge and a man-made well. Yardie Creek and the groundwater system most likely pre-date the present day groundwater system. Area 4 (Turquoise Bay) is indentified as having a prominent marine channel, circular marine features, Ficus trees, drainage discharge points and a known karst location. Area 5 (Lakeside) fresh groundwater indicators are the prominent marine channel, circular marine features, drainage discharge points, a man-made well and a karst location. The four areas display similar fresh groundwater indicators that suggest a continuation of groundwater from the terrestrial to marine environment. The main mode of transportation for the groundwater is likely through the limestone karstic system influenced by the regional topography. Where subsidence has occurred over time the karstic system may have collapsed forming sinkholes where groundwater now upwells. Drainage discharge could have cut marine channels through a once continuous reef crest when rainfall and a more replenished aquifer existed in the area.

Area	Location	Groundwater Indicators	Terrain/ Geology	Mechanism
1	West of Bundera sinkhole	Anecdotal evidence of 'bubbling' groundwater, karst:sinkhole	Limestone coastal plain and sandy beach ridges	Tidal oscillation within sinkhole suggesting a karst conduit.
2	Yardie Creek	Ficus along creek and at coast, marine channel, well, permanent water	Dissected limestone plain and coastal barrier	Freshwater input from adjacent creek and through permeable barrier, rockhole:karst
3	Mandu Mandu Creek	Ficus, drainage discharge points, well, offshore alluvial fans	Limestone plain and coastal alluvial fan complex	Freshwater input from adjacent creek and alluvial fans, karst
4	Turquoise Bay	Marine channel, drainage discharge points, karst, abandoned well and Ficus	Sand cusp backed by limestone plain	Discharge through sandy beach ridges
5	Lakeside	Marine channel, drainage discharge points, karst conduit with south to north waterflow and well	Limestone plain, alluvial fan complex, sand cusp and sandy beach ridges	marine features, karst conduit with south to north water flow in coastal plain, surveyed length ~450m, porous alluvial fan
6	Mangrove Bay	Well, drainage discharge ponts, mangroves likely influenced by freshwater	Limestone plain, alluvial fan, embayments with mangroves and sand barriers	cluster of springs, porous alluvial fan

Table 4.3 Summary of remote sensing findings. Areas of high probability of groundwater discharge described by groundwater indicators, terrain and likely discharge mechanism.

In conclusion, it was identified that spatial patterns do exist in the fresh groundwater data for the Ningaloo Reef Marine Park. The Null Hypothesis can therefore be accepted that states “A predictive model can be used to help identify groundwater discharge into a marine environment”. The prediction model used in this study provides suggested areas for freshwater groundwater occurrence.

4.8 Recommendations

Recommendation for continued research into fresh groundwater occurrence in the Ningaloo Reef Marine Park includes groundtruthing and spectral signature analysis.

Groundtruthing can be time consuming, expensive and impinge on the natural ecosystem although at the same time can provide invaluable information for spatial predictive models. The more known sites available allow more accurate and precise predictive models to be developed. Establishing at least five more known fresh groundwater sites could greatly improve the likelihood of predicted areas. These additional five groundtruth areas could involve investigated the suggested areas found in this Ningaloo study. The new groundtruthed sites could then be developed into an inductive prediction model that could aid future environment conservation. An inductive prediction model would be based on observed patterns where additional data is inferred. Groundtruthing would also increase knowledge of the area for weighting of data.

Spectral signature analysis could be developed to include a standard signature for comparisons. This standard signature could represent fresh groundwater in a shallow marine environment. The signature could be used as numerical values, for more accurate results, and analysed against predicted site signatures for similarities. This analysis would reduce/increase the probability of finding fresh groundwater occurrence in the Ningaloo Reef Marine Park.Regional Studies

5. Conclusions and Future Work

The initial intention of Node 3 managers was to link groundwater analysis to concurrent work on the stygofauna, but this project proposal foundered before implementation in the initial stages of Node 3 activities.

Subsequent to a Curtin seminar and review of groundwater issues held jointly with Government hydrogeologists and CSIRO cluster researchers, during 2007, WAMSI Project 3.10 was established as a remote sensing study of the groundwater system, as described in this report. In the sites identified in Table 4 there is a strong probability of submarine groundwater discharge associated with karst conduits and alluvial fan systems and channels in the coastal plain and reef lagoon, with probable but unquantified influences on lagoon biotic communities. The remote sensing outcomes relate to objective 5 and conclude this part of the project.

In a separate Curtin study of the Exmouth borefield (Lee, 2008) a hydrogeological model prepared for the eastern coastal plain provided, in the absence of western borehole information, a useful model for the western coastal plain, since the geology and stratigraphy are similar on either side of the Cape Range anticline. These findings (summarised in this report) are applicable to objectives 1-2 of WAMSI project 3.10.

Working in the offshore region during AIMS seabed surveys, researchers in Projects 3.1.1 and 3.4 discovered seafloor mounds which are likely submarine groundwater discharge points. These features are close to the Last Glacial Maximum shoreline (SL-120m/18ka BP; Fig 4.7) and may represent termination points of lowstand karst features which would be expected to have developed along this palaeoshoreline. The controls exerted by oscillating sea levels operating at geological timescales are important for processes such as karst development, submarine groundwater discharge and stygofauna evolution.

Discussions of research progress during the second half of 2009 led to formulation of a partnership between project 3.10 and the Bundera project led by Dr Bill Humphreys of WAM, in which it is proposed to drill and instrument a borehole transect at Bundera for stygofauna and groundwater monitoring within the western coastal plain at Bundera, a known stygofauna and karst conduit site. This proposal (extending beyond the effective life of 3.10) has been agreed to by the Node 3 leader and WAMSI, and is summarised in Appendix -. It will produce data on objectives 3-5 of project 3.10 during 2010 and potentially beyond, re-establish the link between groundwater and stygofauna research (an original goal of WAMSI managers), pool scarce resources for expensive drilling, and is a logical continuation of groundwater related research at Ningaloo Reef.

ACKNOWLEDGEMENTS

This research was funded by WAMSI. Thankyou to Halina Kobryn for her assistance and advice on the Hymap data, Wojciech Klonowski for providing data and advice on benthic signatures, Department of Spatial Sciences, Curtin University and Darren Brooks from the Western Australian Speleological Group for providing cave points, maps and valuable advice on the karst system of the western coastal plain. Thanks also to Emily Twiggs and Ben Fitzpatrick for providing information on the area and assistance with data.

COMMUNICATION ACHIEVEMENTS

Reports:

Milestone Report 1 – Startup and Progress Report July 2008 - Assessment of Coastal Groundwater dynamics and linkages with the Ningaloo Reef

Milestone Report 2 - Progress Report December 2008 - Assessment of Coastal Groundwater dynamics and linkages with the Ningaloo Reef

Milestone Report 3 – Final Report February 2010 - Assessment of Coastal Groundwater dynamics and linkages with the Ningaloo Reef

Theses

Sam Lee, Department of Applied Geology. Hydrogeology of Cape Range Limestone Aquifers, NW Australia. Completed 2008. PhD Thesis, Curtin.

Deanna Wilson,2008, Department of Spatial Sciences, Curtin: GIS Analysis of Groundwater Occurrence in Ningaloo Reef Marine Park, Western Australia. Completed December, 2008. Masters by Coursework Thesis, Curtin.

Sira Tecchiato, 2009. Geomorphology, habitats and substrates of the shelf adjacent Ningaloo Reef. Masters Thesis, University of Rome/Curtin.

Conferences, presentations and abstracts

Groundwater Symposium/Workshop at Curtin in 2007. Sponsored by Tourism Node of CSIRO Wealth from Oceans and Curtin Applied Geology (Lindsay Collins). Attended by 12 hydrogeologists from the Carnarvon region and researchers from Curtin, CSIRO and WA Museum to discuss regional groundwater issues etc. An outcome of the symposium was the application for Node 3.10 Groundwater project with a remote sensing focus.

Marine Science in WA Show and Tell 'Newsflash' February 2008**.** Alexandra Stevens Assessment of Groundwater impacts on the Ningaloo Reef system. (seminar presentation)

COGS 2009 Alexandra Stevens Assessment of Groundwater impacts on the Ningaloo Reef system. (Consortium for Ocean Geosciences of Australian Universities Conference, Perth, 2009; conference presentation)

Marine Science in WA Show and Tell 'Newsflash' February 2010**.** Alexandra Stevens Assessment of Groundwater impacts on the Ningaloo Reef system. (seminar presentation)

Other

Lindsay Collins, 2008/9. Ningaloo Coast World Heritage nomination Reference Group Invited participant (Department of the Environment, Water, Heritage and the Arts).

REFERENCES

Allen. A.D. 1993. *Outline of the geology and hydrogeology of Cape Range, Carnarvon Basin, Western Australia*, ed. W.F. Humphreys, 25-38. Perth: Western Australian Museum.

Australian Marine Conservation Society, 2007. *Ningaloo Marine Park*. http://save-ningaloo.org/

Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J., and Van Rensburg, H.J, 1995, *Manual on quantitative estimation of groundwater recharge and aquifer storativity.* WRC report No TT 73/95.

Collins, L.B, Zhu, Z.R, McNamara, K.J and Wood, D. 2006. *Evolution of Tertiary to Quarternary Carbonates of the Cape Range region and Ningaloo Reef, Northwest Australia.* INQUA Project 0419/IGCP 464. Department of Applied Geology, Curtin University of Technology.

Commonwealth of Australia, 2006. *Ningaloo Marine Park (Commonwealth Waters) - brochure*. Designed and Typeset by Levitate Graphic Design. www.environment.gov.au/coasts/mpa/publications/pubs/ningaloo-brochure.pdf

Corbett, D.R, Dillon, K, Burnett, W.C and Chanton, J. 2000. *Estimating the groundwater contribution into Florida Bay via natural tracers 222Rn and CH4.* Limnology and Oceanography 45: 1546-1557.

Corbett, D.R and Fourqurean, J. 1999. P*atterns of groundwater discharge into Florida Bay.* Limnology and Oceanography 44: 1045-1055.

Corner, R.J. 1993. Passive spectral bathymetry using satellite remote sensing in Cockburn Sound W.A. Curtin University of Technology, Masters Dissertation.

D'Adamo, N. and C. J. Simpson . 2001. Review of the Oceanography of Ningaloo Reef and Adjacent Waters. Technical Report: MMS/NIN/NIN-38/2001. Marine Conservation Branch. Department of Conservation and Land Management, Fremantle, Western Australia.

Desbarats, A.J, Logan, C.E, Hinton, M.J, Sharpe, D.R, 2001. *On the kriging of water table elevations using collateral information from a digital elevation model.* Journal of Hydrology 255 (2002): 25-38. Geological Survey of Canada

DOIR, 2008. Department of Industry and Resources: Government of Western Australia http://www.doir.wa.gov.au/

ENVI, 2008. *ENVI Software – Image Processing and Analysis Solutions*. ITT Visual Information Solutions. http://www.ittvis.com/ProductServices/ENVI.aspx

EPA, 1999. *Environmental Protection of Cape Range Province, Position Statement No. 1*. Environmental Protection Authority. http://www.epa.wa.gov.au/docs/1031_PS1.pdf

ER Mapper, 2008. ER Mapper – Geospatial Imagery Solutions GIS. United States of America. http://www.ermapper.com/

ERDAS, 2008. ERDAS – The Earth to Business Company. ERDAS, Inc. United States of America. http://www.erdas.com/

ESRI, 1995-2008. ESRI – GIS and Mapping Software. United States of America. http://www.esri.com/

Forth, J.R. 1972, *Exmouth Water Supply*,. Geological Survey of Western Australia Record 1972/16, Perth.

Forth, J.R. 1973, *Exmouth Water Supply.* Annual Report 1972, Geological Survey of Western Australia, Perth.

Hamilton-Smith, E., Kiernan, K. and Spate, A. 1998, *Karst management considerations for the Cape Range Karst Province, Western Australia*. A report prepared for the Western Australian Department of Environmental Protection.

Humphreys, W.F. 1994. T*he subterranean fauna of the Cape Range coastal plain, northwestern Australia.* A report prepared under the National Eastate Program, Western Australian Museum.

HyVista, 2008. HyVista Corporation Pty. Ltd. Castle Hill, NSW, Australia. http://www.hyvista.com/main.html

Jacobson G., Hill, P.J. & Ghassemi, F. 1997, *Geology and hydrogeology of Nauru*. In: Vacher, H.L., and Quinn, T.M. (Eds), 1997, Geology and Hydrogeology of Carbonate Islands. Elsevier, Amsterdam, Pages 948

Jocson, J.M.U., Jenson, J.W., Contractor, D.N. 2002, *Recharge and aquifer response: Northern Guam Lens Aquifer, Guam. Mariana Islands*. Journal of Hydrology 260: 231-254.

Kirby, J, 2007. *Coordinate Mapping Systems Lecture Notes*. Curtin University of Technology. Unpublished.

Kobryn, H. 2006. Project 3 – Bathymetry - Habitats – Kobryn Presentation. Murdoch University, Western Australia. Unpublished.

Landgate, 2008. Landgate: Government of Western Australia. http://www.landgate.wa.gov.au/

Lee, S.Y., 2008. *Hydrogeology of Cape Range Limestone Aquifers, NW Australia*. Curtin University of Technology. PhD Thesis

Longman, M.W. 1980. *Carbonate diagenetic textures from nearsurface diagenetic environments*. Bull, AAPG 64: 461-487.

Martin, M. 1990, *Exmouth Town Water Supply Investigation Report and Recommendations for Future Work*. Unpublished Report, Geological Survey of Western Australia, Hydrogeology Report No 1990/36, Pages 12.

Mather, P.M. 2004. *Computer Processing of Remotely-Sensed Images; An Introduction (Third Edition).* John Wiley & Sons, Ltd. West Sussex, UK.

Mueller, M. 1991, *Karst hydrogeology of the Takaka valley, Golden Bay, northwest Nelson.* New Zealand Journal of Geology and Geophysics 34: 11-16.

Muir Environmental 1995, *Extensions to Exmouth Borefield for Water Authority of Western Australia. Consultative Review*, Unpublished report. Muir Environmental 95-008-007.

Mylroie, J.E. 2001, *Karst features of Guam in terms of a general model of carbonate island karst.* Journal of Cave and Karst Studies 63, 1: 9-22.

Peterson, F.L. 1997, *Hydrogeology of the Marshall Islands.* In: Vacher, H.L. and Quinn, T.M. (eds.), Geology and Hydrogeology of Carbonate Islands, Elsevier, Amsterdam, p.611-636.

Shuster, E.T. and White, W.B., 1971. *Seasonal Fluctuations in the Chemistry of Limestone Stprings: A Possible Means for Characterising Carbonate Aquifers.* Journal of Hydrology, Vol 14, No. 2, P 93-128.

Smart, C.C., and Ford, D.C., 1986, *Structure and function of a conduit aquifer.* Canadian Journal of Earth Sciences 23: 919-929

Taniguchi, M, Burnett, W.C, Dulaiova, H, Siringan, F, Foronda, J, Wattayakorn, G, Rungsupa, S, Kontar, E.A, & Ishitobi, T, 2008. *Groundwater Discharge as an Important Land-Sea Pathway into Manila Bay, Philippines*. Journal of Coastal Research 24(1A):15-24. West Palm Beach (Florida)

Taylor, J.G and Pearce, A.F. 1999. *Ningaloo Reef currents; implications for coral spawn dispersal, zooplankton and whale shark abundance.* Journal of the Royal Society of Western Australia 82: 57-65.

The Weather Co., 2008. The Weather Co. Sydney, Australia. http://www.theweather.com.au/

Urish, D.W. and Gomez, A.L. 2001, *The Temporal and Spatial Distribution of Coastal Groundwater Seepage.* Monitoring, Modeling and Management. Essaouria, Morocco. April 23-25, 2001.

Vanek, V, Lee, D.R. 1991. *Mapping Submarine Groundwater Discharge Areas-an Example from Laholm Bay, Southwest Sweden*. USA: Journal of Limnology and Oceanography 36(6): 1250-1262.

Wyrwoll, K-H. 1993. *An outline of Late Cenozoic palaeoclimatic events in the Cape Range region.* Records of Western Australian Museum, Supplement 45: 39-50.

Wyrwoll, K-H, Kendrick, G.W and Long, L.A. 1992. *The geomorphology and Late Cenozoic geomorphological evolution of the Cape Range – Exmouth Gulf region.* The Biogeography of Cape Range, Western Symposium 1992, Perth, Western Australian Museum: 1-24.

Younger, P. L. 1996, *Submarine groundwater discharge.* Nature 382: 121–122.

BIBLIOGRAPHY

Blackwell, N. 2002. *Quaternary coastal evolution adjacent to the Ningaloo Reef, Western Australia, and implications for land use planning*. Curtin University of Technology, Honours Dissertation.

Cassata, L and Collins, L. 2008. *Coral Reef Communities, Habitats, and Substrate in and near Sanctuary Zones of Ningaloo Marine Park*. Journal of Coastal Research 24(1): 139-151.

Collins, L. (2007) WAMSI DRAFT Project Plan for Node 3 Project 3.10 Assessment of Groundwater and Subterranean Fauna (Groundwater Component) Version 1. *WAMSI and Sigma Management Science,* Western Australia.

Conolly, J & Lake, M. 2006. *Geographical Information Systems in Archaeology*. Cambridge University Press, UK.

Cook, P.G. Fass, T. Herczeg, A.L, and Stieglitz, T. (2007) *Development of Saline Ground Water through Transpiration of Sea Water*. Ground Water 45 (6): 703-710.

Curtin Website, 2008. *Applied Physics Photographs.* http://physics.curtin.edu.au/local/images/apphotolist.cfm Curtin University of Technology, Western Australia.

D'Iorio, M, Jupiter, S.D, Cochran, S.A and Potts, D.C. 2007. *Optimizing Remote Sensing and GIS Tools for Mapping and Managing the Distribution of an Invasive Mangrove (Rhizophora mangle) on South Molokai, Hawaii.* Marine Geodesy, 30: 125-144.

Fortin, M-J & Dale, M. 2005. *Spatial Analysis – A Guide for Ecologists*. Cambridge University Press, UK.

Gross, T.F. Jackson, D.R. Jumars, P.A, and Sherwood, C. 1996. *Acoustic remote sensing of benthic activity: A statistical approach*. Limnology and Oceanography 41(6): 1220-1241.

Hahesy, C. 2004. *Quaternary geological processes and natural resource management of the coastal plain adjacent to Northern Ningaloo Marine Park*. Curtin University of Technology, Honours Dissertation.

Johst, M, Uhlenbrook, S, Tilch, N, Zillgens, B, Didszun, J. and Kirnbauer, R. 2008. *An attempt of process-orientated rainfall-runoff modeling using multiple-response data in an alpine catchment, Loehnersbach, Austria.* Hydrology Research, 39: 1-15.

Kuiper, J.A. and Wescott, K.L. (1999) "A GIS Approach for Predicting Prehistoric Site Locations*", in The Nineteenth Annual ESRI User Conference. San Diego, California: Sponsored by Environmental Systems Research Institute.

Kutser, T, Dekker, A.G, Skirving, W. 2003. *Modeling Spectral Discrimination of Great Barrier Reef Benthic Communities by Remote Sensing Instruments.* USA: Journal of Limnology and Oceanography 48 ((1) Part 2): 497-510.

Lanier, A, Romsos, C. and Goldfinger, C. 2007. *Seafloor Habitat Mapping on the Oregon Continental Margin: A Spatially Nested GIS Approach to Mapping Scale, Mapping Methods, and Accuracy Quantification*. Marine Geodesy, 30: 51-76.

Lee, T.T. 2002. *Implementation, Testing and Refinement of an Archaeological Predictive Model for the Jarrah Forests of South-Western Australia.* Department of Spatial Science, Curtin University of Technology, Australia.

Leeden, C. L. 2003. *Quaternary coastal evolution adjacent to Southern Ningaloo Reef, Western Australia: implications for land use planning.* Curtin University of Technology, Honours Dissertion.

Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. 2005. *Geographic Information Systems and Science (Second Edition).* John Wiley & Sons, Ltd. West Sussex, UK.

Martin, M. 1990, Exmouth Town Water Supply Investigation Report and Recommendations for Future Work, Unpublished Report, Geological Survey of Western Australia, Hydrogeology Report No 1990/36, Pages 12.

Miller, P, Mills, J, Edwards, S, Bryan, P, Marsh, S, Hobbs, P. and Mitchell, H. 2007. *A Robust Surface Matching Technique for Integrated Monitoring of Coastal Geohazards.* Marine Geodesy, 30: 109-123.

Ramirez, E. 2006. *Shuttle Radar Topography Mission.* NASA Jet Propulsion Laboratory, California Institute of Technology, US. http://www2.jpl.nasa.gov/srtm/

Resolution Multibeam Bathymetry Data. IAPSO conference 'Dynamic Planet', July 2005, Cairns, Australia.

Shamsi, U.M. 2002. *GIS Tools for Water, Wastewater, and Stormwater Systems.* ASCE Press, American Society of Civil Engineers, U.S.

Stieglitz, T., Kelley, R. Beaudoin, J., Hughes Clarke, J., Siwabessy, J., Parnum, I. M. and Cameron, D. (2005). Acoustic Mapping in the Great Barrier Reef (Australia): What Kind of Biological and Morphological Habitat Information Can We Extract from High - High-Resolution Multibeam Bathymetry Data? IAPSO conference 'Dynamic Planet', July 2005, Cairns, Australia.

Storming Media LLC. 2001-2008. *NRL Atmospheric Correction Algorithms for Oceans: Tafkaa User's Guide.* http://www.stormingmedia.us/86/8602/A860224.html

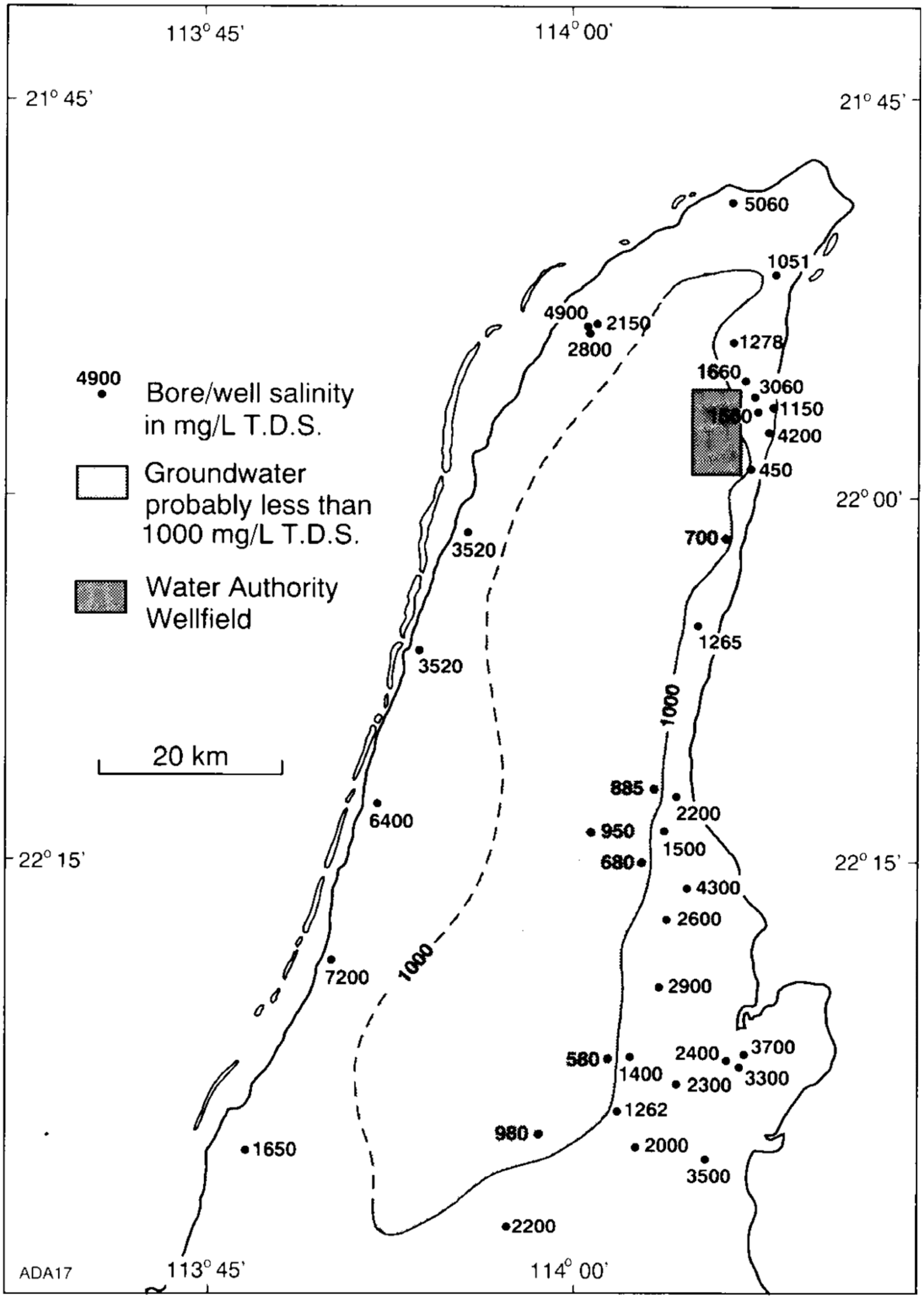
U.S. Department of the Interior | U.S. Geological Survey, 2006. *Shuttle Radar Topography Mission (SRTM) "Finished" 3-arc second SRTM Format*. USA Government. http://edc.usgs.gov/products/elevation.html

Wikipedia. The Free Encyclopedia. 2008. *Electromagnetic Spectrum*. http://en.wikipedia.org/wiki/Electromagnetic_spectrum

Zhixiao, X. and Jun,Y. 2008. *Kernel Density Estimation of traffic accidents in a network space*. Computers, Environment and Urban Systems, In Press, Corrected Proof, Available online 26 June 2008.

Appendix 1

Exmouth Wellfield showing Location of Bores, TDS line and salinity and TDS of measured bores (from Allen, 1993).



From Allen, 1993

Appendix 2

Data Sources for WAMSI project 3.10

Orthorectified Aerial Photographs

Ningaloo Orthophoto South

Data Type: File System Raster
Raster: ningaloo_orthophoto_TM_mosaic_south_mga49.ecw
Projected Coordinate System: GDA_1994_MGA_Zone_49
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 111.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994
Datum: D_GDA_1994
Prime Meridian: Greenwich
Angular Unit: Degree

Ningaloo Orthophoto North

Data Type: File System Raster
Raster: ningaloo_orthophoto_TM_mosaic_north_mga49.ecw
Projected Coordinate System: GDA_1994_MGA_Zone_49
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 111.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994
Datum: D_GDA_1994
Prime Meridian: Greenwich
Angular Unit: Degree

Airphoto North

Data Type: File System Raster
Raster: airphoto-orthorectified_nin+nre+rbp_19990700_utm49_gda94.ecw
Projected Coordinate System: GDA_1994_MGA_Zone_49
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 111.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994
Datum: D_GDA_1994
Prime Meridian: Greenwich

Angular Unit: Degree

Airphoto South

Data Type: File System Raster
Raster: airphoto-orthorectified_egu+nin_20000800_utm49_gda94.ecw
Projected Coordinate System: GDA_1994_MGA_Zone_49
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 111.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994
Datum: D_GDA_1994
Prime Meridian: Greenwich
Angular Unit: Degree

Vector Data

Karst Zone 50

Data Type: Shapefile Feature Class
Geometry Type: Point
Projected Coordinate System: GDA_1994_MGA_Zone_50
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 117.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994
Datum: D_GDA_1994
Prime Meridian: Greenwich
Angular Unit: Degree

Karst Zone 49

Data Type: Shapefile Feature Class
Geometry Type: Point
Projected Coordinate System: GDA_1994_MGA_Zone_49
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 111.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994

Datum: D_GDA_1994
Prime Meridian: Greenwich
Angular Unit: Degree

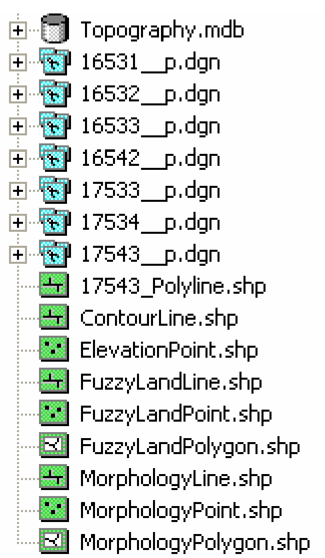
Ficus Locations

Data Type: Shapefile Feature Class
Geometry Type: Point
Geographic Coordinate System: GCS_WGS_1984
Datum: D_WGS_1984
Prime Meridian: Greenwich
Angular Unit: Degree

Honours Geology, Curtin

Data Type: Shapefile Feature Class
Geometry Type: Polygon
Projected Coordinate System: GDA_1994_MGA_Zone_49
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 111.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994
Datum: D_GDA_1994
Prime Meridian: Greenwich
Angular Unit: Degree

Topography



The topographic layers and shape files were obtained through Landgate, Western Australia. The datasets have been copied with details regarding processing and attributes presented in the metadata.

Data Type: Various
Geometry Type: Various
Projected Coordinate System: GDA_1994_MGA_Zone_49
Projection: Transverse_Mercator
False_Easting: 500000.00000000
False_Northing: 10000000.00000000
Central_Meridian: 111.00000000
Scale_Factor: 0.99960000
Latitude_Of_Origin: 0.00000000
Linear Unit: Meter
Geographic Coordinate System: GCS_GDA_1994
Datum: D_GDA_1994
Prime Meridian: Greenwich
Angular Unit: Degree

Raster Data

Digital Elevation Model (DEM)

Data Type: TIF copied to referenced personal geodatabase
Raster Layer: DEM
Projected coordinate system name: WGS_1984_UTM
Projection: Transverse Mercator
Linear Unit: Meter
Geographic coordinate system name: GCS_WGS_1984

Raster dataset information:-
SDTS raster type: Pixel
Number of raster bands: 1

Raster properties:-
Origin location: Upper Left
Has pyramids: TRUE
Has colourmap: FALSE
Data compression type: Run-Length Encoding (ESRI)
Display type: pixel codes

Resolution: ~83m

Scanned Images

Ningaloo Geology Map Sheet

Data Type: File System Raster
Raster: Ningaloo Geology Map1.img
Geographic Coordinate System: GCS_WGS_1984
Datum: D_WGS_1984

Prime Meridian: Greenwich
Angular Unit: Degree

Onslow Image

Data Type: File System Raster
Raster: Onslow.img
Geographic Coordinate System: GCS_WGS_1984
Datum: D_WGS_1984
Prime Meridian: Greenwich
Angular Unit: Degree

Ningaloo Hyperspectral HyMap 2006 airborne survey:

Bathymetry

Data Type: ENVI Raster Format
Raster Layer: blk_g_Bathymetry_Mosiac.bsq
Projected coordinate system name: WGS_1984_UTM_Zone_49S
Projection: Transverse Mercator
Linear Unit: Meter
Geographic coordinate system name: GCS_WGS_1984
Raster dataset information:-
Raster format: ENVI
SDTS raster type: Pixel
Number of raster bands: 1

Raster properties:-
Origin location: Upper Left
Has pyramids: TRUE
Has colourmap: FALSE
Data compression type: None
Display type: pixel codes

Resolution: 3.5m

Bathymetry

Data Type: ENVI Raster Format
Raster Layer: blk_h_Bathymetry_Mosiac.bsq
Projected coordinate system name: WGS_1984_UTM_Zone_49S
Projection: Transverse Mercator
Linear Unit: Meter
Geographic coordinate system name: GCS_WGS_1984
Raster dataset information:-
Raster format: ENVI
SDTS raster type: Pixel
Number of raster bands: 1

Raster properties:-
Origin location: Upper Left

Has pyramids: TRUE
Has colourmap: FALSE
Data compression type: None
Display type: pixel codes

Resolution: 3.5m

Bathymetry

Data Type: ENVI Raster Format
Raster Layer: blk_i_Bathymetry_Mosiac.bsq
Projected coordinate system name: WGS_1984_UTM_Zone_49S
Projection: Transverse Mercator
Linear Unit: Meter
Geographic coordinate system name: GCS_WGS_1984
Raster dataset information:-
Raster format: ENVI
SDTS raster type: Pixel
Number of raster bands: 1

Raster properties:-
Origin location: Upper Left
Has pyramids: TRUE
Has colourmap: FALSE
Data compression type: None
Display type: pixel codes

Resolution: 3.5m

Other Hyperspectral Datasets

Start Date: 21st of April 2006
Location: Ningaloo Reef Marine Park

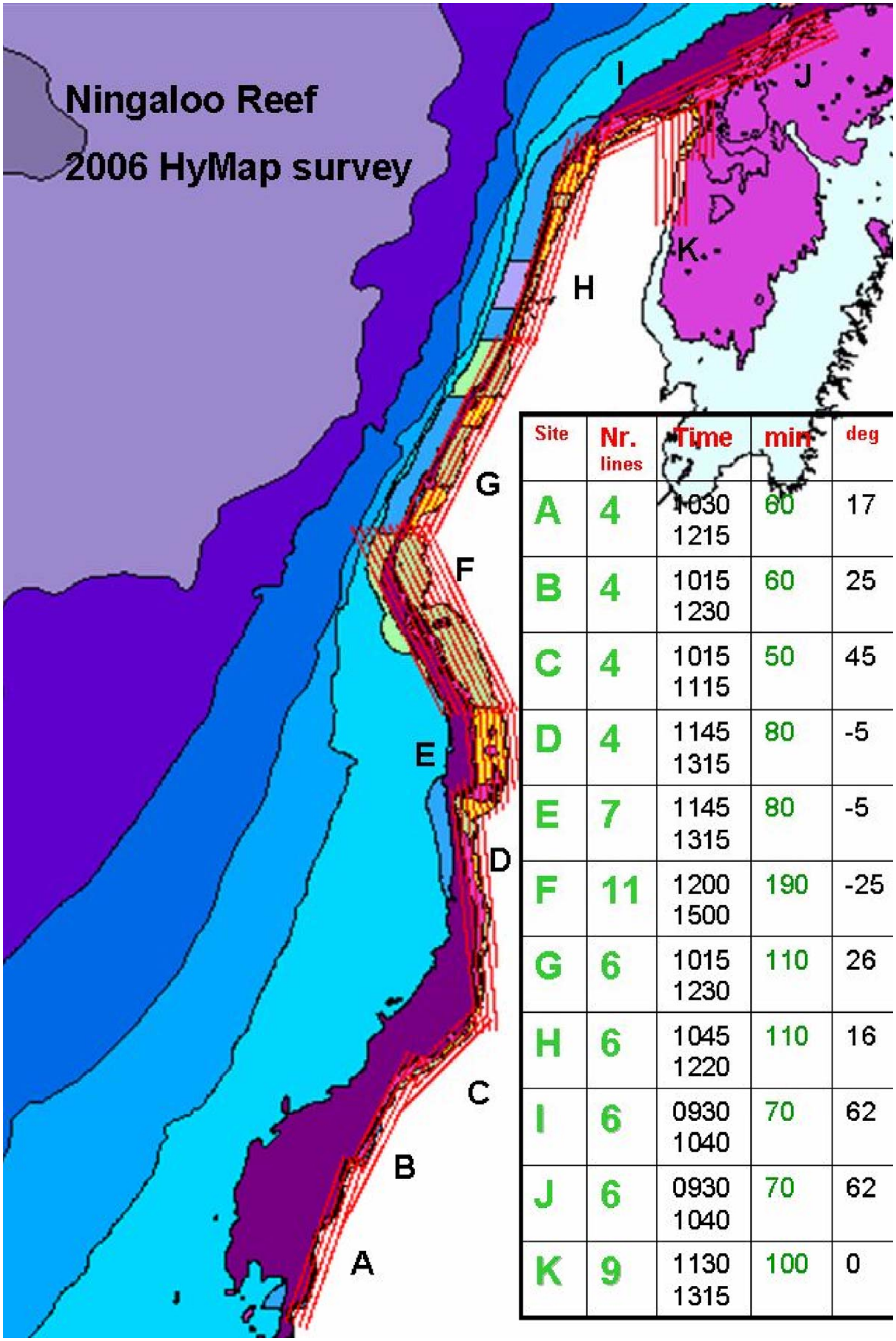
Base: Learmonth, WA

Area: > 3400 km2 in 67 flight lines acquired in 11 blocks

Ground resolution: 3.5 m pixel. Good - but not perfect conditions

Finished Date: 2nd of May 2006

Flown by HyVista Corporation, sponsored by BHP Billiton (Kobryn, H. 2006).



Site	Nr. lines	Time	min	deg
A	4	1030 1215	60	17
B	4	1015 1230	60	25
C	4	1015 1115	50	45
D	4	1145 1315	80	-5
E	7	1145 1315	80	-5
F	11	1200 1500	190	-25
G	6	1015 1230	110	26
H	6	1045 1220	110	16
I	6	0930 1040	70	62
J	6	0930 1040	70	62
K	9	1130 1315	100	0

Appendix 3

Literature Review– Groundwater Discharge Studies, influences and methods for determining likely locations of Submarine Groundwater Discharge

Groundwater Discharge

A general hypothesis is that water quality and associated problems that influence coastal ecosystems are related to past and ongoing contamination of terrestrial groundwater. Groundwater is commonly contained in confined aquifers in permeable and porous rocks in terrestrial environments. Although these aquifers are more commonly associated with land, the underlying aquifer host rocks most likely extend seaward into marine environments. The permeable and porous rock types are generally sedimentary facies and in the Ningaloo area are dominated by carbonates. Transitional zones exist between the terrestrial fresh groundwater and the marine saltwater. Each zone is divided into parts based on movement and saturation of water with respect to calcium (Longman, 1980).

Many coastal environments around the world are exposed to past and ongoing contamination of terrestrial groundwater's because those groundwater's seep along many shorelines (Taniguchi, et al., 2008). The direct discharge of fresh and saline groundwater into the coastal zone is called submarine groundwater discharge (SGD) that is recognised as significant although poorly quantified (Taniguchi, et al., 2008). The SGD acts as a source of nutrients and other dissolved species to coastal waters and ecosystems. Groundwater is likely to contribute no more than 6% of the river flow on a global basis (Zektser, 2000 cited in Taniguchi, et al., 2008), although can contribute as much as 50% total dissolved salts of that contributed by rivers (Zektser, 2000 cited in Taniguchi, et al., 2008). An example by Corbett et al. (1999, 2000) estimated that groundwater nutrient inputs can be approximately equal to nutrient input via surface freshwater runoff as seen in eastern Florida Bay, USA.

Large submarine springs can be detected at the sea surface (Vanek & Lee. 1991). Emerging groundwater is usually different from surrounding seawater and may create a plume which can be measured physically and chemically. Smaller submarine springs, seeps and dispersed seepage through coasts and seafloors can be more representative of submarine groundwater discharge. Cultivated coastal lowlands contribute to nitrogen in coastal waters that cause algal blooms. Coastal lowlands drain toward the sea via rivers but also via direct groundwater runoff (Vanek & Lee. 1991).

SGD influence on coastal ecosystems has been studied at Manila Bay in the Philippines. The bay is heavily affected by harmful algal blooms that were previously expected to have been attributed by surface water run-off. This theory was later revised as algal blooms were also found in the relatively pristine environment of Malampaya Sound (Palawan). Blooms in Manila Bay were also found to be initiated along the western coast of the bay. The western coastal area is relatively uncontaminated in comparisons to the more polluted bay outlet to the open sea (Zektser, 2000 cited in Taniguchi, et al., 2008). These findings suggest something other than surface run-off must have been triggering the algal outbreaks.

Like Manila Bay, The Ningaloo lagoon is a semi-enclosed structure that is influenced by activities of the surrounding marine and terrestrial environments. Ningaloo reef forms a linear crest that stretches parallel off the west coast of the Cape Range peninsula for approximately 280km. The reef crest is broken intermittently by channels that open the lagoons seawards and act as a natural flushing system for nutrients. Whilst investigations of groundwater discharge into coastal zones are relatively common these days, little submarine groundwater discharge (SGD) studies have been conducted in the Ningaloo area.

Elevation data are a basic element for hydrological investigations. Elevation data can be used to identify the direction of groundwater flow and zones of recharge and discharge. Groundwater features can be then used to evaluate surface water-groundwater interactions and assess stresses of the groundwater system (USGS, 1980 cited in Desbarats, et al., 2001). King (1899) (cited in Desbarats, et al., 2001) recognised that a relationship exists between the water table and topography (Desbarats, et al., 2001). Gravity drives flow of groundwater from higher towards lower elevations and the phreatic (groundwater below the static water table) surface is a subdued replica of the land surface. According to Desbarats et al (2001), Kings' fundamental observations suggest topography can be used as a guide and constraint to map water table elevations which otherwise would be solely based on sparse water well data. Digital Elevation Models (DEM's) offer large spatial characteristics of landform and drainage patterns that can be used to improve the accuracy and plausibility of mapped phreatic surfaces.

Some other common methods for SGD studies include compilation of geological and hydrological data, reconnaissance drilling and installation of observation wells, thermal infrared scanning, geoelectrical and seismic soundings, pore-water salinity surveys along the shoreline and seepage meter measurements (Vanek & Lee. 1991).

Consideration needs to be made for groundtruth studies that are suggested to follow-up this project. These considerations include salinity continuality and variability of the terrestrial and marine water chemistry, different sources of terrestrial freshwater (e.g. more than one aquifer, surface run-off, cyclone related), tide and wave-induced currents, bioturbation, thermal and density-driven advection, sedimentation and sediment compaction that could all led to variability in seawater water chemistry. A conductivity ratio could be made between shallow pore water and near-bottom seawater to measure the saltwater/freshwater interface (Vanek & Lee. 1991).

Appendix 4

Agreement between the Department of Applied Geology, Curtin University and Western Australian Museum regarding the Bundera Groundwater drilling and groundwater dynamics study project.