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HYPERSPECTRAL IMAGERY IN A GIS FRAMEWORK AS A TOOL FOR MARINE PLANNING IN TEMPERATE SOUTH-WESTERN AUSTRALIA

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ABSTRACT

The oligotrophic coastal waters of Western Australia provide a unique opportunity to apply hyperspectral remote sensing techniques. This project aims to use HyMap images of Rottnest Island to create thematic classification maps of the marine benthic habitats for use as a planning tool by managers and planners. This involves building a spectral reflectance library of the dominant benthic substrates, creating a digital elevation model for the island and classifying the images. Preliminary results have revealed that dominant substrates are spectrally separable and that the Krigging interpolation algorithm results in the most accurate digital elevation model.

Keywords: HYPERSPECTRAL REMOTE SENSING, MARINE HABITATS, ROTTNEST ISLAND, GIS, TEMPERATE COASTAL WATERS

INTRODUCTION

Australia's Oceans Policy was released in 1998 to provide a framework for integrated and ecosystem-based planning and management for Australia's vast marine territories (Commonwealth of Australia 1998). At the core of the policy is the development of regional marine plans for Australia's entire exclusive economic zone. A regional marine plan has been developed for the south-east region and preparation of the northern and south-western regional plans is underway (National Oceans Office 2005). The primary goals of the regional marine plans include ensuring marine ecosystem health into the future, protection of marine biodiversity, promotion of diverse and sustainable marine industries and ensuring the establishment of a National Representative System of Marine Protected Areas (Commonwealth of Australia 1998).

For a marine protected area to be classed as representative of the ecosystems they are designed to protect, they must "reasonably reflect the biotic diversity of the marine ecosystems from which they derive" (ANZECC 1998). Therefore, in order to define representative areas, there is a basic need to measure and map the biodiversity of Australia's vast coastline (Margules *et al.* 2002, Stevens 2002).

There has been a significant amount of research that has examined methods of both defining and measuring biodiversity (e.g. Gray 1997, Margules *et al.* 2002, Sarkar and

Margules 2002) and the need to use biodiversity surrogates for practical applications is widely accepted (Ward *et al.* 1999, Faith *et al.* 2001, Banks and Skilleter 2002, Margules *et al.* 2002, Stevens and Connolly 2004). The aim of a biodiversity surrogate is that it both serves as an reliable indicator of general biodiversity and is readily measurable in the environment (Sarkar and Margules 2002). A number of studies done in Australia, on the use of biodiversity surrogates, have found that marine habitats can be used as a biodiversity surrogate with a reasonable level of confidence (Vanderklift *et al.* 1998, Ward *et al.* 1999, O'Hara 2001).

Historically the mapping of marine benthic habitats has been done using traditional field methods, which are both costly and labour intensive. More recently, passive remote sensing techniques have been used as a means of mapping marine benthic habitats (Mumby *et al.* 1997, Sotheran *et al.* 1997, Louchard *et al.* 2003, Werdell and Roesler 2003). Initially, most remote sensing of marine benthic habitats has been done using aerial photography or multispectral satellite data, such as Landsat 7 TM+, with varying results (Armstrong 1993, Dustan et al. 2001, Naseer and Hatcher 2004, Purkis and Pasterkamp 2004). In addition to this, the bulk of the work has been restricted to shallow coral reef environments and freshwater systems, with reasonably clear water. There has been very little work conducted in temperate waters, due to the poor visibility of most temperate marine environments. In the coastal regions of south-western waters of Australia we have a unique opportunity to apply this technology in the clear oligotrophic waters, maintained by the presence of the southward flowing Leeuwin Current (Pearce 1991, Hanson *et al.* 2005).

The use of HyMap hyperspectral data to map the shallow marine benthic habitats of Rottnest Island Reserve (115º30’E, 32º S) is the focus of a current research project. The overall aim of the project is to utilise HyMap imagery to create thematic classification maps of the marine benthic habitats of Rottnest Island Reserve that can be used as a planning tool by the managers and planners. The project uses a multi-faceted approach in utilising the hyperspectral data. The first two components involve the development of a spectral reflectance library of the dominant marine benthic substrates in Perth coastal waters and building a digital elevation model (DEM) for the bathymetry of Rottnest Island Reserve. The next step of the process will be the image analysis of the hyperspectral data to classify the benthic substrates and fine tuning of these results using second order inputs to the classification. The final step will be to apply these results within a GIS framework to various planning and management scenarios in the Rottnest Island Reserve.

STUDY SITE

This study is being carried out in the Rottnest Island Reserve, which lies approximately 18 km offshore from Fremantle, Western Australia (Figure 1) The waters of reserve extend approximately 800 m from the island covering an area of 3 828 ha and vary in depth from inter-tidal platforms that are exposed at low tide to waters >40m deep. There are currently two fully protected sanctuary zones within the reserve covering 131 ha, with three more currently under review, along with extensions to the existing zones. If these changes are adopted the total area protected within sanctuary zones will increase to 555 ha (Rottnest Island Authority 2006).

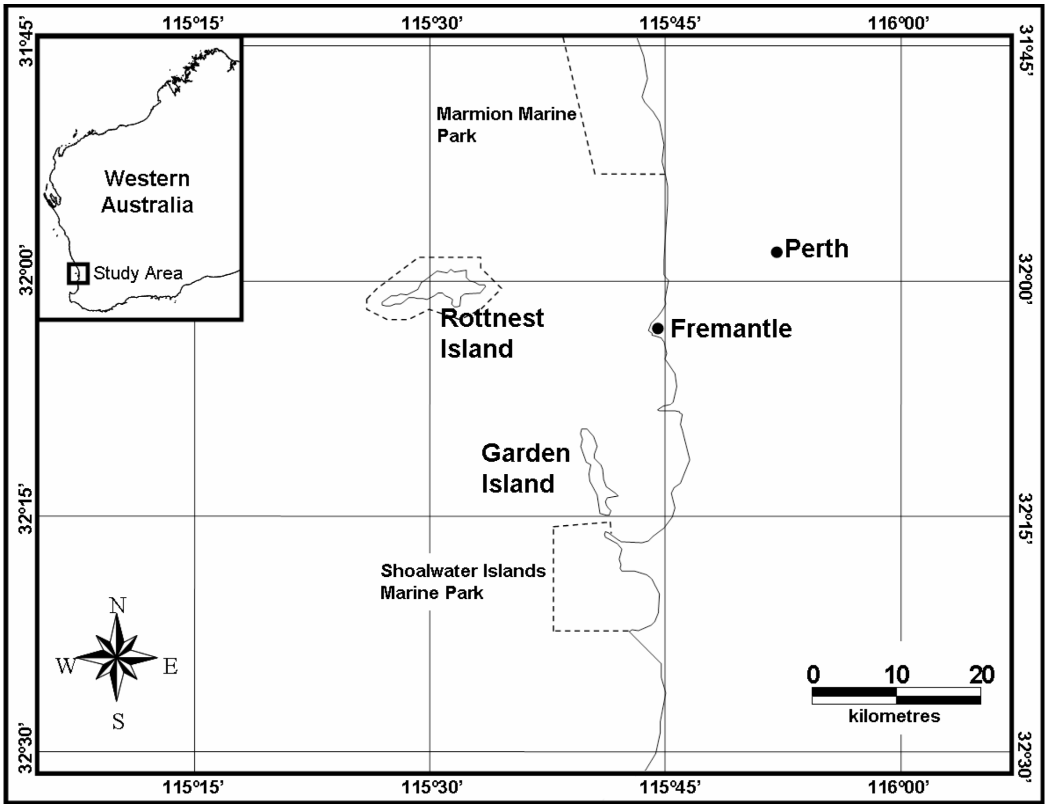

Figure 1: Map indicating Rottnest Island study area in south-west Australia. Dashed lines indicated boundaries of marine protected areas.

METHODS

The HyMap data for Rottnest Island were flown by the HyVista Corporation on the 26th April 2004 (Figure 2). The data were collected in four flight lines at 3.5 m pixel resolution in 125 bands ranging from 450 nm to 2048 nm.

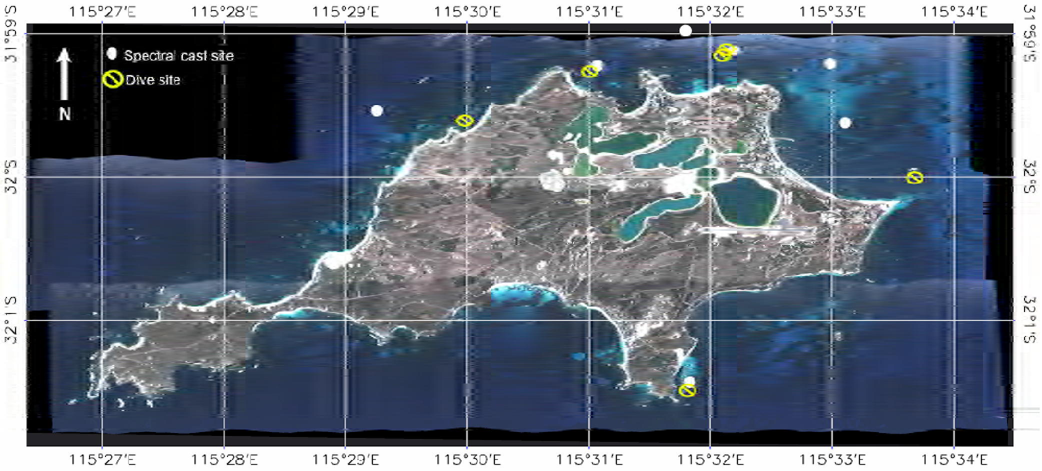

Figure 2: HyMap image of Rottnest Island showing three of the four flight lines collected and various sampling sites around the island. Image is an RGB composite using bands 15, 9 and 3.

Spectral Reflectance Library

There are many approaches in interpretation and classification of hyperspectral data. One of these is through spectral libraries. The development of the spectral reflectance library involved in-situ field collection of reflectance spectra and determination of the spectral (optical) depth of the water column. This collection of reflectance spectra was carried out using a spectrometer, attached to a laptop computer. The basic spectrometer setup consisted of a single channel spectrometer fitted with a 30m long, 500 µm diameter fibre optic with a stainless steel probe. When triggered by the diver using a control cable attached to the fibre optic, the spectral data were recorded by the computer as a text file (Figure 3). Spectral data were collected in pairs, the upwelling radiance from the target substrate and the downwelling radiance, using a calibrated Teflon reflectance target. For each target 10 pairs of spectra were collected. Where spectral signatures were collected at depths >5m a halogen light source was used to supplement light lost. A dark current reading was taken with the light source blocked prior to sampling. The spectra were collected from Rottnest Island Reserve and also at Marmion and Shoalwater Marine Parks, to provide a representative sample for the Perth coastal waters.

The spectra were converted to absolute reflectance values using the following formula (Murphy et al. 2005):

$$\text{Reflectance (\%)} = \frac{\text{Upwelling radiance } (\lambda) - \text{Dark current } (\lambda)}{\text{Downwelling radiance } (\lambda) - \text{Dark current } (\lambda)} \quad (1)$$

Each pair of spectra was processed and the results for each target were averaged. The reflectance spectra were analysed to determine how spectrally separable different substrates were at both spectrometer resolution (~0.3 nm) and HyMap sensor resolution (~15 nm).

To determine the spectral depth, or the depth to which natural sunlight penetrates the water column, a spectral sampling frame was used. This device consists of a weighted frame with a calibrated Teflon reflectance panel mounted in the base and the fibre-optic probe mounted at 45º to the base to record the intensity of downwelling radiance (Figure 3). The frame was lowered on a calibrated line and 10 spectra were recorded at each from the surface to the bottom in one meter increments and again on the way up. Spectral data were then averaged for each depth and converted to percentage of light lost at each depth.

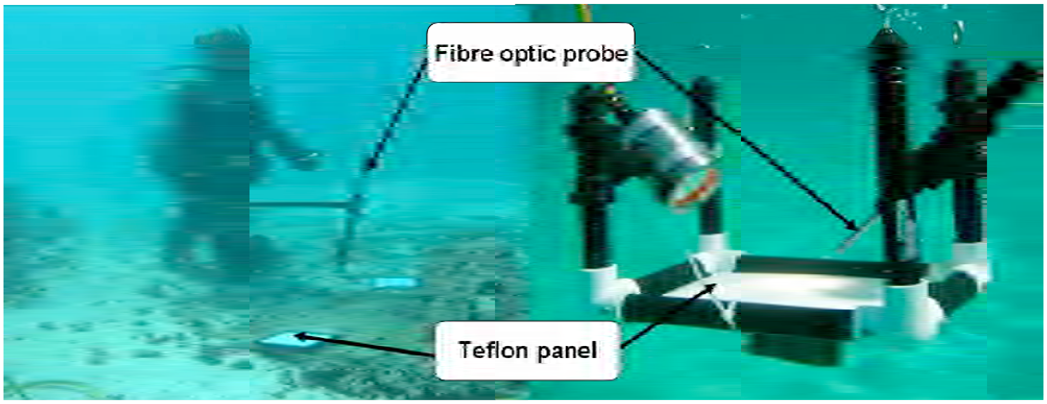

Figure 3: The underwater spectrometer setup for collecting spectral reflectance signatures of benthic substrates (left) and sampling spectral depth of the water column (right).

Digital Elevation Model

The DEM for Rottnest Island Reserve was developed using approximately 150 000 depth soundings, collated from various sources including the Western Australian Department for Planning and Infrastructure and Western Australian Department of Land Information. These data were supplied in both digital and hardcopy format.

The digital data were supplied in xyz format and each individual file was reprojected to UTM 50 South from various projections and the depth data were corrected to Low Water Mark (LWM) Rottnest (0.715 m below the Australian Height Datum). The hardcopy maps were photographed, geo-referenced and then hand digitised to create ‘xyz’ files for each. Those maps with a height datum other than LWM Rottnest were corrected. All these individual data files were then combined into a single file. Due to a lack of depth sounding data in the 0 – 5 m range around the island a zero contour was generated from the HyMap image and added to the depth soundings. This was achieved by creating a polygon of the coastline of the island using infrared bands and converting it to a point file with a 50 m spacing using the “Poly to Points” extension for ArcView 3.2 (Huber 2002). The complete data set was then checked for erroneous data and those found were removed.

The data were cross-validated using exact interpolation algorithms including triangulated irregular networks (TIN), inverse weighted distance (IWD), various radial bias functions and Krigging. The cross-validation process was carried out using Surfer 8 software using 15 000 random validation points. This process involved the removal of random data points, one at a time and the estimation of that point using surrounding data and the selected interpolation algorithm. The output of this process was the actual value, the estimated value and the residual for each data point tested. For each interpolation algorithm, the cross-validation process was carried out five times and the average RMS error values calculated for each cross-validation using the following formula (Desmet 1997):

$$\text{RMS error} = \sqrt{\frac{\sum_{i=1}^{n} |z_{i,act} - z_{i,est}|^2}{n - 1}} \qquad (2)$$

where z_{act} and z_{est} are the actual depth of the sample point and the depth estimated by the interpolation algorithm, respectively.

The total of 75 000 points tested for each algorithm were also pooled and analysed to determine the spread of the residual around zero, calculate the mean absolute error (MAE) and the standard deviation of the MAE ($\text{SDTEV}_{(MAE)}$) for the total data set. The MAE and the $\text{STDEV}_{(MAE)}$ were calculated using the following formulas (Li 1988, Desmet 1997):

$$\text{MAE} = \frac{\sum_{i=1}^{n} |z_{i,act} - z_{i,est}|}{n} \qquad (3)$$

$$\text{Stdev} = \sqrt{\frac{\sum_{i=1}^{n} (|z_{i,act} - z_{i,est}| - \text{MAE})^2}{n - 1}} \qquad (4)$$

The last factor investigated in relation to the interpolation of the DEMs using the different algorithms was the time taken to carry out the interpolation. The complete data set was interpolated using the most appropriate algorithm, both in relation to accuracy and processing time, at a 3.5 m pixel resolution to match the HyMap data.

PRELIMINARY RESULTS

Spectral Reflectance Library

Extensive field testing of underwater spectrometer equipment and collection of in-situ reflectance signatures was carried out at Rottnest Island in depths <10 m. The spectral signature collection focussed on collecting the dominant substrate types typically found in the reserve. These where broadly classified as bare sand, seagrass meadows, *Ecklonia radiata* dominated reef, *Sargassum* spp. dominated reef and turfing algae complexes.

Examples of the spectra collected of some seagrass genera, sand, *Ecklonia radiata* and S*argassum spp*. are given in Figure 4 and revealed obvious differences in the spectral reflectance curves between the sand and plant spectra. The spectra of the two dominant seagrass genera found in Rottnest Island Reserve, *Posidionia* and *Amphibolis* show little visible differences. They do, however, separate quite obviously from the two brown algae genera (*Ecklonia* and *Sargassum*). It should be noted that these results are presented at the full 3 nm resolution of the spectrometer and that analysis of the spectral characteristics of the dominant bottom types dominant substrate types found is still preliminary.

A number of spectral casts were completed in April 2006 in Rottnest Island Reserve around the east end of the island (Figure 2). These spectral casts indicate that, as expected, light penetration is dependent on both depth and wavelength. The least light was lost in the blue/green region of the spectrum (450 – 570 nm), while the most light was lost at the red part of the spectrum (610 – 750 nm) (Figure 5). At a depth of 5 m >80% of the light in wavelengths above 600 nm did not reach the bottom and by 10 m depth this has increased to >95%.

Digital Elevation Model

Cross-validation of seven DEM interpolation algorithms was carried out and the RMS error for each calculated. The results of this indicate that Krigging, using a linear variogram had the lowest RMS error of 4.86×10^{-3} m (Table 1). The interpolation algorithm with the greatest error was the radial bias function, using a natural cubic spline, with a RMS error of 8.63×10^{-3} m. Further analysis of the cross validation data revealed that the radial bias function algorithm, using a multi-quadratic function, had the lowest overall MAE of 0.364 m, based on the 75 000 test points. This was only slightly lower than that found for the Krigging with an MAE of 0.366 m. Both algorithms had a fairly even spread of MAE for points with estimates greater than the actual and those less than actual (Table 1). However, the time taken to complete the surface interpolation using the different algorithms was significantly different between the TIN and Krigging algorithms. The quickest was TIN which took 0.003 hours and the longest was RBF(MQ) which was completed in 28.980 hours (Table 1).

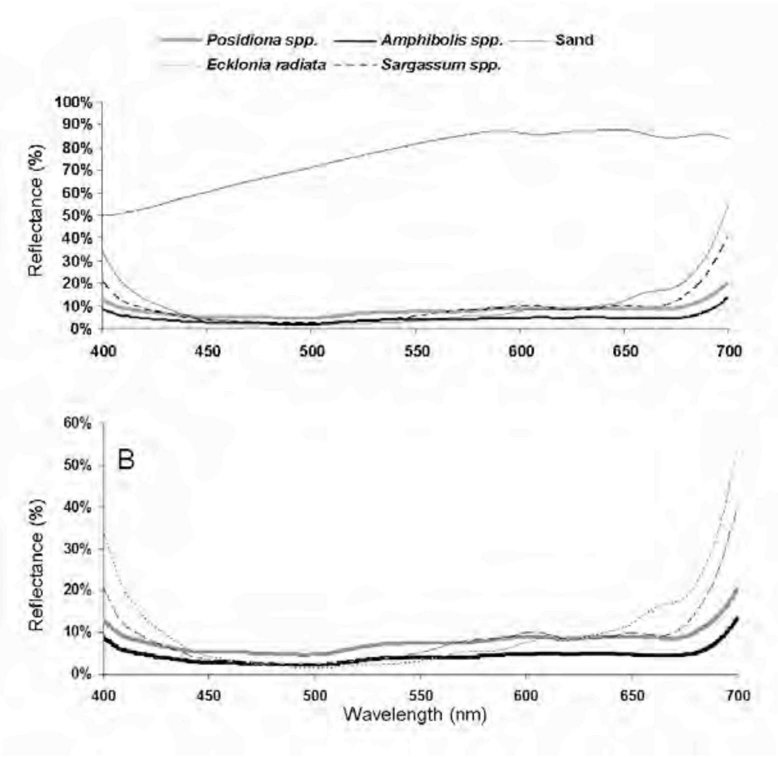

Figure 4: Examples of reflectance spectra for the dominant substrate types collected around Rottnest Island in Jan - April 2006. Graph A includes sand for comparision and Graph B shows only the segrass and algae spectra.

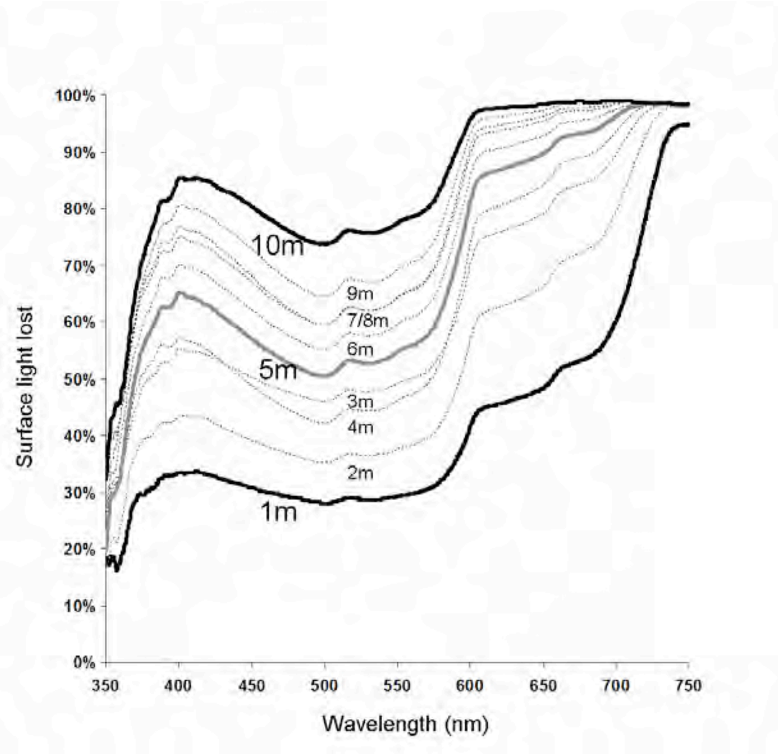

Figure 5: Results of the spectral casts carried out around Rottnest Island in April 2006 indicating the percentage of light lost at depths of 1 to 10m.

Table 1: Summary of cross validation results for the seven interpolation algorithms tested.

Interpolation algorithm	**RMS error (SD)**	**MAE**			**STDEV** $_{(MAE)}$	**Interpolation Time (hours)**
		All est.	Est.> act.	Est.<Act.		
IWD^2	5.72x10^{-3} (1.43x10^{-4})	0.448	0.437	0.461	0.539	18.429
IWD^3	5.32x10^{-3} (8.74x10^{-5})	0.398	0.394	0.403	0.515	19.880
IWD^4	5.21x10^{-3} (5.82x10^{-5})	0.378	0.377	0.380	0.514	18.288
Krigging	4.86x10^{-3} (5.49x10^{-5})	0.366	0.365	0.367	0.470	18.570
RBF(MQ)	4.94x10^{-3} (1.45x10^{-4})	0.364	0.367	0.362	0.482	28.980
RBF(NCS)	8.63x10^{-3} (2.08x10^{-3})	0.488	0.489	0.486	0.965	-
TIN	5.24x10^{-3} (8.31x10^{-5})	0.378	0.455	0.472	0.518	0.003

Two digital elevation models have been created using the Krigging and the TIN algorithms (Figure 6). Preliminary analysis of the gross differences between the two DEMs revealed that 8.39% of 30 866 ha which makes up the interpolated surface is not processed by the TIN algorithm. Of the area processed by both algorithms, 86.68% showed a difference of <1 m. Analysis of the reclassified DEMs showed that the greatest variation between the two interpolations occurs in the 0 – 20 m depth range (Figure 7).

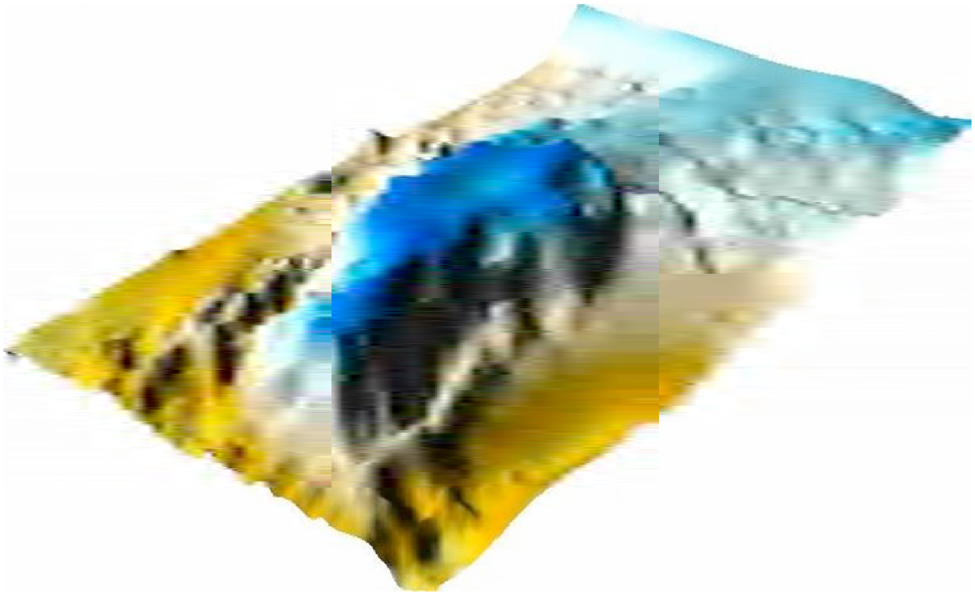

Figure 6: A 3D representation of the bathymetry of Rottnest Island Reserve interpolated using the TIN algorithm.

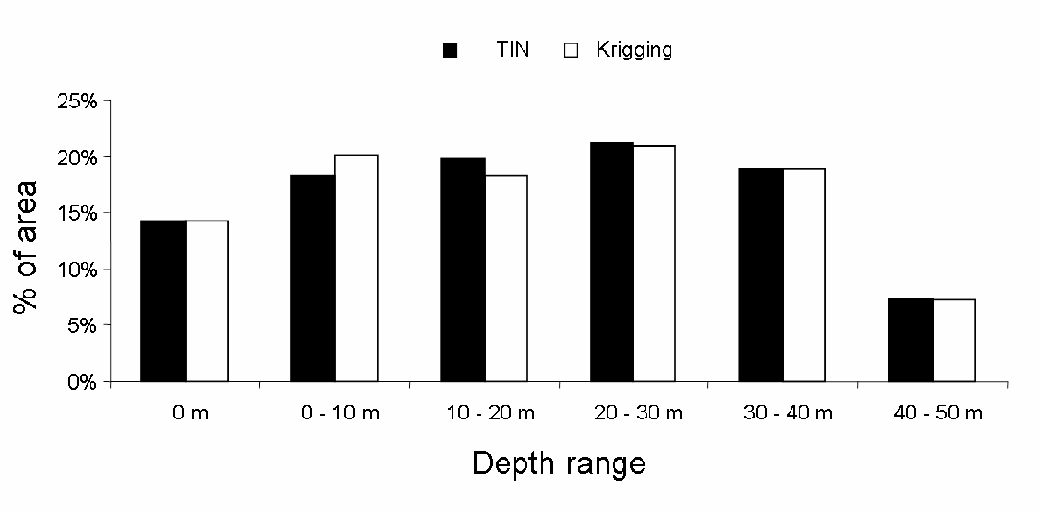

Figure 7: A comparison of the percentage of the total area classified into 10 m depth intervals for the Rottnest Island DEMs interpolated using the TIN and Krigging algorithms.

DISSCUSSION AND FUTURE WORK

The collection of the data for the creation of the spectral library has been carried out using a similar technique to that described by Murphy (2005) and Hochberg *et al.* (2004). By using this technique we have been able to collect data *in-situ*, which is advantageous as we are not sure how plants respond in terms of their spectral reflectance when removed from the water, and also because in many situations it is not practical or possible for logistical and regulatory reasons to remove biota. Furthermore, collecting the data *in-situ* means that the entire process has very low impact and can be carried out in sensitive areas, such as sanctuary zones which are often the areas that have a high priority for habitat mapping (Stevens 2002).

Although the processing and analysis of the spectral reflectance data collected as part of this ongoing project is in its early stages there are definite indications that some of the dominant habitat types are spectrally separable. There are, however, a number of issues when relating these signatures to pixels in the hyperspectral images. The most obvious of these is that in any optically remote sensed image there will be a water column of variable depth included in the spectral signature of each individual pixel (Mumby *et al.* 1998, Holden and LeDrew 2002). To help better understand this factor the spectral casts were carried out to determine how much of the surface light reached the bottom of the water column at various depths. The aim of this was twofold, to determine, based on the depth of the water column in each pixel, the regions of the image which are candidates for being processed and which of the image bands have sufficient water penetration properties to be useful in classification algorithms. The basis for this is that if no light of a particular wavelength is reaching the seafloor in a pixel then any signal that is being retrieved by the sensor is not being reflected by the seafloor, but rather something in the water column or at the water surface.

The development of the DEM for this project is an integral part of being able to utilise the information obtained from the spectral casts. In addition to this it will provide second order inputs, such as depth and slope, to the classification process. The process of cross-validating the interpolation algorithms combined with the testing of finished DEMs is showing that, with such large data sets and high data point density, it may not always be necessary to use the most accurate method, especially at a cost of processing time. This process is however not complete with further testing continuing as to how these differences in accuracy will propagate thought the classification process. This propagation will be examined for both errors in secondary outputs and in processing the HyMap data to account for the depth of the water column. Testing of this data set is also being carried out to determine if the same results, or results that fall within an allowable accuracy threshold in term of final project outcomes, could be obtained from a smaller data set. This will be carried out by thinning the data set to a number of different point spacings and then interpolating DEMs and testing the estimated depths against points of known depth. This will provide the baseline level of depth data required to carry out these analyses.

Once the spectral library, spectral depth data and DEM analysis are completed the HyMap image will be classified into ecologically relevant discrete habitat types based on the spectral information in the image and using second order inputs such as depth, slope and wave exposure (Figure 8).

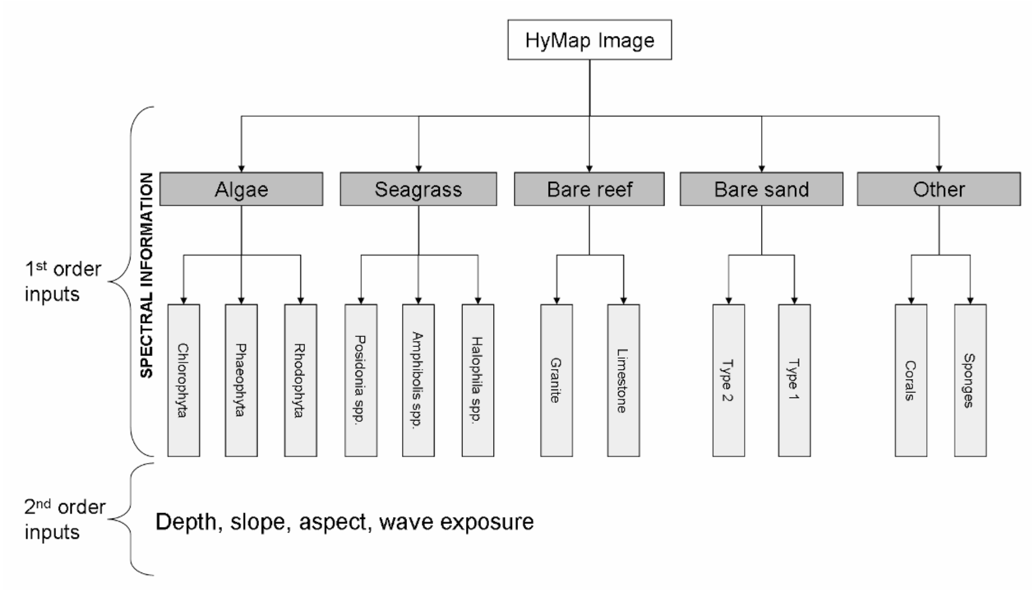

Figure 8: A conceptual outline of the hierarchical classification scheme proposed for use in the habitat classification of the hyperspectral images.

The working hypothesis for this project is that hyperspectral data can be used to create habitat maps for shallow temperate marine systems in Western Australia, based on the dominant subtidal marine benthos, at a scale that is both ecologically relevant and applicable to the management of these areas. This will be directly applicable to planning and testing of representative marine protected areas, using habitat as a surrogate for biodiversity. It will also provide an inventory of habitat types for regional marine planning, natural resource management and assisting with planning for future coastal development such as fisheries habitat management, port and marina development, dredging, aquaculture and the offshore oil and gas industry.

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