

# **CLASSIFYING SHALLOW WATER BENTHIC HABITATS IN THE SWAN MARINE REGION**



## **Final Report**

**Project 01-0608-HM**

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## EXECUTIVE SUMMARY

This study was aimed at achieving the following broad objectives in order to directly address Resource Condition Targets CMR2 and CMR3 established under the National Framework for Natural Resource Management, and provide crucial baseline information for a range of other targets established for the Swan Marine Region (SMR), *i.e.* CMM2.1-MAT and CMM3.1-MAT (Swan Catchment Council 2004).

1. Production of a spatially-explicit map of the broad categories of benthic habitats, based on the first level of a hierarchical classification framework (*i.e.* bare *vs* biosubstrate), present in the shallow waters of the SMR. This was achieved by classifying recently-acquired Quickbird satellite imagery of the region in a Geographic Information System (GIS).
2. Ground-validation of the accuracy of the above map by employing a large number of spatially-relevant photographic samples collected throughout the SMR using a drop-camera system.
3. Development of an interactive GIS database containing the percentage contributions of the various benthic habitat types in each of the above photographic samples, calculated for every level of the five-tiered hierarchical benthic habitat classification framework, *i.e.* bare *vs* biosubstrate at the broadest level and, where relevant, species of biosubstrate at the finest level.

The broad-scale (level 1) map showing the distributions of bare *vs* biosubstrate, with the latter representing biotic components including seagrasses, macroalgae, sponges and corals, was produced by subjecting depth categorised sections of the Quickbird imagery to an unsupervised method of classification, *i.e.* K-means clustering. Any areas of the resultant classification that had obviously been misclassified were then corrected by contextual editing. This map was assessed for accuracy using percentage contribution data for bare and biosubstrate habitats derived from 6602 photographic samples collected in the field using a specifically designed drop-camera system. This system, which integrated software and hardware for the acquisition of photographic, differential GPS (DGPS) and depth data, enabled the camera field of view (FOV), geographic position and associated positional error and the height of the camera above the seafloor to be viewed

and recorded *in situ*. When each photographic reference sample was matched to the classified pixel to which it most likely corresponded, the resultant accuracies were high (*i.e.* 90.55% and 76.93 for overall and Kappa accuracies, respectively).

Mapping of particular categories of the benthic habitats at the second broadest level of the classification framework, *i.e.* seagrass and macroalgae, was attempted for the Rottneest Island section of the SMR imagery, which contained some of the clearest nearshore waters and greatest proportion of biotic substrate at varying depths. This was achieved by subjecting the imagery to several supervised classification procedures after it had been corrected for the influence of variable depth on the spectral reflectance of biosubstrate. Although the benthic habitats in these maps initially appeared to be reasonably represented, they were less accurate than those for the level 1 classification (*i.e.* overall accuracies <70% in both cases) and should thus be used with caution. These lower accuracies largely reflect the limitations associated with the low spectral resolution of Quickbird data.

An ArcView v9.1 digital database accompanies this report, and contains the following components; (i) the Quickbird image of the SMR, (ii) an associated digital elevation model of the region constructed from available bathymetric data, (iii) benthic habitat maps classified at levels 1 and 2 of the hierarchical classification framework, (iv) photographs of the benthic habitat at every ground validation point and associated files showing their geographical locations, acquisition information and percentage contributions of each benthic habitat at every level of the classification framework. This database provides a permanent quantitative record of benthic habitat types in the SMR and can be queried to investigate a host of ecological questions regarding their distributions. Moreover, it provides a sound framework for (1) quantifying the extent of any future changes in benthic habitat distribution in the SMR, (2) overlaying other ecologically-relevant and spatially-explicit data recorded in this region and (3) developing finer-scale benthic habitat maps in the future.

## TABLE OF CONTENTS

<b>1</b>	<b>INTRODUCTION .....</b>	<b>1</b>
<b>2</b>	<b>METHODS .....</b>	<b>5</b>
2.1	Site description.....	5
2.2	Overview of Methodology.....	8
2.2.1	Data sets.....	9
2.2.2	Digital Bathymetric Model.....	9
2.3	Benthic habitat classification framework.....	12
2.4	Classification of the Quickbird satellite imagery.....	13
2.4.1	Level 1 benthic habitat classification.....	13
2.4.1.1	Atmospheric correction.....	15
2.4.1.2	Masking unwanted areas.....	15
2.4.1.3	Correction for the influence of depth.....	16
2.4.1.4	Unsupervised Classification.....	16
2.4.2	Level 2 benthic habitat classification.....	17
2.4.2.1	Correction for the influence of depth.....	18
2.4.2.2	Supervised Classification.....	18
2.5	Ground validation of benthic habitat classes .....	19
2.5.1	Field data collection.....	19
2.5.2	Field data processing.....	23
2.5.3	Accuracy assessment .....	24
<b>3</b>	<b>RESULTS .....</b>	<b>27</b>
3.1	Level 1 classification of broad-scale benthic habitats .....	32
3.2	Level 2 classification of benthic habitats.....	33
3.3	Benthic habitat database .....	39
<b>4</b>	<b>DISCUSSION .....</b>	<b>40</b>
4.1	Classification of broad-scale benthic habitats.....	42
4.2	Advantages of the drop-camera system and method of ground validation.....	43
4.3	Image pre-treatment .....	44
4.4	Suggestions for future benthic habitat mapping of the SMR.....	46
<b>5</b>	<b>REFERENCES.....</b>	<b>49</b>
	<b>APPENDIX 1.....</b>	<b>55</b>
	<b>APPENDIX 2.....</b>	<b>57</b>

## LIST OF FIGURES

<b>Figure 1</b>	<b>The location of the SMR in southwestern Australia.....</b>	<b>6</b>
<b>Figure 2</b>	<b>The three Quickbird tiles obtained on separate dates in early winter 2007, mosaiced together to cover the SMR.....</b>	<b>10</b>
<b>Figure 3</b>	<b>The digital bathymetric model created by kriging interpolation of depth-sounding data. ....</b>	<b>11</b>
<b>Figure 4</b>	<b>Benthic habitat classification framework developed for the SMR.....</b>	<b>14</b>
<b>Figure 5</b>	<b>The location of the large and small grids used for sampling the benthic habitats in the SMR. N.B Black areas are those waters &gt;15 m and thus not included in this study. ....</b>	<b>21</b>
<b>Figure 6</b>	<b>Photographic sample overlaid with evenly spaced points used to calculate the % compositions of benthic habitat.....</b>	<b>23</b>
<b>Figure 7</b>	<b>The photographic sample vs pixel matching procedure showing the geographic location of the photographic sample containing &gt;30% biosubstrate <span style="color: yellow;">■</span> and a pixel classed as biosubstrate laying within a given radius of the coordinates of the photographic sample <span style="color: green;">■</span>. The target pixel <span style="color: yellow;">■</span> would be recorded as correct due to the presence of the pixel classed as biosubstrate within its given radius. ....</b>	<b>26</b>
<b>Figure 8</b>	<b>Classification of level 1 benthic habitats, i.e. bare vs biosubstrate, in waters &lt;15 m depth in the SMR. ....</b>	<b>28</b>
<b>Figure 9</b>	<b>Distribution of level 1 benthic habitats in waters &lt;15 m depth in the northern SMR. ....</b>	<b>29</b>
<b>Figure 10</b>	<b>Distribution of level 1 benthic habitats in waters &lt;15 m depth at Rottnest Island in the SMR.....</b>	<b>30</b>
<b>Figure 11</b>	<b>Distribution of level 1 benthic habitats in waters &lt;15 m depth in Cockburn Sound in the SMR.....</b>	<b>31</b>
<b>Figure 12</b>	<b>The level 1 classification at (a) the southern flats, (b) Rottnest Island, (c) Point Peron and (d) Marmion Marine Park, overlaid with the location of the photographic samples collected in the field that have been coded as containing predominantly biosubstrate (&gt;30%) or bare substrate.....</b>	<b>34</b>
<b>Figure 13</b>	<b>Supervised classification (minimum distance) of the distributions of seagrass and macroalgae at Rottnest Island derived from employing the Euclidean distance measure. N.B The Bare substrate class derived from the level 1 unsupervised classification and breaking reefs derived by contextual editing were overlaid as separate layers.....</b>	<b>35</b>
<b>Figure 14</b>	<b>Supervised classification (minimum distance) of the distributions of seagrass and macroalgae at Rottnest Island derived from employing the Mahalanobis distance measure. N.B The Bare substrate class derived from the level 1 unsupervised classification and breaking reefs derived by contextual editing were overlaid as separate layers. ....</b>	<b>36</b>
<b>Figure 15</b>	<b>The level 2 classification (based on Mahalanobis distance), at Geordie Bay, Rottnest Island, overlaid with the location of the photographic samples collected in the field which were classed as either seagrass (&gt;60% coverage), macroalgae, (&gt;60% coverage) or bare substrate (&gt;70% coverage).....</b>	<b>37</b>

<b>Figure 16</b>	<b>The level 2 classification (based on Mahalanobis distance), at Thomsons Bay, Rottnest Island, overlaid with the location of the photographic samples collected in the field which were classed as seagrass (&gt;60% coverage). .....</b>	<b>38</b>
<b>Figure 17</b>	<b>Example of the onscreen working environment of the ArcView v9.1 benthic habitat database. The dialogue box contains the percentage contributions of benthic habitats identified at level 3 of the benthic habitat classification framework for a selected sample.....</b>	<b>41</b>

#### LIST OF TABLES

<b>Table 1</b>	<b>Producers and users accuracies calculated for each level 1 benthic habitat class. ....</b>	<b>33</b>
<b>Table 2</b>	<b>Producers and users accuracies calculated for seagrass and macroalgae at Rottnest Island using Euclidean distance as a minimum distance supervised classification measure.....</b>	<b>39</b>
<b>Table 3</b>	<b>Producers and users accuracies calculated for seagrass and macroalgae at Rottnest Island using Mahalanobis distance as a minimum distance supervised classification measure.....</b>	<b>39</b>

#### LIST OF PLATES

<b>Plate 1</b>	<b>The Drop camera .....</b>	<b>22</b>
<b>Plate 2</b>	<b>Labeled photographic sample of benthic habitat in the SMR. ....</b>	<b>25</b>

## 1 INTRODUCTION

The Swan Marine Region (SMR) is a large area covering ~1100 km<sup>2</sup> of Perth metropolitan coastal waters and is highly valued for its natural, economic and social assets. The substrates of this environment comprise nearshore and offshore reefs as well as sandy and silty areas. The reefs support numerous macroalgal species, a variety of sponges and some corals, which in turn sustain both tropical and temperate fish and invertebrate species (Hutchins 1979; Department of Environmental Protection 1996; Hutchins 2001; Toohey *et al.* 2007; Tuya *et al.* 2008; Wemberg and Goldberg 2008). The shallow sandy areas of this region contain among the highest number of seagrass species in the world for a temperate region (Kirkman and Kuo 1990), which provide nursery areas and habitat for numerous commercially and recreationally important fish species (e.g. pilchard, mackerel, anchovy, whiting, western rock lobster, blue manner crab, king prawn, herring, tailor, pink snapper and cobbler; Ayvazian and Hyndes 1995; Hyndes *et al.* 1996; Valesini *et al.* 2004). Some of the most bio-diverse areas within the region have been protected from excessive fishing by their designation as either Marine Parks or Reserves, *i.e.* Marmion and Shoalwater Islands marine parks and Rottnest Island Reserve. Since the natural features of the SMR are relatively unmodified when compared to other metropolitan coastal regions around the world, they provide an attractive draw-card for both residents and tourists of the Perth region. This region contains ~75% of Western Australia's population (~2.1 million) and attracts about 240 000 visitors each year (2005-2007, Australian Bureau of Statistics 2008). As a consequence, there is a strong demand for coastal real-estate and water-based recreational activities such as boating, diving and fishing are common. The SMR also supports a strong export trade via Fremantle Port, as well as aquaculture and biotechnology industries (Swan Catchment Council 2004).

The increasing exploitation of the assets of the SMR has resulted, in some cases, in a variety of detrimental changes to the environmental health of these waters. Such changes include increasing pressure on stocks of marine fauna through recreational and commercial fishing (Wise *et al.* 2007), loss of habitat through modifications to the coastline for urban developments and the construction of more harbours, ports and marinas and greater eutrophication and pollution by storm water, sewage and industrial drainage (Kendrick *et al.* 2002; Swan Catchment Council 2004).

In order to better understand the ecological consequences of such pressures and ameliorate their detrimental effects, a set of standards and targets have been established for the SMR by the Swan Catchment Council under the National Framework for Natural Resource Management (Swan Catchment Council 2004). Resource condition target CMR2 and CMR3, *i.e.* Maintain and improve the condition of marine habitats and fauna, respectively, in the Region, as measured at representative sites, by 2020, are of particular importance, not only for the overall maintenance of ecosystem health, but also for the conservation of marine fauna. Many studies carried out in coastal waters have demonstrated that differences in habitat type, and particularly in benthic habitats, largely reflect spatial and temporal changes in the compositions of marine faunal assemblages (*e.g.* Connolly 1997; Barros *et al.* 2001; Schafer *et al.* 2002; Skilleter and Loneragan 2003; Valesini *et al.* 2004; Wildsmith *et al.* 2005). It is thus now widely accepted that successful management of these biota hinges on the maintenance of their habitats, including those that are both distinct (*i.e.* rare) and representative (Pearce 1991; Simberloff 1998; Szaro *et al.* 1998; Roff and Taylor 2000; Field and Francis 2006; Frid *et al.* 2006). It therefore follows that, in order to effectively implement the above target, the various types of benthic habitat present in the region must firstly be identified and their spatial distributions mapped with accuracy. Once this has been achieved, several other important targets, *i.e.* determination of key indicator species (CMM3.1-MAT) and identification of 100% of priority marine habitats for protection (CMM2.1-MAT) can then be addressed (Swan Catchment Council 2004).

The functionality of benthic habitat maps produced for coastal waters, with respect to their ability to provide a reliable basis for predicting the distribution of marine fauna, is determined largely by whether the resultant habitat classes are ecologically relevant. Such mapping studies should thus be underpinned by a sound classification framework that accounts for differences in habitat type structure, geomorphology and taxonomic composition. Such a framework must be unambiguous, determined objectively, based on the results of relevant studies and easily interpretable. Ideally, it should also have a hierarchical structure to facilitate its application to a range of spatial scales, equipment capability (*i.e.* differences in imagery, software and remote sampling

equipment) and user requirements (Mumby and Harborne 1999; Zacharias and Roff 2000; Mumby 2004).

Although several maps of the spatial distribution of benthic habitats have been produced for certain areas of the SMR, *i.e.* Owen Anchorage, Cockburn Sound, Warnbro Sound and Marmion Marine Park (Ong *et al.* 1998; Kendrick *et al.* 2002; DAL Science and Engineering 2004), there is currently no such map, at least for nearshore waters, that covers the entire region. Each of the above maps differ in the type of habitat classification framework, remote imagery and classification algorithms they employ. As they are not directly comparable, such inconsistencies limit the usefulness of these maps at the regional scale. Mapping the distribution of benthic habitats over regional scales has commonly posed methodological problems in the past, due firstly to the fact that as the size of the images able to be captured by traditional airborne sensors (*i.e.* those producing aerial photographs) is relatively small, many samples are required to cover the entire study area. Such a large number of component images has typically resulted in long and complicated processing times and large cumulative spatial errors attributable to the numerous image orthorectifications that are required (Mumby *et al.* 1998). Moreover, since the lighting and atmospheric conditions can vary markedly within a region, the images often require different corrective treatments and classification techniques. However, some of the more recently-developed high resolution satellites (*e.g.* Quickbird and IKONOS ) provide multispectral imagery that can overcome some of the above issues due to their ability to capture far larger areas in a single pass and the resulting greater spatial accuracy (Fornes *et al.* 2006; Kobler *et al.* 2006; Mishra *et al.* 2006; Benfield *et al.* 2007). Moreover, the continuing development of computer systems now allows such for large images to be processed efficiently in fewer steps.

A highly important component of benthic habitat maps produced from remotely-sensed images, which ultimately determines their usefulness for guiding management and/or research decisions, is a rigorous assessment of their accuracy with respect to the identity and spatial distribution of their various mapped categories. Such assessments require firstly, that numerous spatially-referenced points within the area of interest are visited in the field, and that the type and/or amount of benthic habitat present at those locations is recorded and compared to that which has been calculated for the same

locations in the mapped image, *i.e.* ground validation (Congalton and Green 1999). The most common approaches used to ground validate marine benthic habitat maps include diver observation, boat-towed video and drop-down camera techniques (Congalton 1991; Barker *et al.* 1999; Smith *et al.* 2006). Although the first approach is the most direct and thus allows for fine-scale observation and collection of benthic cover types, it is impractical for assessing large spatial scales, due to it being both costly and labour intensive. Furthermore, while towed-video is a fast and effective method of ground-validation that can be used to cover large areas of the seafloor, many studies that have employed this technique have failed to address the often large locational errors that can occur due to differences between the position of the video camera (often >20 m behind the vessel) and that of the global positioning system (GPS) being used to pinpoint its location (usually on the vessel). Moreover, in most cases, the highly variable position of the video camera in the water column is unknown, thus producing imagery with a variable and unknown field of view (FOV) of the seafloor. Thus, although this method produces highly comprehensive qualitative data, it cannot be used to quantify, with certainty, the cover of the benthic habitats being recorded. In contrast, a drop-down camera system, in which a camera attached to a fixed frame is lowered over the edge of a boat and placed on the seafloor, allows for a constant FOV among photographic samples and thus a consistent measurement of benthic habitat cover. However, if this latter technique were to be applied to the present study, a large and reasonably heavy frame would be required, which would necessitate the use of a reasonably large boat and several operators to lower the equipment into the water. Thus, in considering the large area of the SMR, a far less cumbersome drop-camera system is required for ground validation purposes.

The main aims of this study were to (1) produce a spatially-explicit map of the broad categories of benthic habitats present in the shallow waters of the SMR by classifying a recently-acquired Quickbird satellite image, (2) validate the accuracy of the above map using a large number of spatially-relevant photographic samples collected throughout the SMR using an efficient and reliable drop-camera system and (3) measure the percentage contributions of the various benthic habitat types in each photographic sample at each level of a hierarchical benthic habitat classification framework.

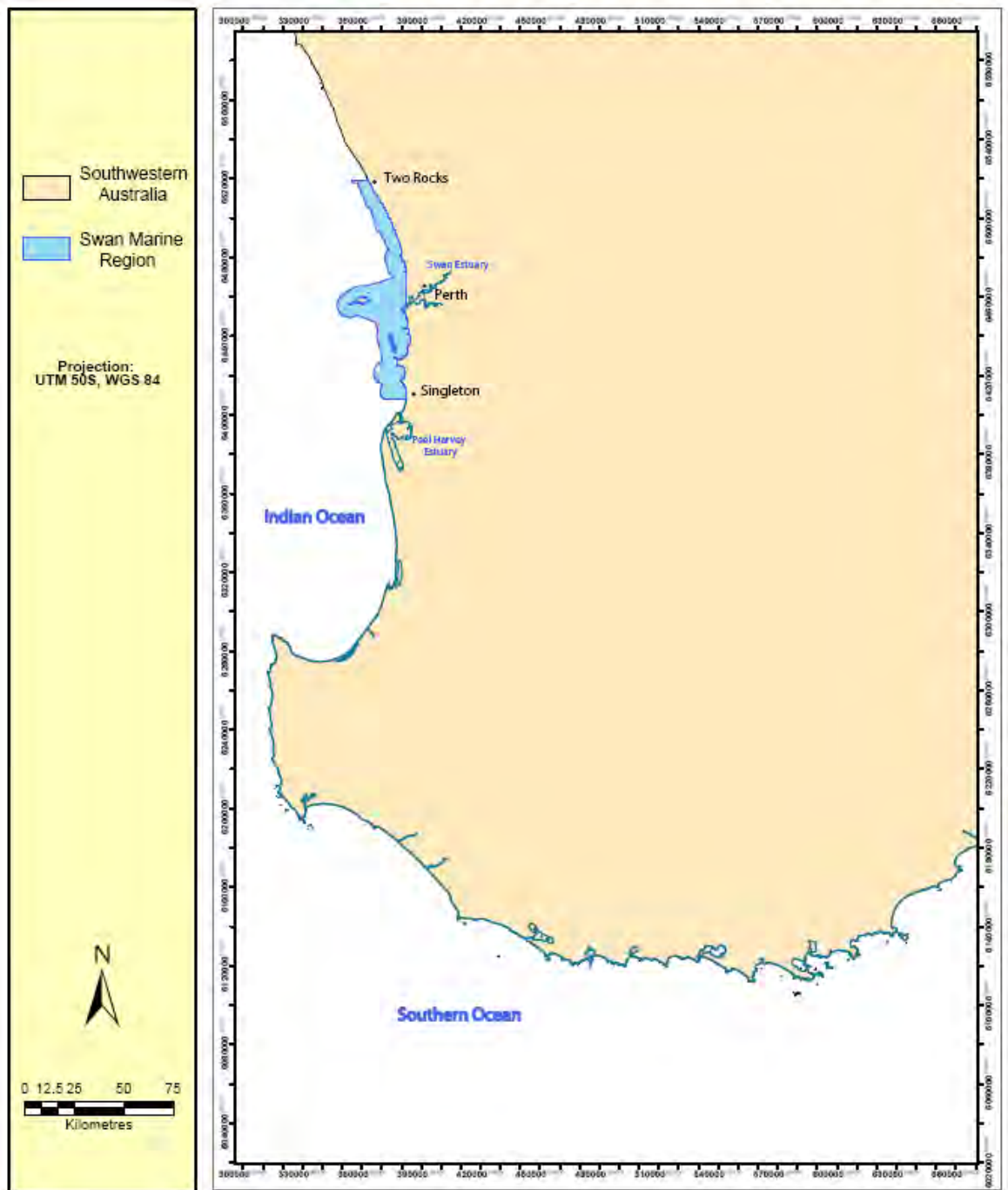
Together, the above components will provide a spatially-explicit tool that can be queried in order to extract quantitative information at specific locations on benthic habitat types at successively finer levels of identification, *e.g.* vegetated *vs* unvegetated at broad scales to species of macroalgae or seagrass at the finest scale. These data will also provide a sound benchmark against which to quantify the extent of any future changes in cover of various benthic habitats, and a reliable framework that can be adapted to overlay other ecologically-relevant and spatially-referenced data recorded in the SMR in the future, *e.g.* quantitative faunal information.

## **2 METHODS**

### **2.1 Site description**

The SMR covers an area of  $\sim 1100 \text{ km}^2$  and incorporates the waters within the Perth metropolitan region between Two Rocks in the north and Singleton in the south and extends  $\sim 6 \text{ km}$  west of Rottnest Island (Fig. 1). It has a gentle gradient and experiences diurnal tides that have a mean tidal range of less than  $0.5 \text{ m}$  (Hegge *et al.* 1996; Lemm *et al.* 1999), which are often exceeded by storms and changes in barometric pressure. The region has a Mediterranean climate, with hot, dry summers and mild wet winters. Approximately 70% of the rainfall in this region occurs between May and September and is mainly a consequence of cold fronts that move from west to east across Australia at that time of year (Hope *et al.* 2006). Larger-scale weather patterns of this region are controlled by a latitudinal shift of a belt of anticyclonic high-pressure systems between the south and north. Thus, during winter (June to August), these high pressure systems are displaced northwards and become located over the southern part of Western Australia. They produce strong winds that generate seas from south-westerly and northwesterly directions (Hope *et al.* 2006). During summer (December to February), they are located to the south of the continent and easterly Trade Winds predominate and swell-waves are minimal (Gentili 1971).

The winds, and thus waves, produced by these large-scale systems are modified by locally-occurring and highly seasonal wind systems. Thus, during summer, an energetic diurnal land-sea breeze system operates, producing easterly winds in the



**Figure 1** The location of the SMR in southwestern Australia

morning and south-westerly winds in the afternoon. This wind system, which is one of the strongest of its type in the world, plays a significant role, in generating seas and littoral sand transport in this region (Lemm *et al.* 1999). The onset of the seabreeze, which blows almost parallel to the shore, generates waves that approach the shoreline from the south to southwest and a strong northward flowing alongshore current. This results in an almost continuous band of suspended sand during the summer months, with patterns of erosion and deposition occurring throughout the region, depending on the shape and aspect of the coastline. During winter, local winds are substantially more variable and may prevail from the north, west and south quadrants. North-westerly storms at this time of the year cause a reversal in alongshore currents and thus sediment is transported southward, often resulting in the opposite patterns of erosion and deposition to those that occur during summer (Pattiaratchi *et al.* 1997).

Oceanic swell approaching the Perth coastline is generated mainly by the low-pressure mid latitude cyclones in the Indian and Southern oceans. During summer, these waves originate from the south to south-west and have a significant wave height of 1-2 m, while in winter, they originate from the west to south-west and have a significant wave height of 1-3 m (Lemm *et al.* 1999). The total wave climate (seas and swell) reaching any particular part of the Perth coastline varies considerably due to differences in the extent of sheltering structures such as reefs and islands and differences in local bathymetry. Thus, offshore swell and storm wave activity is attenuated appreciably (often to <1 m) by a large chain of shallow limestone reefs and islands that are located approximately 8 km offshore and extend about 100 km along the coastline. Wave activity closer to the shore may be further modified by the presence of local headlands, reefs sand bars or islands (Pattiaratchi *et al.* 1997).

The SMR contains a diverse range of shallow benthic habitats including sands, silts and rocky outcrops, which, in parts, support a diverse range of seagrasses and macroalgae. Eighteen species of seagrass have been recorded in this coastal region, but the majority of the meadows comprise monospecific or mixed stands of *Posidonia australis*, *P. sinuosa*, *Amphibolis antarctica* and *A. griffithii*. Less common species include *Halophila ovalis*, *Ruppia megacarpa*, *Zostera mucronata* and *Heterozostera* sp (Carruthers *et al.* 2007). Eighty-two macroalgal taxa have been recorded on limestone

reefs in the northern coastal waters of the region, with the brown canopy algae *Ecklonia radiata* and *Sargassum* sp. being the most abundant (Phillips *et al.* 1997). Mid-story and turfing algae include diverse assemblages of rhodophytes and chlorophytes (Toohey 2007; Wernberg and Goldberg 2008).

## 2.2 Overview of Methodology

The following major steps were taken to (1) map the distributions of two broad benthic habitat types, *i.e.* bare substrate and biosubstrate (*i.e.* biotic components including seagrasses, macroalgae, sponges and corals) in the shallow waters (less than 15 m depth) throughout the SMR and (2) quantify the distributions of the different substrates and submerged vegetation types at successively finer scales of identification in a large number of photographs collected within those broad habitat types:

- i. A hierarchical framework was developed as a basis for classifying benthic habitats in the SMR.
- ii. A Quickbird satellite image of the SMR was acquired and subjected to atmospheric and noise correction procedures in order to maximize differences between the spectral signatures of the broad benthic classes that were to be mapped.
- iii. Together with a digital bathymetric model (DBM) of the SMR, the areas corresponding to depths less than 15 m in the above image were identified and isolated.
- iv. The broad benthic habitat types within those shallow waters were classified into several broad groups using a Cluster analysis.
- v. Georeferenced photographs were collected in the field using a drop-camera system and the percentage contributions of the different substrate and submerged vegetation types present in each were quantified at various levels of a hierarchical scheme.
- vi. The broadest-scale level of the benthic habitat data derived from these photographs was used to validate the resultant broad-scale classification produced from the satellite image, while the georeferenced finer-scale benthic habitat data was overlaid on the classified image in a GIS.

The data required to undertake these steps and the detailed methodology underlying their completion are described below. All GIS based tasks were carried out using either ENVI 4.4, ArcView3.2 or ArcMap 9.1 GIS software packages.

### **2.2.1 Data sets**

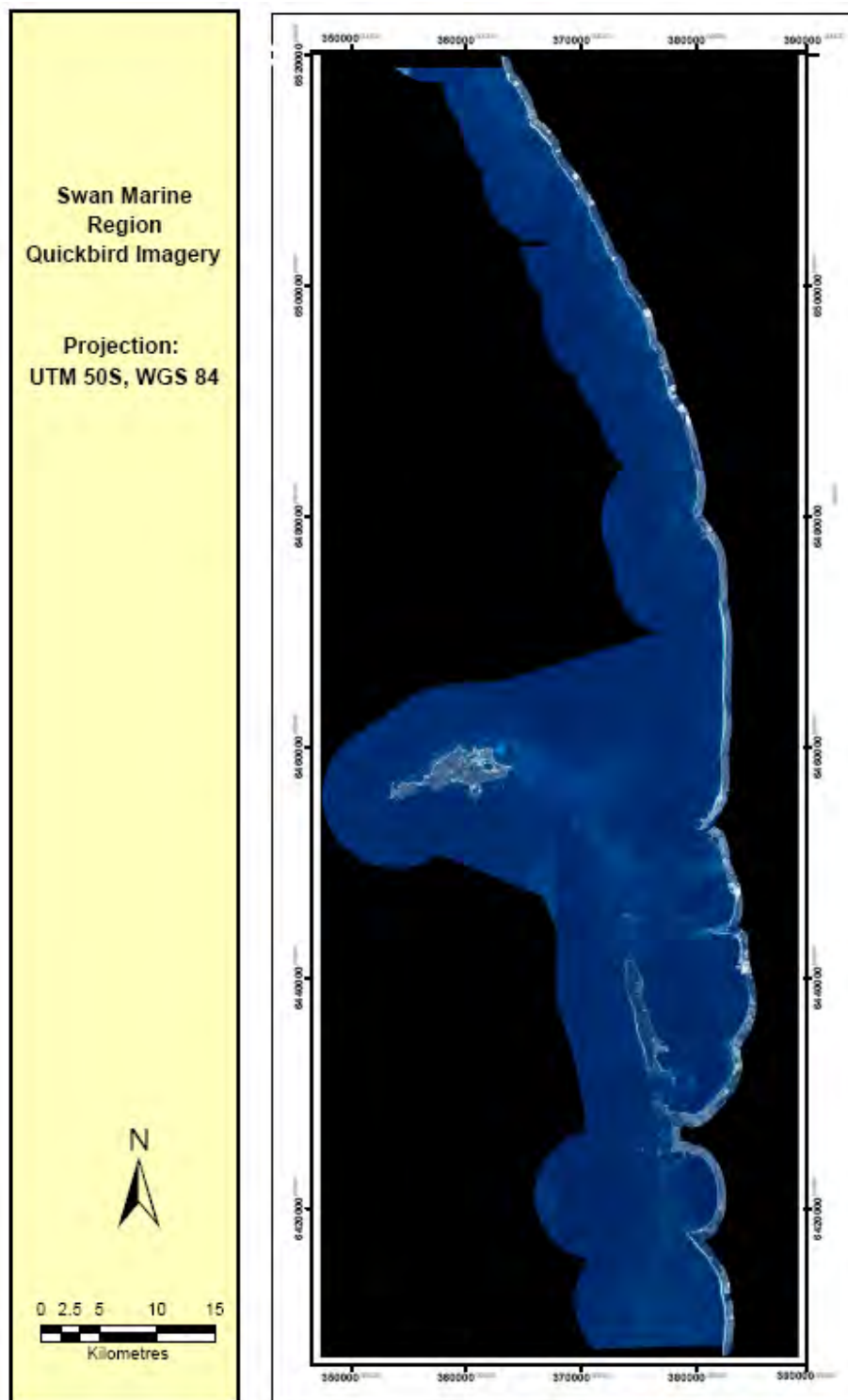
A digitally georeferenced (geographic co-ordinates: lat/long, WGS84) satellite image of the SMR, which included a terrestrial strip that extended 1 km inland, was obtained from Digital Globe Corporation during June 2007 during minimal (0.001%) cloud and low swell conditions (Fig. 2a). The composite image consisted of three separate tiles and had a pixel to ground resolution of 1: 2.4 m. Each tile consisted of the blue (band 1, 450-520 nm), green (band 2, 520-600 nm), red (band 3, 630-690 nm) and infrared (band 4, 760-900 nm) spectral bands, the values of which had been scaling to correspond to reflectance, *i.e.* digital integers between 0 and 255.

Digitally georeferenced depth-sounding data for the SMR (Map projection: MGA50, Datum: GDA94, ~ 100 m resolution) was obtained from the Department of Planning and Infrastructure, Western Australia. This dataset consisted mainly of the depth and geographic location of ~ 6 million subtidal points throughout the region, but also included the elevation of some points located above the waterline along the coast. Both the image and depth data sets were re-projected to the same co-ordinate system, *i.e.* Universal Transverse Mercator, zone 50, south (UTM-50S) and datum, *i.e.* World Geodetic System 1984 (WGS 84).

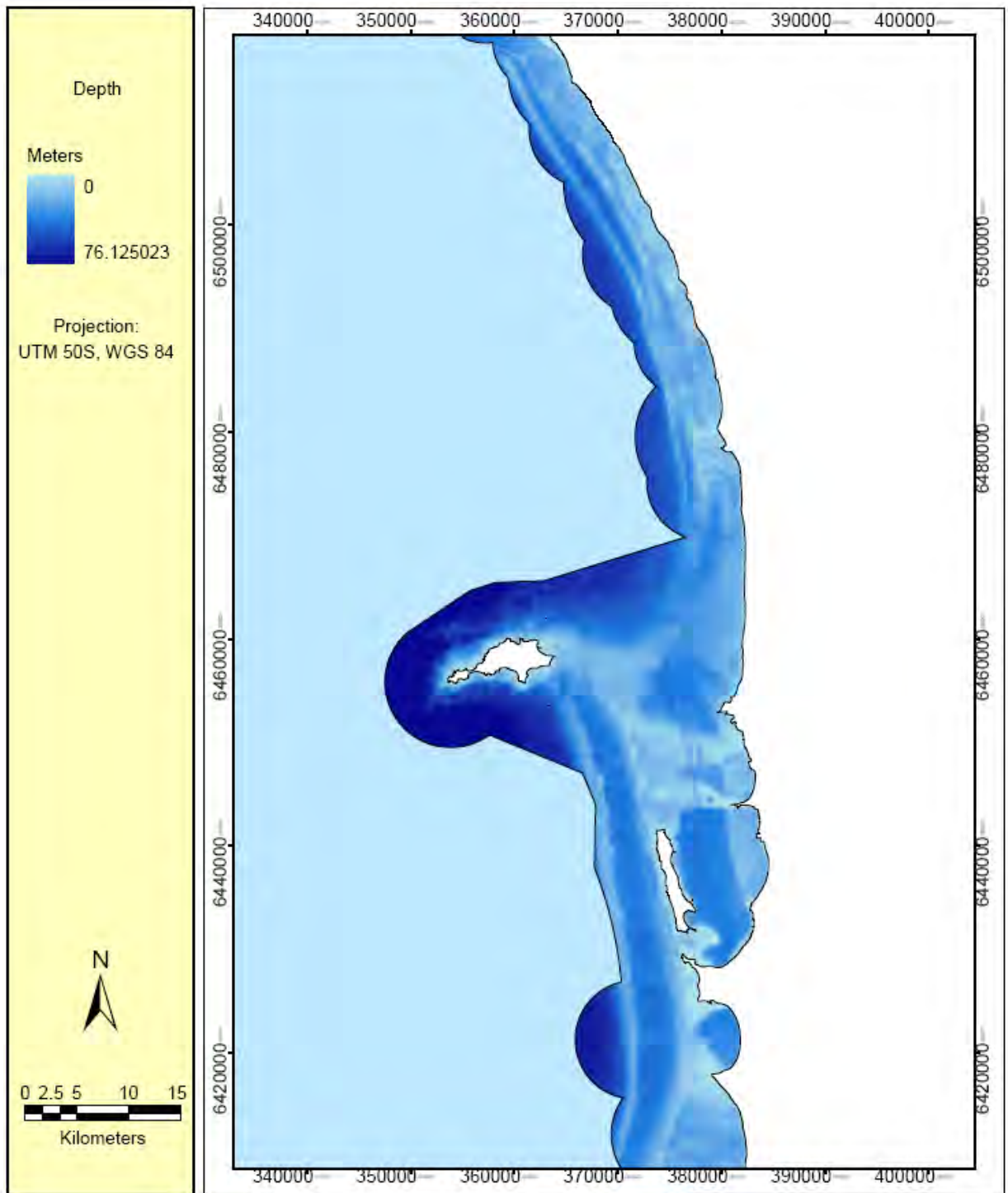
### **2.2.2 Digital Bathymetric Model**

The depth-sounding data and the infrared band of the three Quickbird tiles were used to produce a DBM of the region (Figs. 2 & 3) by undertaking the following steps.

1. A point shapefile of the depth-sounding data was produced in the Arc View 3.2 GIS package. This file displayed the location (co-ordinates) and depth of each sounding point in the dataset.



**Figure 2** The three Quickbird tiles obtained on separate dates in early winter 2007, mosaiced together to cover the SMR.



**Figure 3** The digital bathymetric model created by kriging interpolation of depth-sounding data.

1. Since points located along the coastline (above the waterline) were not spaced evenly or densely enough to enable clear delineation of the land/water interface, a second point shapefile was generated by the following steps

- i. The infrared band of the three Quickbird tiles was initially used in the ENVI v4.4 software package to produce a raster Boolean mask of the area which distinguished between areas of land and water and thus provided an accurate representation of the coastline. The mask was then converted to an ENVI polygon vector file and exported as a shapefile to ArcView 3.2.
- ii. The above shapefile was then converted to a point shapefile in which all mainland and island coastlines in the region were represented by points spaced 100 m apart and had a depth of zero.
- iii. The depth-sounding shapefile was combined with the (zero depth) coastline point shapefile to create a single file in which any coastline point was set at a depth of zero and any sounding point was represented by a depth value.

1. The above file was then subjected to kriging interpolation to accurately represent the depth gradient between the coastline and deeper waters as a spatial continuum. This method calculates the depth at an unobserved location from nearby depth data. This is achieved by calculating the best linear estimator  $Z(x_0)$  based on a stochastic model of spatial dependence that is quantified by a variogram, which is the expected squared increment of the values between locations  $x$  and  $y$  (Wackernagel 2003). The search radius in which nearby data could be detected was set to 5000 m, and the output resolution was set to 2.4 m to match that of the Quickbird image.

### **2.3 Benthic habitat classification framework**

A hierarchical benthic habitat framework was constructed to provide the basis for (1) mapping broad benthic habitats in the SMR, (2) collecting and quantifying field data for assessing the accuracy of the resultant benthic classification (*i.e.* ground validation) and (3) quantifying and establishing a database of the finer-scale benthic habitat types throughout the SMR (Fig 4). Several broad criteria were applied to the construction of this framework.

1 Applicability of a range of compositional, structural and/or taxonomic levels. The hierarchical levels should apply to a range of spatial scales

2 All categories should (a) be readily distinguished in remotely sensed data and (b) reflect differences among faunal communities.

The broadest level of the benthic habitat classification framework comprised two categories, namely, bare substrate and biosubstrate. Further division of these categories was as follows:

Level 2 - Bare and biotic categories were divided into broad-scale sediment and vegetation types, respectively, in which the former remained as such for subsequent levels.

Level 3 – Broad-scale vegetation type categories were divided according to various structural characteristics,

Levels 4 and 5 – Where appropriate, structural categories were divided into taxonomic categories which were readily identifiable in photographic samples and were dominant components of the benthos in the SMR. For example, all structural categories of seagrass as well as the canopy macroalgae category could be readily divided into genera and species (levels 4 and 5, respectively), whereas those of mid-story macroalgae were more appropriately divided into phyla (Level 4).

## **2.4 Classification of the Quickbird satellite imagery**

### ***2.4.1 Level 1 benthic habitat classification***

An unsupervised approach, which does not require any initial inputs of spectral data to classify and image data set, was considered to be adequate for distinguishing the relatively large differences in spectral signatures between the benthic habitats at level 1 of the hierarchical classification framework, *i.e.* bare vs biotic substrate.

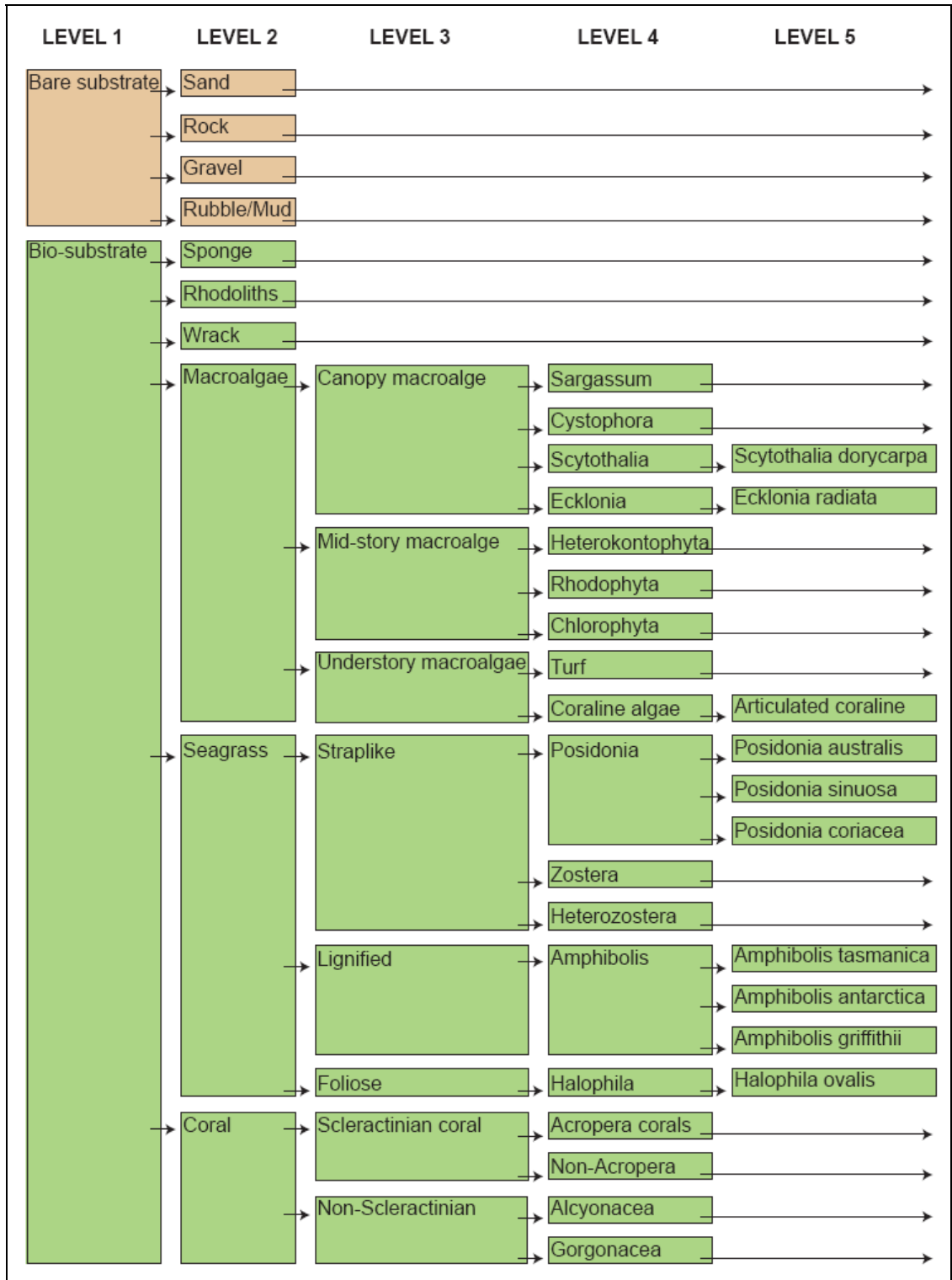


Figure 4 Benthic habitat classification framework developed for the SMR.

Upon visual examination of each band it was decided that only bands 1 and 2 would be used for classification of benthic habitats. Band 3 contained relatively little information in areas corresponding to the SMR, due to the fact that the majority of red light is absorbed by the water column. Before being subjected to classification bands 1 and 2 were subjected firstly, to atmospheric correction and then masking. All procedures were carried out on each tile separately to account for the different lighting and atmospheric conditions between the three days on which they were captured.

#### *2.4.1.1 Atmospheric correction*

Atmospheric correction of the Quickbird image was carried out using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) module in ENVI 4.4 to remove the influence of atmospheric noise caused by the presence of airborne particles. Each tile of reflectance values was firstly transformed to correspond to radiance values. For multispectral data, FLAASH simulates spectral radiance for a range of atmospheric conditions and solar angles over various surface radiance values in order to establish a set of baseline atmospheric parameters. The radiance values for the multispectral data are then compared, pixel-by-pixel, against the set of baseline parameters to determine scaled surface reflectance. The particular baseline model used to determine atmospheric conditions for the SMR Quickbird data was a standard mid-latitude winter model.

#### *2.4.1.2 Masking unwanted areas*

A second Boolean image was made to mask out terrestrial areas by firstly examining and then reclassifying the digital values in the infrared band of the Quickbird image (see section 2.2.2). Thus, all digital values  $<500$ , *i.e.* those representing areas of water, were reclassified as 1 while those  $>500$ , *i.e.* representing land, were classified as 0. These masks were then overlaid on each Quickbird tile.

Waters up to approximately 15 m depth were sufficiently clear to enable bare and bio- substrate present to be detected from the image. However, due to the darkness of the water column, the benthic habitats in the regions greater than 15 m depth could not be

reliably discerned from these images. Thus, before any further corrections were undertaken, all waters deeper than 15 m were excluded by using another Boolean mask. This was achieved by reclassifying the value of each pixel in the DBM to 0 if it was  $>15$  (m) and 1 if it was  $\leq 15$  (m).

#### 2.4.1.3 *Correction for the influence of depth*

Each image tile was masked according to three depth categories to account for differences in pixel values that could be attributed to variation in depth rather than variation in substrate type. Thus, three separate images masking all waters except those between 0 and 5 m, 5 and 10 m and 10 and 15 m, respectively, were created for each tile using the DBM and the method described above.

Although depth corrections can be applied to Quickbird imagery using a modified version of the method developed by Lyzenga (1978) and published by Mumby and Edwards (2000), these weren't possible for the largest sections of the imagery for the SMR due, primarily, to the confounding influence of large spatial differences in water quality. Moreover, it was also difficult to isolate an adequate number of pixels comprised entirely of a non-bare substrate type, *i.e.* seagrass or macroalgae, over each of the different depth ranges, which is a requirement for producing the depth invariant images using this method.

#### 2.4.1.4 *Unsupervised Classification*

The corrected and depth categorised images were subjected to k-Means clustering, an unsupervised method of digital image classification, to organise their pixel values into the two benthic habitat classes that comprised the first level of the benthic classification framework, *i.e.* bare substrate and biosubstrate. K-means clustering initially randomly allocates a specified number of class "centres" in the data space (10 initial class centers in the present study), and then iteratively clusters the pixels into the nearest class according to a minimum distance measure (Tout and Gonzalez, 1974). During each iteration, the class means are recalculated and pixels are reclassified with respect to the new means. This process continues until the number of pixels in each class changes by less than a

specified threshold or the maximum number of iterations is reached. The resultant classification was examined visually against the satellite imagery to determine whether any classes should be grouped, i.e. they were clearly representing the same broad benthic habitat, and to highlight any areas that had obviously been incorrectly classified

Contextual editing, *i.e.* editing in accordance with a visual comparison of the satellite imagery and field data (see section 2.5.1), was carried out on any large and/or erroneous areas of the classified imagery. This was achieved by producing a vector polygon file from each of the (raster) classified images and importing both into ArcView 3.2 and then overlaying them over the Quickbird image to confirm the identification of each class, and thus whether any required combining or splitting. Any classes that required splitting were first converted to polygon vector files. The class was then split by isolating polygons of a particular class, extracting them into a separate file and recoding them to the new class. The newly classed polygons were then incorporated back into the image as separate classes.

#### **2.4.2 Level 2 benthic habitat classification**

Mapping of particular biosubstrate classes at level 2 of the benthic habitat classification framework, *i.e.* seagrass and macroalgae, using a supervised classification approach was attempted for the Rottnest Island section of the imagery. Distinguishing between those habitats was possible only with a supervised approach due to the similarities between their radiance values and thus the need to “train” the pixels into their respective classes. It was considered achievable, at least for the Rottnest section of imagery, due firstly to the fact that those waters were relatively clear and contained large homogenous areas of both of these benthic habitat types and secondly the fact that these features allowed for the application of Mumby and Edwards (2000) modified version of Lyzenga’s water column correction technique. These corrections were crucial in order to carry out the supervised classification, since the whole section was required in order to generate enough pixels to train each benthic habitat classification type.

Supervised classification of the other level 2 benthic habitat categories was not attempted due to at least one of the following reasons:

1. The categories comprised only a very small component of the benthic habitats in the SMR and there was thus an inadequate number of training pixels to undertake the classification, *e.g.* coral, sponges.
2. The low spectral resolution of the Quickbird imagery in general does not allow for reliable spectral separation of certain categories, *e.g.* sand, rock, mud and gravel.
3. The spectral characteristics of detached weed were undistinguishable from several other level 2 biotic categories, *i.e.* seagrass and macroalgae, due to it being comprised of those submerged vegetation types.

#### 2.4.2.1 *Correction for the influence of depth*

The ratio of attenuation coefficient between bands 1 and 2 ( $k_1/k_2$ ) was calculated for selected ln transformed pixel values of a uniform substrate type, *e.g.* macroalgae, at various depths using a regression analysis (Mumby and Edwards 2000). However, rather than use the traditional regression equation, *i.e.* calculating the mean square deviation from the regression line in the direction of the dependant variable, the regression line was placed at the point at which the mean square deviation perpendicular to the line was minimized. The gradient of the resulting biplot does not depend on which band is chosen to represent the dependent variable. A single depth invariant image, in which the confounding influence of depth was minimised and thus differences between the spectral signatures within each broad benthic habitat type were enhanced, was then produced using the equation:

$$\text{Depth invariant image}_{\text{band 1 vs band 2}} = \ln(\text{band 1}) - [(k_{\text{band 1}}/k_{\text{band 2}})^* \ln(\text{band 2})]$$

#### 2.4.2.2 *Supervised Classification*

The area corresponding to biosubstrate in the Rottnest Island section of the Quickbird imagery was then subjected to minimum distance classification using the following distance measures:

1. Euclidean distance. The natural distance in space between the spectral values of a sample pixel and the mean of a set of reference samples (based on classical or Euclidean geometry).
2. Mahalanobis distance. This measure is calculated using the inverse of the variance/co-variance matrix and thus differs from that above by taking into account the correlation between variables (bands). This results in a measure of not only the distance of each test pixel from the mean of the reference pixels, but also its direction as it (De Maesschalck *et al.* 2000).

Both seagrass and macroalgae were mapped separately, using each distance measure, by firstly identifying a large number of training pixels corresponding to that habitat type in order to establish a reference signature. This was achieved by examining field sample data (described in section 2.5) and isolating those samples which contained >60% of the substrate of interest. The corresponding locations of those samples on the Quickbird image were identified and band 1 and 2 radiance data for each pixel within a particular radius of that location (*i.e.* determined by the positional error of the sample) was extracted. The median radiance values for the various locations were meaned to thus provide a reference signature for each benthic habitat type. The distance of each pixel in bands 1 and 2 of the Quickbird imagery from the reference signature for a particular benthic habitat type was measured and converted to a probability and mapped. The probability maps for both seagrass and macroalgae were then standardized and compared. Each pixel was then assigned to the benthic habitat class that had the greatest probability of occurring

## **2.5 Ground validation of benthic habitat classes**

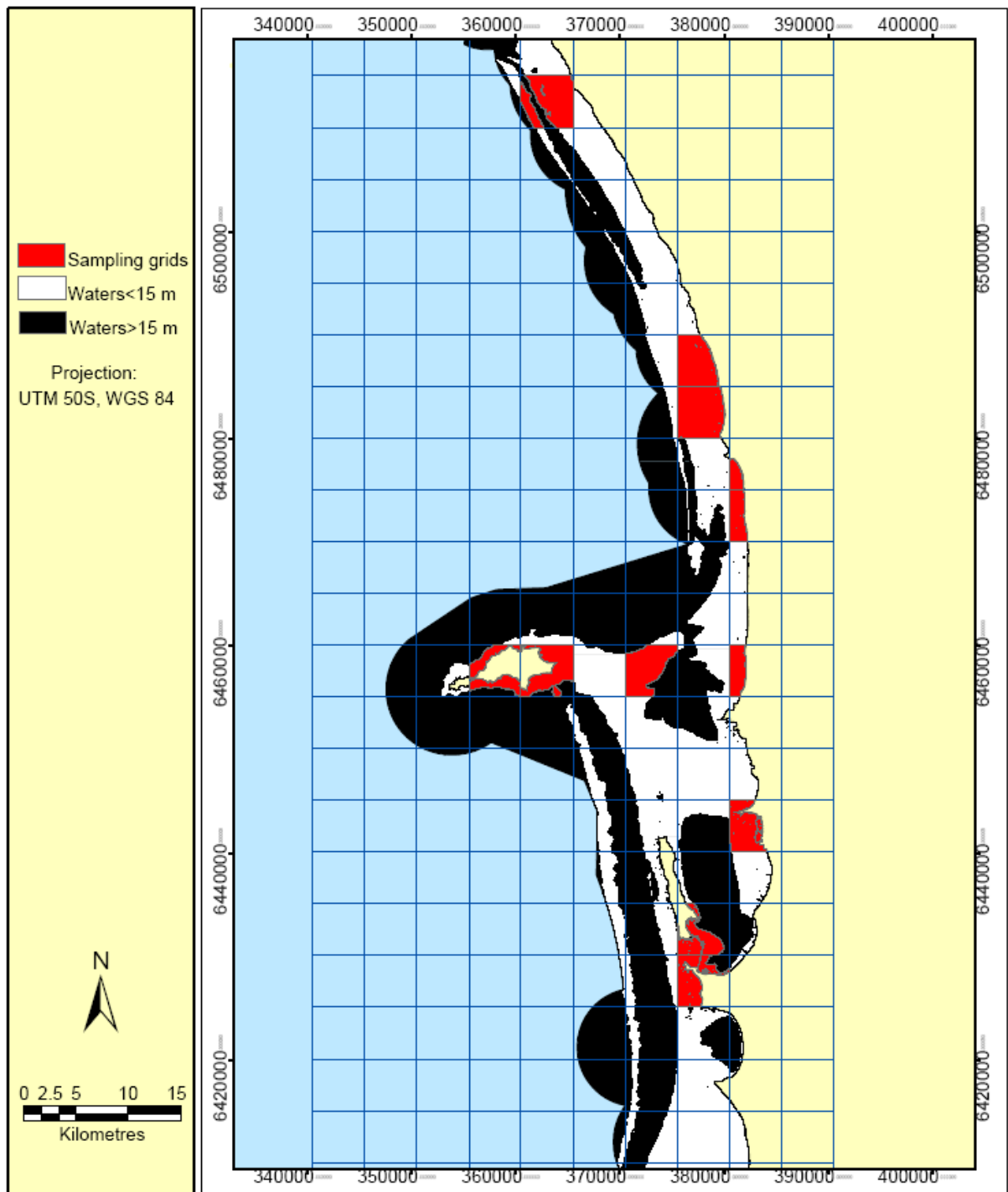
### **2.5.1 Field data collection**

Ground validation refers to the collection of field data for verifying both the identity and accuracy of output classes generated by an image classification procedure (Congalton 1991). In order to evenly distribute the collection of samples to be used for ground validation throughout the SMR, the area was divided into 5 x 5 km (large) grids. Sampling efforts were directed towards those grids that contained the most diverse and/or

variable benthic categories and those which were considered to be representative of the others in the SMR (Fig. 5). Within these grids, photographic samples were taken along random transects at intervals determined by the diversity of the seafloor, *e.g.* ~3-10 m apart in diverse macroalgal covered reef environments and 20-50 m apart in bare sandy areas. Although less importance was placed on large grids containing more homogenous substrate types (*i.e.* mainly sand), a representative number of samples were still collected.

The samples were taken using a state-of-the-art drop camera system (Plate 1), which integrated software and hardware for the acquisition of photographic, DGPS and depth data. The camera, a Dalsa digital video Genie Camera with a 3.5 mm wide-angle lens and a 1024 x 763 pixel resolution, was housed in a heavy-duty PVC custom-built housing and was lowered over the edge of a boat using an electric winch. The camera conformed to the GigE-vision communications protocol and thus enabled data to be sent via ethernet cable to a laptop computer on board the boat, thus allowing the features of the benthos to be constantly viewed and the frequency of photo collection modified to suit the level of benthic diversity. As each image was viewed on the computer screen, frames were captured using the Dalsa camera software package Sopera LT and stored on the hard drive as bitmap images.

A depth sounder attached to the camera housing allowed the distance that the camera was positioned from the seafloor to be measured and thus for the target field of view (FOV) to be captured for each image. The target FOV, *i.e.*  $2.4 \text{ m} \pm 25\%$  which best corresponded to the pixel resolution of the Quickbird image, was obtained by regularly using the electric winch to adjust the height of the camera relative to undulations in the seafloor. The required height of the camera, in order to capture the target FOV, was determined by placing a 3 m pole, marked at 10 cm intervals, underwater and taking photographs (with the pole oriented horizontally across the frame) at varying noted heights from the seafloor. These photographs were then viewed and the width of the seafloor in each was determined from the markings on the pole. The relationship between the height of the camera and width of the seafloor in the FOV was determined by regression and used to identify the height at which the target FOV was captured. All



**Figure 5** The location of the large and small grids used for sampling the benthic habitats in the SMR. N.B Black areas are those waters >15 m and thus not included in this study.

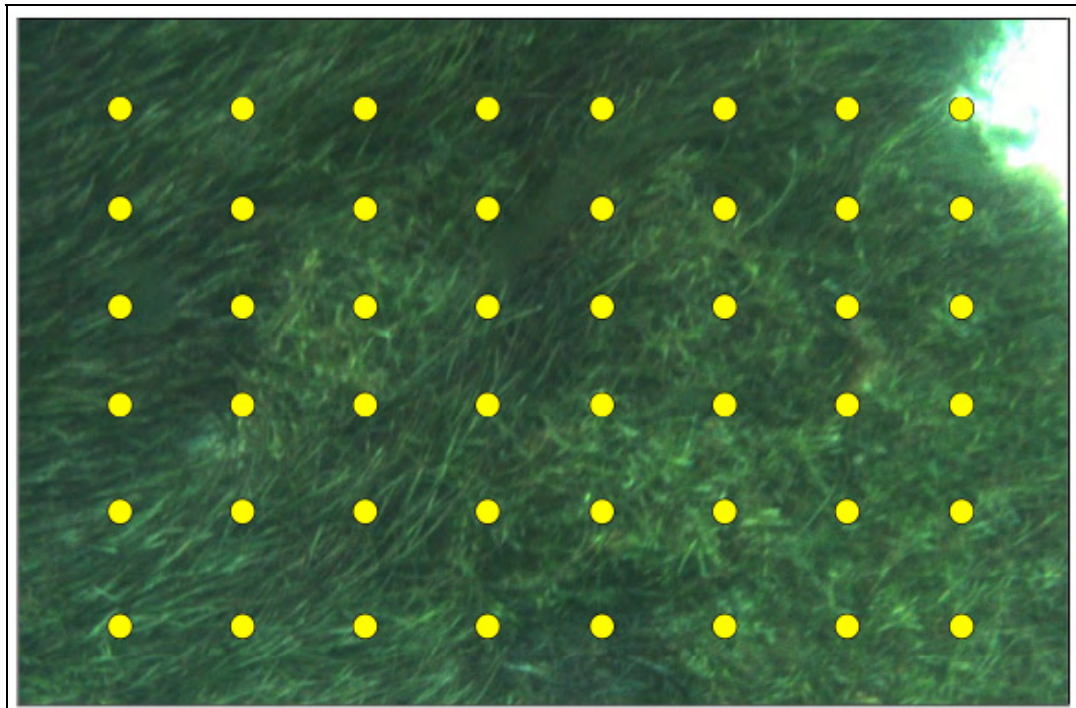


**Plate 1**      **The Drop camera**

photographic samples collected in the field were archived along with their date and time of acquisition, geographic co-ordinates, estimates of locational error, FOV and the depth of the water column in which the photograph was captured.

### 2.5.2 *Field data processing*

For each photograph collected in the field a data analysis system was used to quantify the percentage contributions of the various benthic habitat categories at each level (where possible) of the benthic habitat classification framework. Thus, each photograph was overlaid with a series of evenly spaced points, *i.e.* 20 cm apart (the number varied according to the FOV, Fig. 6). The benthic habitat category identifiable at the most detailed level of the classification framework that was present under each point was recorded and the percentage contributions of each category were calculated by tallying the number for each and dividing by the total number of points overlaid on the photograph.



**Figure 6** Photographic sample overlaid with evenly spaced points used to calculate the % compositions of benthic habitat.

The percentage contributions of each benthic category at each level of classification in each photograph was imported into ArcView 3.2, where it was displayed spatially, *i.e.* as points showing the location of each photographic sample across the SMR. This file also contained information on the date and time of acquisition, geographic co-ordinates and estimates of positional error, FOV, the depth of the water column and the number of points used to calculate the quantitative data for each benthic category for each photograph. This information was also labeled on each bitmap photographic record (Plate 2).

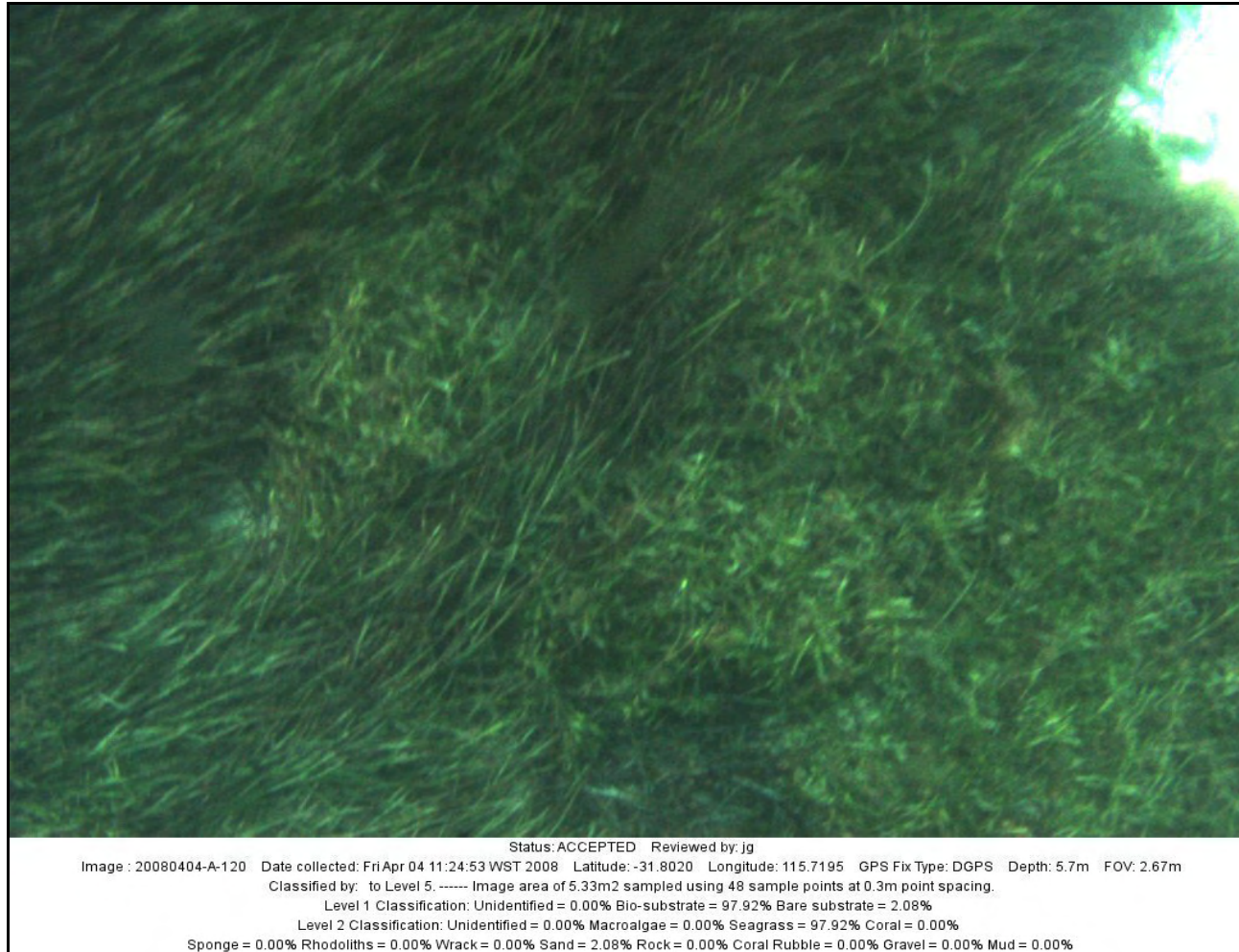
### **2.5.3 Accuracy assessment**

In order to assess the accuracy of the level 1 classified map, data for each photographic sample collected in the field was extracted from the GIS database at the level 1 of the classification framework. Any sample containing more than 20% of unidentified substrate was discarded. The samples were split into two groups based on the following threshold percentage contributions of biosubstrate in each:

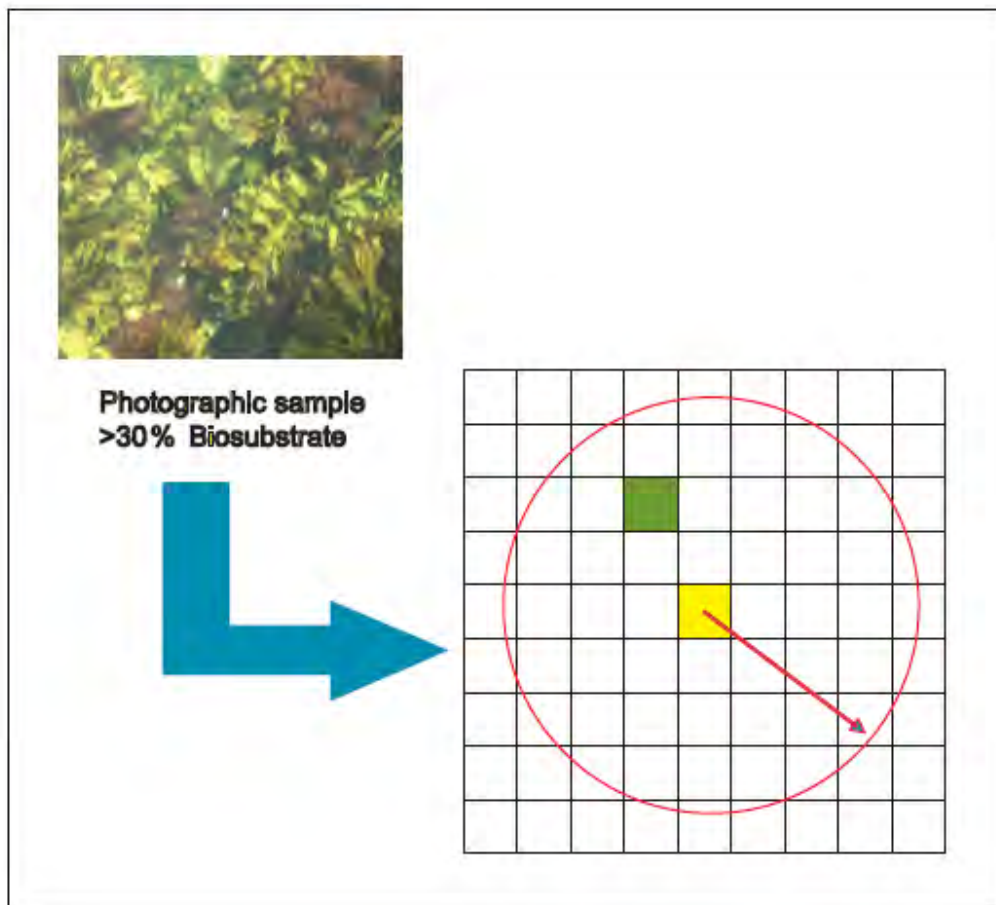
1. Samples with <30% biosubstrate cover were coded as bare. This threshold was chosen for matching “bare” samples because brightness of sand is more likely to dominate a pixel even when some biosubstrate is present (M. Harvey unpubl.).
2. Samples with >30% biosubstrate cover were coded as biosubstrate.

The photographic samples were then matched with their corresponding pixels in the classified map, *i.e.* according to their location. If the allocated class of any mapped pixel within a variable radius of the sample point, (*i.e.* determined by the positional error of that sample), matched that of the photographic sample, it was recorded as correct, whereas it was recorded as incorrect if the opposite was true (Fig. 7).

The data derived from the above pixel vs photograph comparisons was then put into an error matrix, *i.e.* an array of numbers set out in rows (representing the classified data) and columns (representing the field data) which expresses the number of pixels assigned to a particular class (including incorrect pixels) relative to the actual class as recorded on the ground (Congalton 1991). The error matrix was then used to calculate several measures of map accuracy, namely overall, users, producers and Kappa accuracies. The overall accuracy is simply the total number of correct pixels divided by



**Plate 2** Labeled photographic sample of benthic habitat in the SMR.



**Figure 7** The photographic sample vs pixel matching procedure showing the geographic location of the photographic sample containing >30% biosubstrate ■ and a pixel classed as biosubstrate laying within a given radius of the coordinates of the photographic sample ■. The target pixel ■ would be recorded as correct due to the presence of the pixel classed as biosubstrate within its given radius.

the total number of pixels in the error matrix. The producers and users accuracies are the overall accuracies of each benthic class from two different perspectives. In the case of producers accuracy, the number of correctly classified pixels for a particular class is divided by the total number of samples of that class as derived from the ground data, and indicates the probability of a ground sample being correctly classified. Alternately, users accuracy is the number of correct pixels for a particular class divided by the total number of pixels that were classified as that class, and is the probability that a pixel classified on the map actually represents that class on the ground (Congalton 1991). Kappa accuracy is a measure of agreement between the overall accuracy of the error matrix (as indicated by the agreement between the classified pixels and the ground data) and the chance

agreement in the same error matrix (as indicated by the row and column totals; Congalton and Green 1999). The values for this measure of accuracy are expected to range between 0 and 1 and can generally be organised into three groupings, *i.e.* >0.8 represents strong agreement, 0.4-0.8 represents moderate agreement and <0.4 represents poor agreement (Congalton 2001).

The accuracy assessment process was repeated for the level 2 benthic habitat map derived from the supervised classification of the Rottnest Island section of the SMR imagery with the exception that photographic field data in which biosubstrate was greater than 70% was firstly, extracted from the GIS database. The samples were then split into two groups based on the following threshold percentage contributions of seagrass and macroalgae in each:

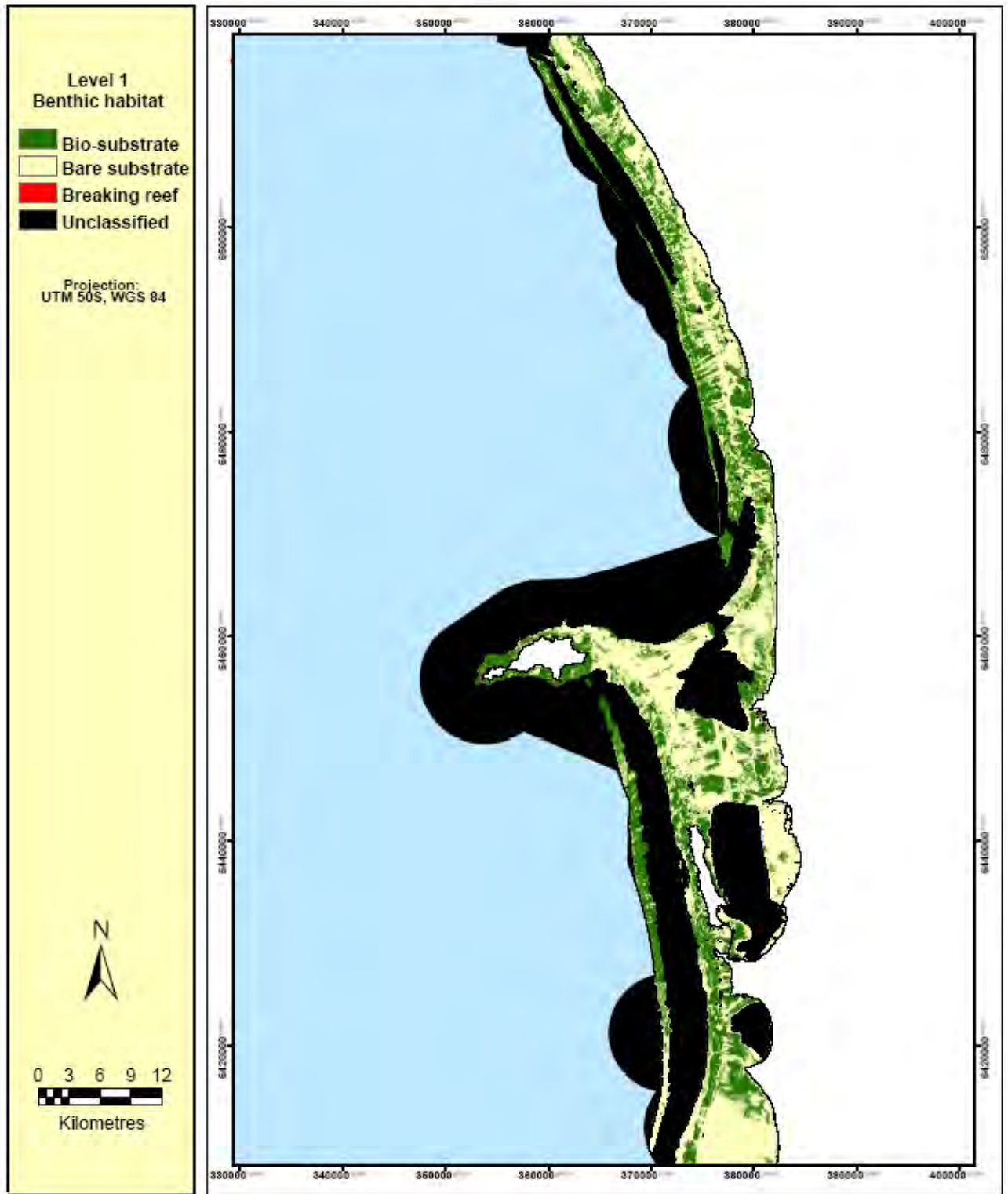
1. Samples with seagrass >60% cover were coded as seagrass.
2. Samples with macroalgae >60% cover were coded as macroalgae.

### 3 RESULTS

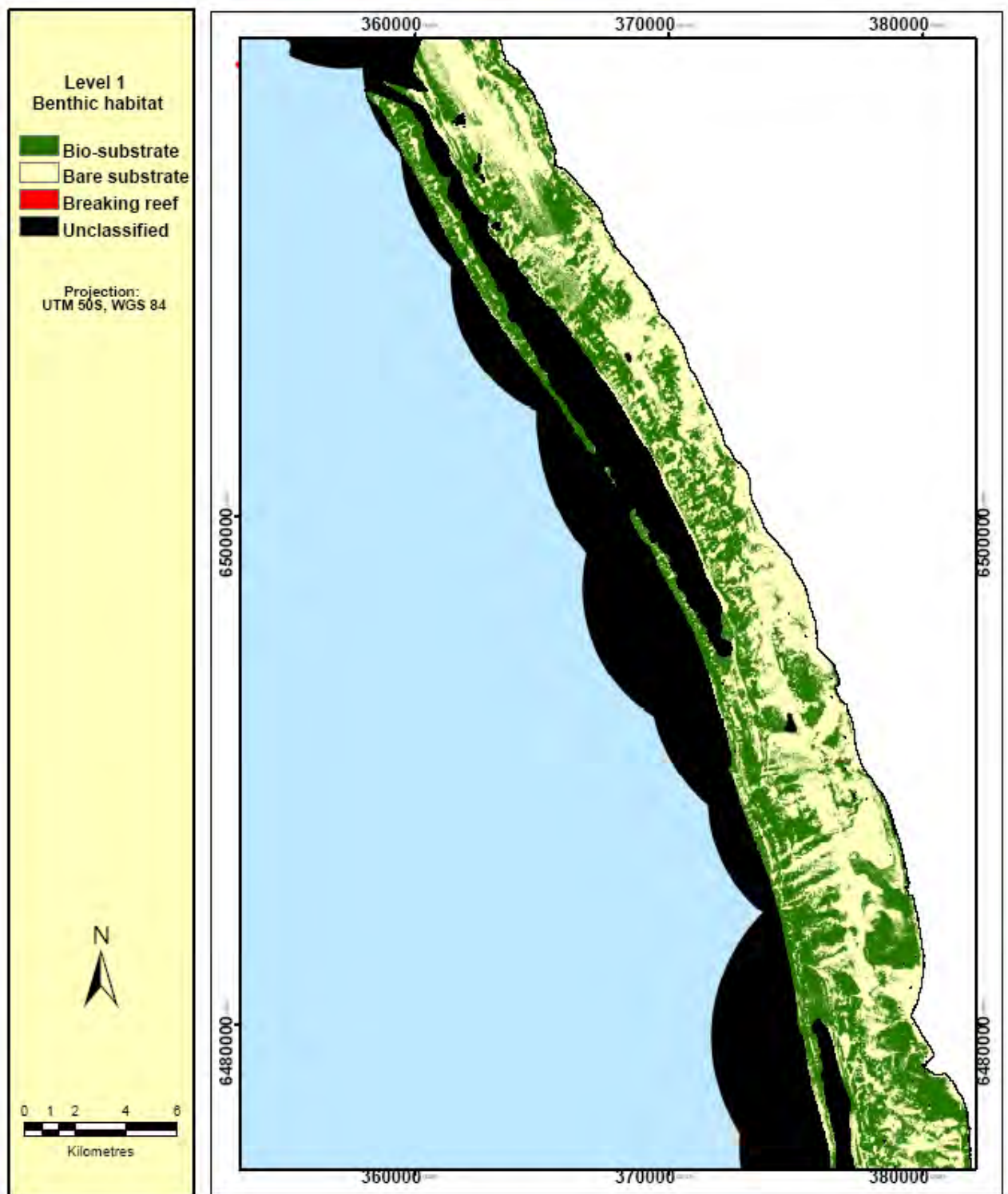
In this study, the following maps of broad-scale benthic habitats in the shallow waters of the SMR, *i.e.* those habitats that were categorised according to levels 1 and 2 of the hierarchical classification framework presented in Fig. 3, were produced by subjecting recently-acquired Quickbird imagery to unsupervised and supervised classification, respectively.

1. The distribution of bare *vs* biotic substrate for the entire SMR (Fig. 8. Figures 9-11 correspond to various sections of the SMR, *i.e.* the northern beaches, Rottnest Island and Cockburn Sound, respectively, which have been magnified to show finer spatial detail of the classification).
2. The distribution of bare substrate *vs* seagrass and macroalgae for Rottnest Island (Figs 13-14).

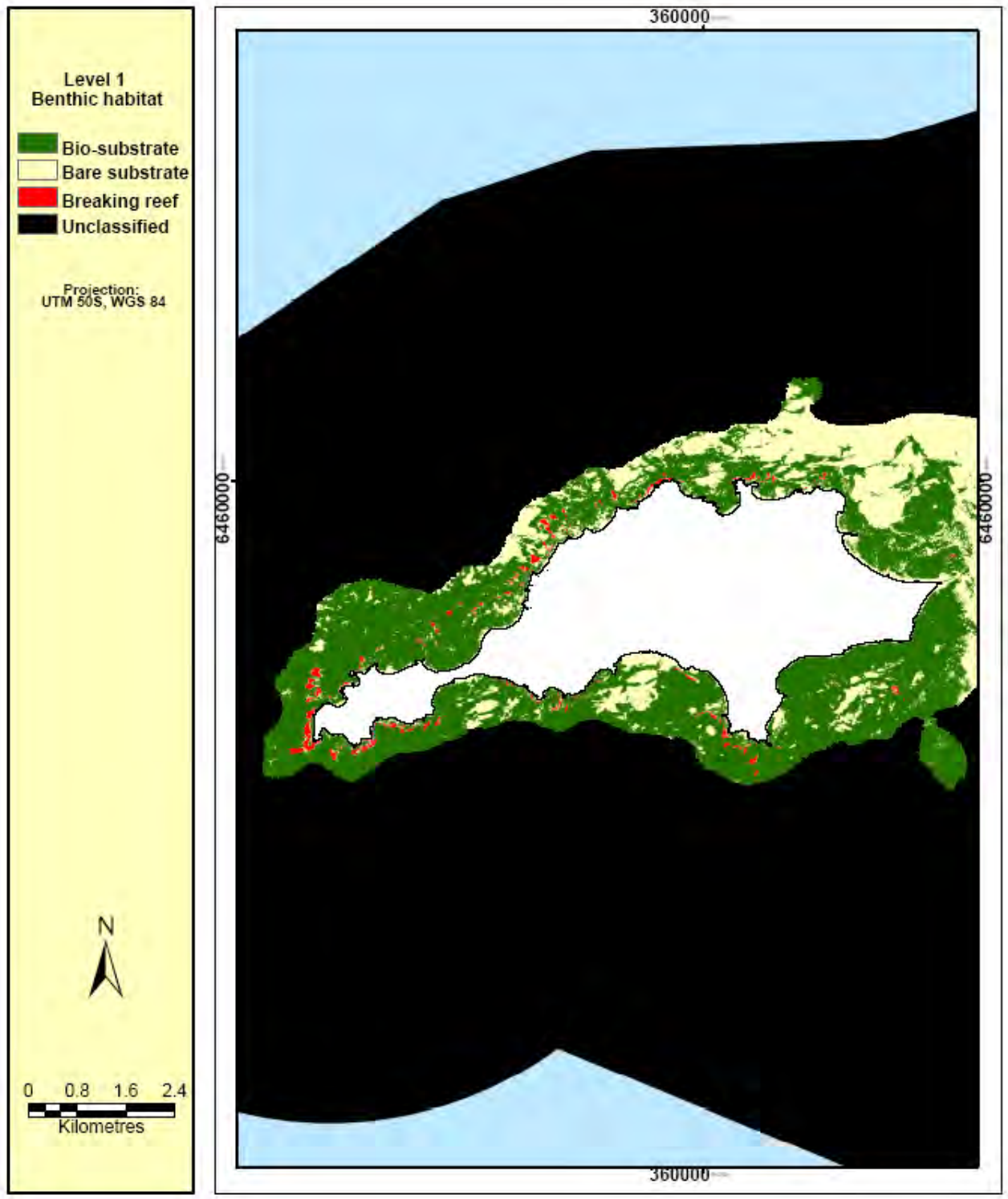
These maps were assessed for accuracy using percentage contribution data for the relevant level of benthic habitat discrimination that was derived from 6602 photographic samples collected in the field. These maps, photographic samples and, in each of those photographs, percentage contribution data recorded for benthic habitats at each of the five levels of the hierarchical classification framework, have been collated in an



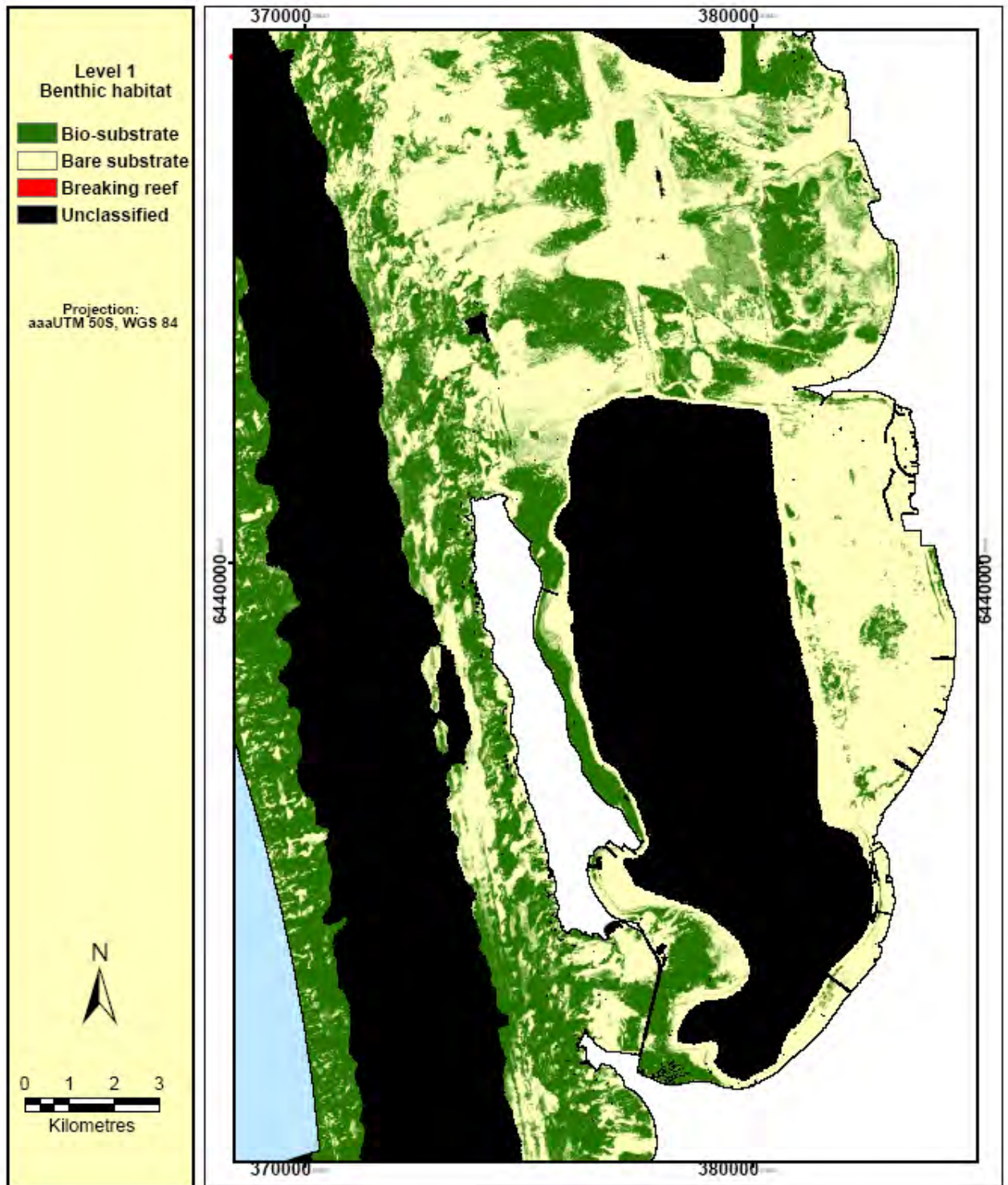
**Figure 8** Classification of level 1 benthic habitats, i.e. bare vs biosubstrate, in waters <15 m depth in the SMR.



**Figure 9** Distribution of level 1 benthic habitats in waters <15 m depth in the northern SMR.



**Figure 10** Distribution of level 1 benthic habitats in waters <15 m depth at Rottneest Island in the SMR.



**Figure 11** Distribution of level 1 benthic habitats in waters <15 m depth in Cockburn Sound in the SMR.

ArcView v9.2 GIS to provide a permanent and quantitative database of the distributions of benthic habitat types in the SMR. The full complement of files included in this digital database is given in Appendix 1.

### **3.1 Level 1 classification of broad-scale benthic habitats**

The unsupervised K-means Cluster analysis initially produced 10 classes of pixels pertaining to a gradient of brightness values, *i.e.* class 1 was represented by the darkest pixels while class 10 was represented by the brightest. Visual comparison of the classified image against the Quickbird image clearly showed that the classes represented by the brightest pixels were typically bare substrate (4 or 5 classes in each section of the images), and were subsequently grouped into one class. The remaining classes were represented by the darkest pixels, which, when examined against the image, typically coincided with biosubstrate and were also grouped into one class

Those areas of the image that were obviously misclassified, *i.e.* as known from field experience and/or photographic samples collected in the field, were very bright pixels representing breaking reefs around Rottneest Island and very dark pixels representing the poor water quality in Cockburn Sound. These pixels were incorrectly classified as bare and biosubstrate, respectively. Contextual editing of these pixels resulted not only in the rectification of the Cockburn Sound pixels to bare substrate (Fig. 11), but also in the creation of a new class representing breaking reefs (Fig. 10). However, it is important to recognize that this latter class does not comprise a benthic habitat category in the classification framework, but is simply a way to distinguish those pixels from very bright sand.

The overall and Kappa accuracies generated from the error matrix that was produced when the photographic sample points were matched to their corresponding pixels in the classified map, were 90.55% ( $\pm 0.71\%$ ) and 76.93% ( $\pm 1.03\%$ ), respectively. The producers and users accuracies associated with each benthic habitat class are given in Table 1. Thus there is an 86.56 and a 91.68% probability that a field sample of bare and biosubstrate substrate, respectively, will be correctly classified in the map (producers accuracies). Conversely, there is a 79.87 and a 95.13% probability that a pixel classified

as bare and biosubstrate, respectively, actually represents each of these categories in the field.

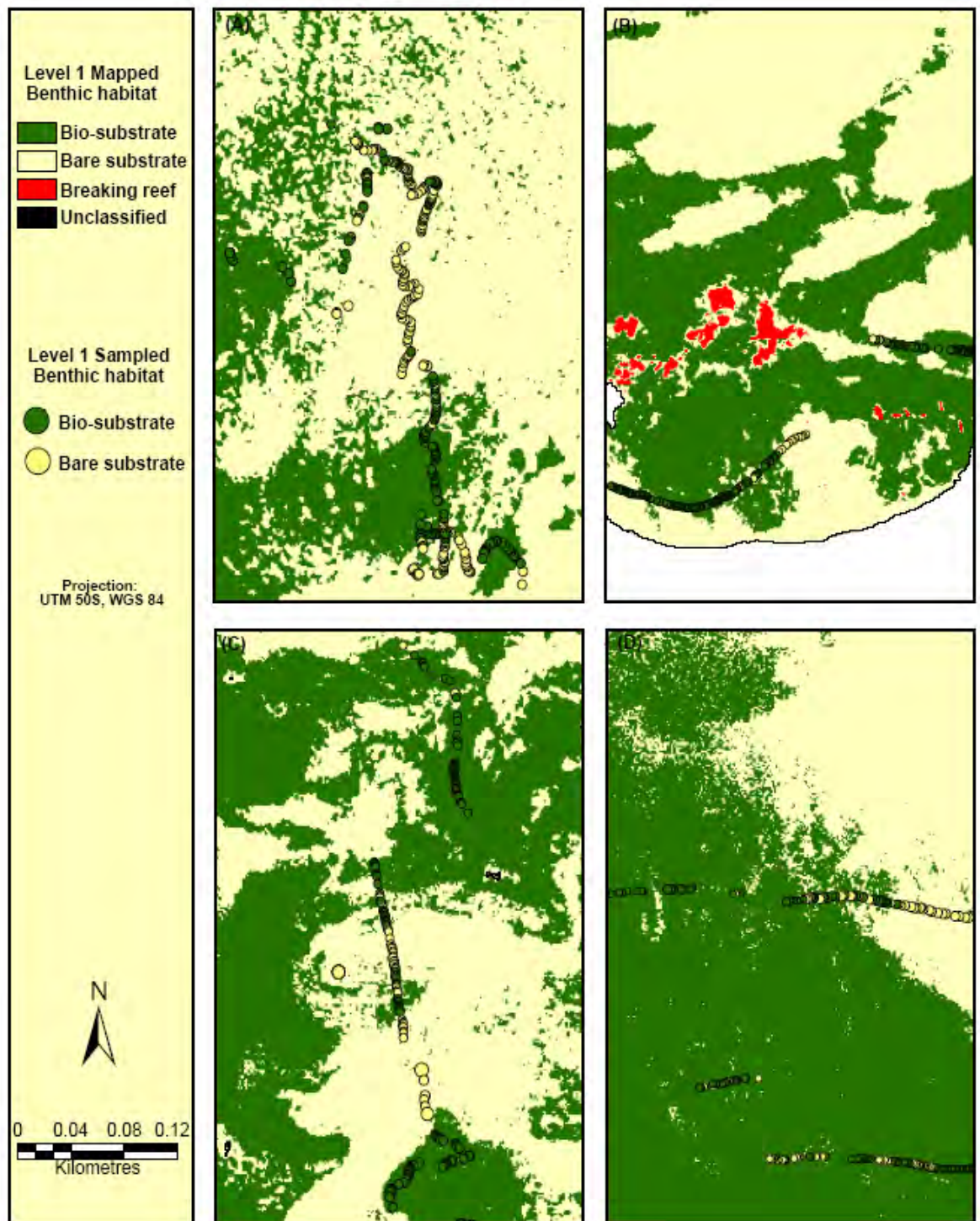
**Table 1** Producers and users accuracies calculated for each level 1 benthic habitat class.

	Bare Substrate	Biosubstrate
<b>Producers Accuracy</b>	86.56% ( $\pm 1.58\%$ )	91.68% ( $\pm 0.79\%$ )
<b>Users Accuracy</b>	79.87% ( $\pm 1.78\%$ )	95.13% ( $\pm 0.63\%$ )

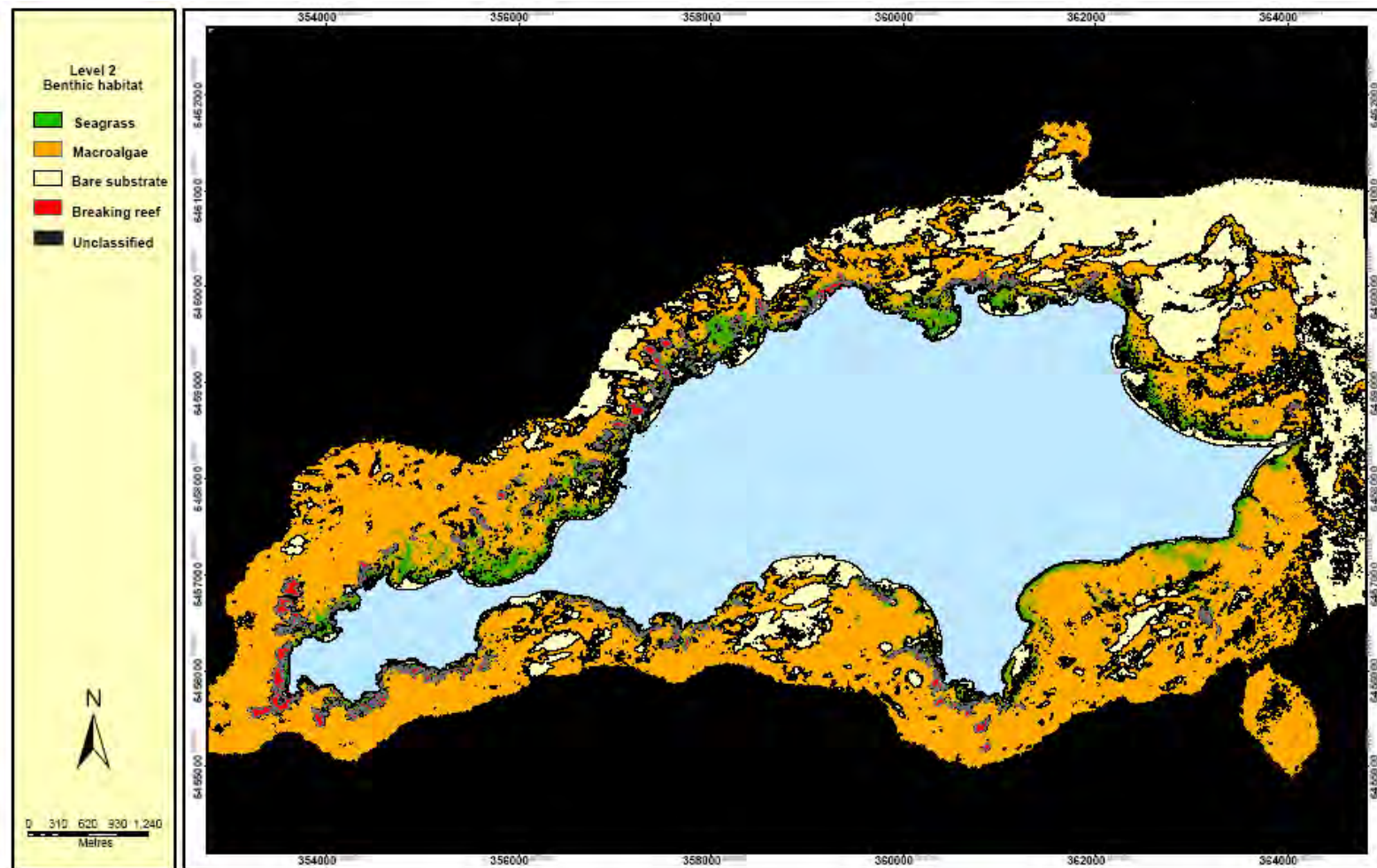
These high accuracies are reflected particularly by the distinction made between the two broad habitat classes even in very heterogeneous areas at fine spatial scales. Thus at magnified scales, it is clear that when photographic sample points coded for their dominant level 1 habitat type are overlaid on their corresponding pixels in the classified image, the classification is well able to distinguish these habitats throughout patchy ground (Fig. 12).

### 3.2 Level 2 classification of benthic habitats

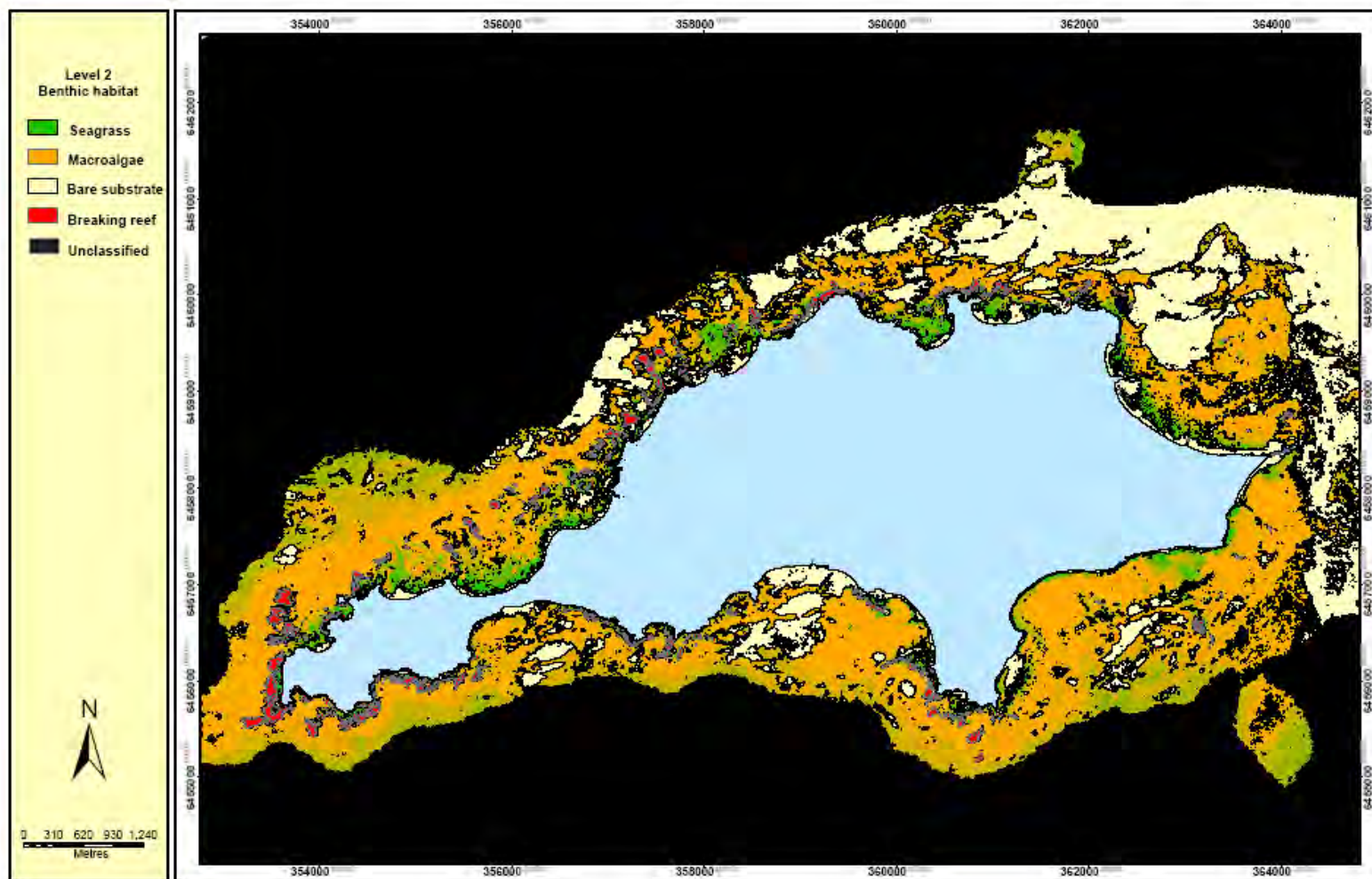
Maps of the biosubstrate around Rottneest Island representing particular categories of level 2 of the benthic habitat classification framework, *i.e.* seagrass and macroalgae, that were produced when the depth-corrected images were subjected to supervised classification are shown in Figs 13 and 14. Euclidean and Mahalanobis distance measures were employed, respectively, to produce those classifications, but the resultant maps were very similar, irrespective of which distance measure was used (Fig. 13 and 14). In both cases, the distribution of the seagrass class initially appeared to be reasonably represented, with most being located in the nearshore areas of bays on the northern and eastern sides of the island. Similarly, macroalgae also appeared to be reasonably represented throughout the images, with most of the pixels representing this class being located on the western and southern sides of the island. Moreover, in certain areas, these classifications appeared to accurately reflect smaller-scale variations in the distribution of these two classes (Fig. 15). However, the most obvious flaws in these classifications occurred in the nearshore areas of Thompsons Bay, on the eastern side of the island (Fig. 16). Examination of data collected from field samples in this area showed that a large number of these pixels were incorrectly allocated to the macroalgae class.



**Figure 12** The level 1 classification at (a) the southern flats, (b) Rottnest Island, (c) Point Peron and (d) Marmion Marine Park, overlaid with the location of the photographic samples collected in the field that have been coded as containing predominantly biosubstrate (>30%) or bare substrate.



**Figure 13** Supervised classification (minimum distance) of the distributions of seagrass and macroalgae at Rottnest Island derived from employing the Euclidean distance measure. N.B The Bare substrate class derived from the level 1 unsupervised classification and breaking reefs derived by contextual editing were overlaid as separate layers.



**Figure 14** Supervised classification (minimum distance) of the distributions of seagrass and macroalgae at Rottneet Island derived from employing the Mahalanobis distance measure. N.B The Bare substrate class derived from the level 1 unsupervised classification and breaking reefs derived by contextual editing were overlaid as separate layers.

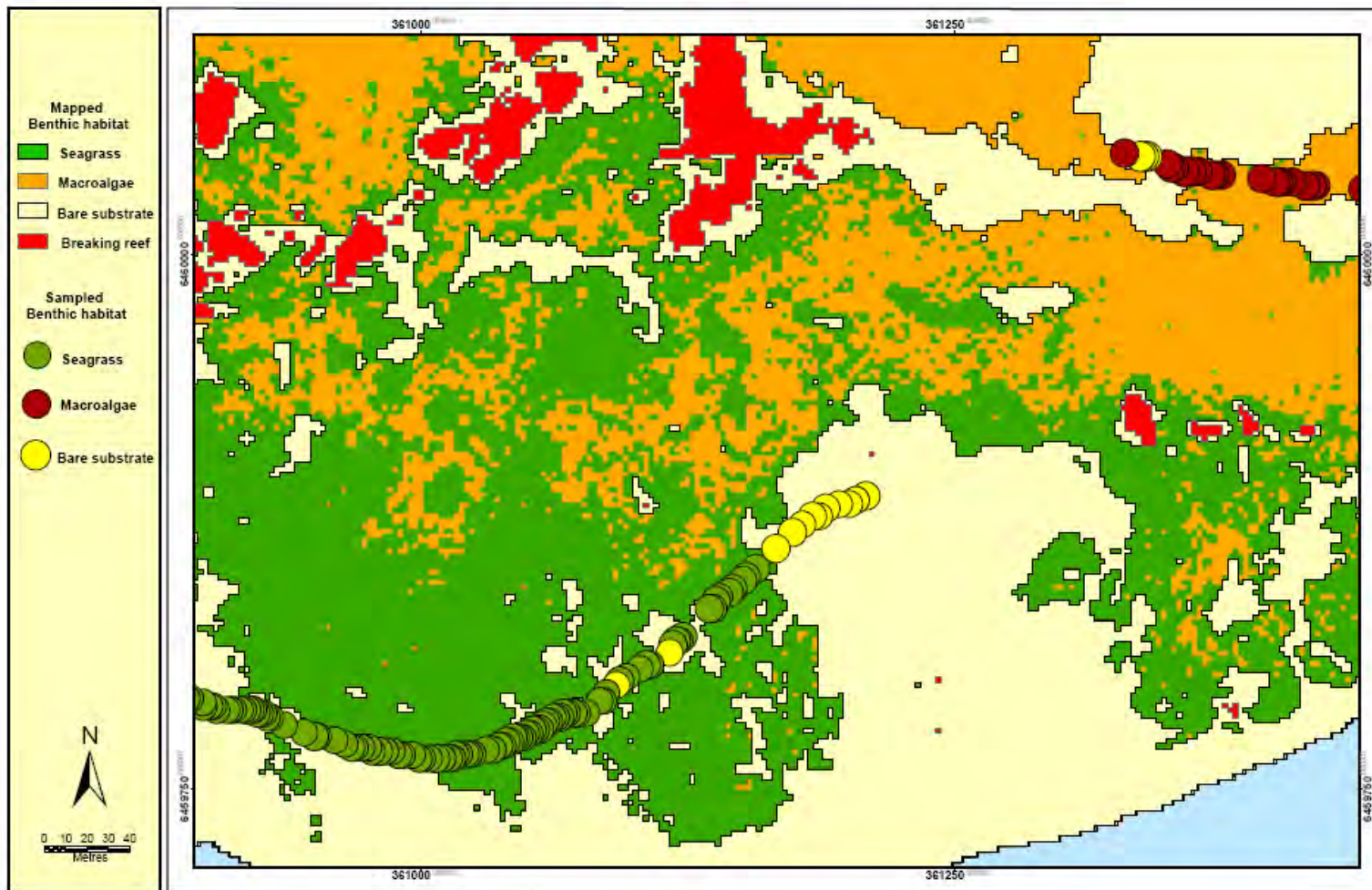
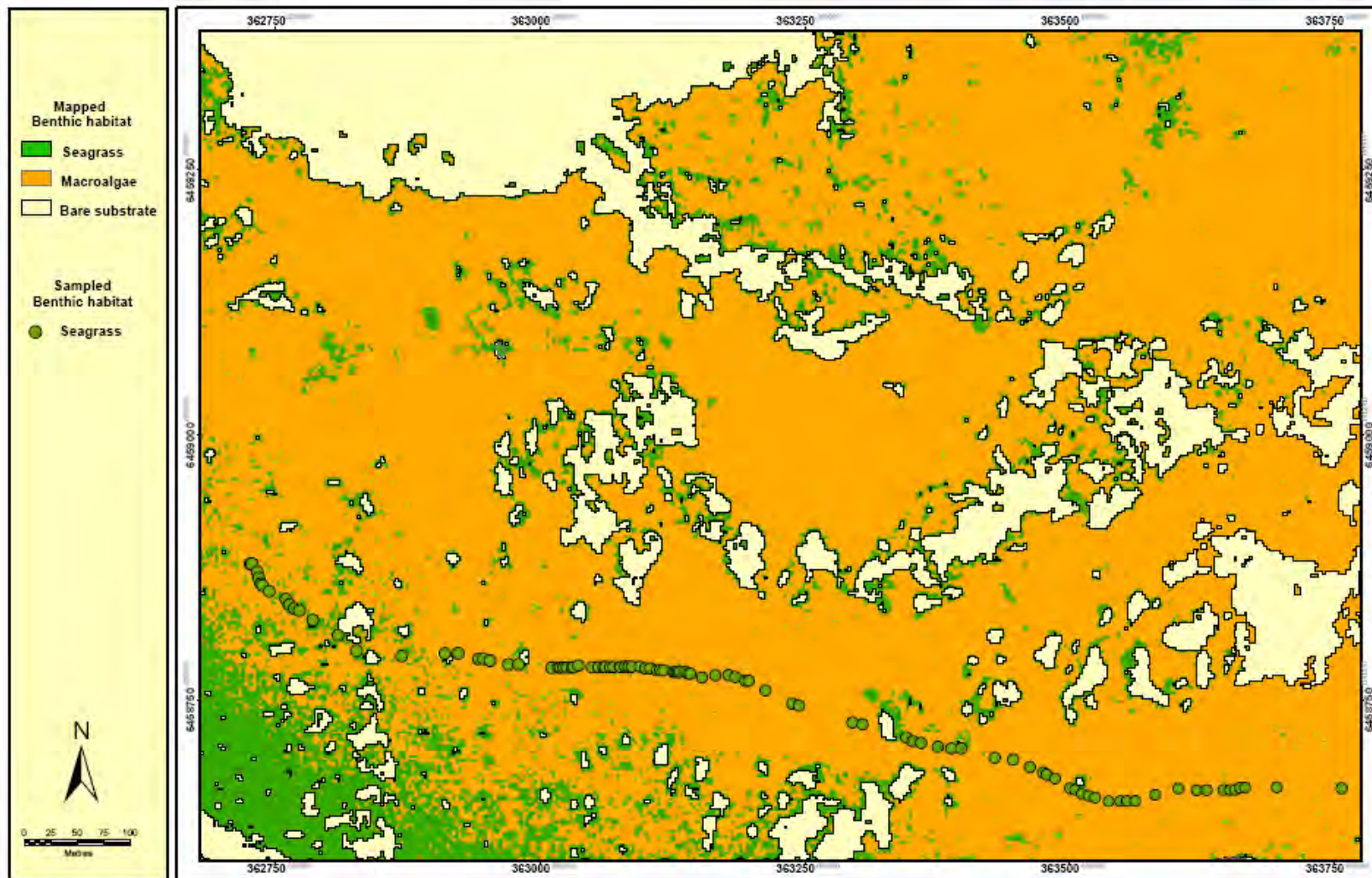


Figure 15 The level 2 classification (based on Mahalanobis distance), at Geordie Bay, Rottne Island, overlaid with the location of the photographic samples collected in the field which were classed as either seagrass (>60% coverage), macroalgae, (>60% coverage) or bare substrate (>70% coverage).



**Figure 16** The level 2 classification (based on Mahalanobis distance), at Thomsons Bay, Rottne Island, overlaid with the location of the photographic samples collected in the field which were classed as seagrass (>60% coverage).

The overall accuracies of both the Euclidean and Mahalanobis distance maps were 69.33 and 68.89% ( $\pm 3.01\%$ ), respectively, while Kappa accuracies were 0.34 and 0.33 ( $\pm 0.03$ ), respectively. The producers and users accuracies associated with each benthic habitat class are given in Tables 2 and 3. In both cases, the producers and users accuracies for macroalgae were greater than those for seagrass. This is due largely to the obvious misclassification of pixels in the Thompsons Bay area as described above, but is also likely to be attributable to the fact that the macroalgal class is far more broadly distributed and thus has a greater chance of being classified correctly, whereas seagrass is distributed in much finer patches.

**Table 2** Producers and users accuracies calculated for seagrass and macroalgae at Rottneest Island using Euclidean distance as a minimum distance supervised classification measure.

	Seagrass	Macroalgae
<b>Producers Accuracy</b>	55.43% ( $\pm 4.13\%$ )	78.13% ( $\pm 4.30\%$ )
<b>Users Accuracy</b>	61.61% ( $\pm 4.77\%$ )	73.46% ( $\pm 3.81\%$ )

**Table 3** Producers and users accuracies calculated for seagrass and macroalgae at Rottneest Island using Mahalanobis distance as a minimum distance supervised classification measure.

	Seagrass	Macroalgae
<b>Producers Accuracy</b>	55.98% ( $\pm 4.12\%$ )	77.07% ( $\pm 4.39\%$ )
<b>Users Accuracy</b>	60.72% ( $\pm 4.79\%$ )	73.44% ( $\pm 3.83\%$ )

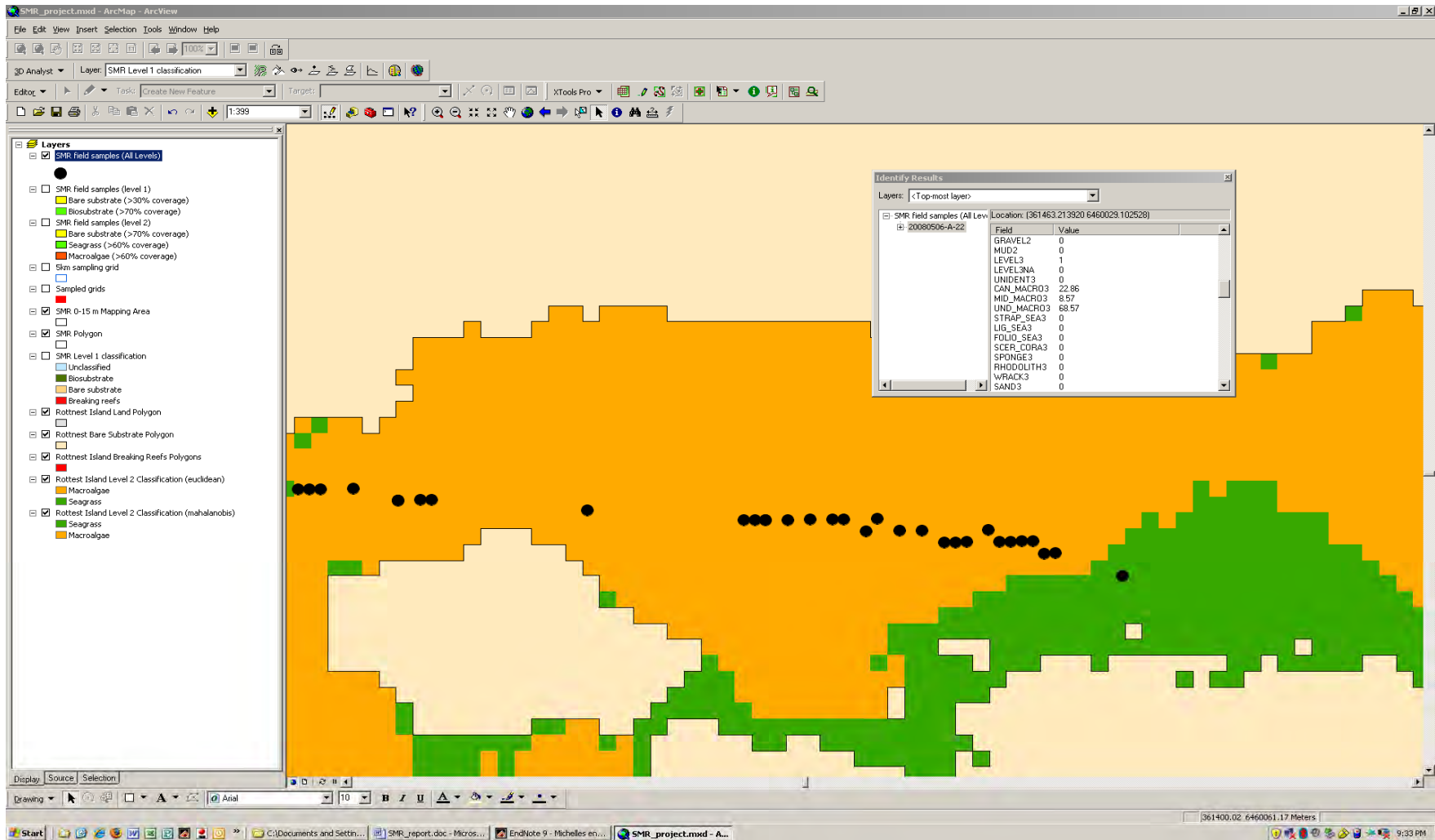
### 3.3 Benthic habitat database

A quantitative database of benthic habitats in each of the 6602 photographic samples that were collected throughout the SMR has been developed as part of this study. This database contains the percentage contributions of benthic habitats at up to five levels of identification as detailed in the hierarchical classification framework, *i.e.* broad-scale (bare vs biosubstrate) habitats at level 1 to fine-scale (species) habitats at level 5. This information, along with the date and time of photo-acquisition, geographic co-ordinates and estimates of positional error, FOV and the depth of the water column, is linked to a georeferenced shapefile of the locations of each photographic sample in the SMR, and is

able to be queried through an ArcView 9.1 project environment. For example, if a photographic sample point is selected using the “identify” key in that software package, the percentage contributions of the benthic habitats in that sample from level 1 to the highest possible level of identification, are displayed onscreen (*e.g.* Fig. 17). Each sample point in the shapefile is tagged with a unique identification number which can be cross-referenced to a file containing all of the sample photographs. Furthermore, each of these photographs is labeled with all of the above information and the number of points that was used to calculate the percentage contributions of the benthic habitats.

#### **4 DISCUSSION**

This study has produced a highly accurate, ground-validated map of the broad-scale benthic habitats in the SMR, *i.e.* bare vs biosubstrate, and has quantified the percentage contributions of benthic habitats at successively finer levels of identification in accordance with a hierarchical classification framework in 6602 photographic samples collected in the field. The benthic habitats that comprised this framework were chosen after careful assessment of the many relevant studies that have been carried out in southwestern Australia, and which have elucidated the ways in which differences in benthic habitat reflect those among faunal assemblages (*e.g.* Edgar and Shaw 1995; MacArthur and Hyndes 2001; Walker *et al.* 2001; Hyndes *et al.* 2003; Goodsell *et al.* 2004; Irving *et al.* 2004; Valesini *et al.* 2004; Wildsmith *et al.* 2005; Crawley *et al.* 2006; 2007; Tuya *et al.* 2008). The hierarchical structure of the framework, which comprised a range of taxonomic and geomorphologic categories, ensures that it can be applied to mapping benthic habitats at a range of ecological scales, *e.g.* sub-regional to highly localized areas. Furthermore, it also allows for the inclusion of new categories as more data is acquired for a region and/or remote methods for distinguishing fine-scale benthic habitats components are developed. Consequently, this framework could be adapted for use in any coastal region.



**Figure 17** Example of the onscreen working environment of the ArcView v9.1 benthic habitat database. In this case, the dialogue box contains the percentage contributions of benthic habitats identified at level 3 of the benthic habitat classification framework for a selected sample.

The digital (ArcView v9.1) data package that accompanies this report, *i.e.* containing (i) the Quickbird imagery, (ii) digital elevation model, (iii) benthic habitat maps classified at levels 1 and 2 of the classification framework, (iv) georeferenced photographs of the benthic habitat at every ground validation point and (v) the percentage contributions of each benthic habitat at every level of the five tiered classification framework (see Appendix 1 for more detail), can be queried to investigate a host of ecological questions regarding benthic habitat distribution in the SMR. These components also provide an excellent benchmark for quantifying future changes in benthic habitat distribution throughout the region and a sound basis upon which other ecologically relevant and spatially-explicit data can be incorporated.

#### **4.1 Classification of broad-scale benthic habitats**

Within the scope of this study, a broad-scale (*i.e.* level 1 of the classification framework, or bare *vs* biosubstrate) approach was considered the most appropriate for classifying the shallow water benthic habitats throughout the entire SMR. The accuracies recorded for the resultant map (*i.e.* 76.93 and 90.55% for Kappa and overall accuracy, respectively) are among the highest published for comparable benthic habitat classifications derived from satellite imagery, and are particularly impressive given the size and water quality characteristics of the study area. Indeed, most of the studies that have focused on classifying shallow benthic habitats in marine waters using satellite imagery (*e.g.* those derived from Quickbird, Landsat, SPOT XS and IKONOS satellites) have been carried out in the tropics where the water clarity is far greater and more homogenous than in the SMR (*e.g.* Mumby and Edwards 2002; Mishra *et al.* 2006; Phinn *et al.* 2006). Furthermore, although some of the multispectral images employed in those studies have been subjected to similar classification procedures as those used in the current study to successfully map finer-scale marine benthic habitats, few have been applied over spatial scales as large as the SMR.

The high accuracy of this broad-scale map is attributable to several factors, the most obvious of which is its thematic simplicity. However, it was also facilitated by the high spatial resolution of the Quickbird imagery (2.4 m), which allowed for mapping of the fine scale distribution of biotic habitat around small coastal features. Furthermore,

while the spectral resolution of Quickbird imagery is relatively low, it is ideal for distinguishing benthic habitats that vary markedly in their ability to reflect light, *e.g.* sand *vs* seagrass. Combined with the relatively low cost of Quickbird satellite data, particularly when considering areas as large as the SMR, the broader-scale but highly accurate benthic maps that can be produced from this type of imagery are among the best for these types of studies. Furthermore, the highly rigorous methods of ground validation and accuracy assessment that were employed in this study (see following sections) ensure that not only is the broad-scale habitat map of the SMR accurate, but also that it is reliable. This map thus forms a sound basis on which finer-scale benthic habitat classes can be represented in the future.

In contrast, the maps of particular benthic habitats at level 2 of the classification framework (*i.e.* seagrass and macroalgae) that were produced for Rottnest Island, were less accurate, particularly with respect to the seagrass class. Potential users of these maps should thus be mindful, at the very least, of those areas that contain obvious errors (highlighted in section 3.2). The lower accuracies that were calculated for these maps were attributable largely to the relatively broad spectral resolution and low dimensionality of Quickbird data, which limits its ability to efficiently define benthic habitats at finer taxonomic/geomorphologic scales. Consequently, this level of classification was not attempted for the entire SMR, particularly when taking into consideration the heterogeneous water quality throughout the region, *e.g.* clear shallow waters surrounding Rottnest Island and the northern coastal areas *vs* turbid waters within the relatively enclosed Cockburn Sound and nearshore waters adjacent to outflow from the Swan-Canning and Peel-Harvey estuaries. Such characteristics inflict further inconsistencies on the spectral signatures of the finer-scale benthic habitats in the region.

#### **4.2 Advantages of the drop-camera system and method of ground validation**

This study has highlighted several of the advantages of the approach used to collect ground validation data and to provide finer scale quantitative detail on the composition of benthic habitats in the SMR. The drop-camera system that was employed enabled a large number of photographic samples to be collected over a vast area within a relatively short period and at reasonably low cost. Furthermore, this large photographic

dataset provides a permanent record of the characteristics of the benthic habitats present in the SMR at various levels of identification. This not only provides accurate baseline information that can be used to reliably detect future changes in those habitats, but also the potential to be used in conjunction with different classification schemes or ecological studies being undertaken in the region.

The drop-camera system employed in this study, which was specifically developed, enabled the camera FOV, geographic position and associated positional error and the depth of the water in which it was located to be viewed and recorded *in situ*, *i.e.* tagged to each photograph as it was taken. The desired FOV (*i.e.*  $2.4 \text{ m} \pm 25\%$ ) could thus be easily targeted for each photograph, simply by adjusting the height of the camera in the water column. This feature ensured that the benthic area captured was consistent across photographs and was as close as possible to that represented by a pixel on the Quickbird imagery. Moreover, the exact FOV was used to determine the number of grid points to be overlaid on each photograph for the calculation of the percentage contributions of each benthic habitat category. Calculating these contributions using a variable number of points with a fixed distance further ensured that this data was consistent between photographs, despite slight variations in the FOV.

An accurate recording of the geographic position and positional error of each photograph allowed it to be reliably compared to the mapped pixel to which it most likely corresponded, *i.e.* by locating it on the classified map and comparing it to a number of pixels within a radius determined by its positional error. Differences in the positional error among photographs, and thus the number of pixels permissible in the associated accuracy assessment, were due largely to the number and position of satellites available in the sky and whether a DGPS signal was available at the time of photo-acquisition.

### **4.3 Image pre-treatment**

Prior to undertaking the level 1 classification of benthic habitats in the SMR, the Quickbird images were subjected to a basic atmospheric correction to separate that portion of the radiometric signal received from atmospheric affects such as particle scattering, from that received from the water column and substrate. Ideally, the portion of the signal received from sun glint and the water column and its constituents would also be

removed to maximize that received only from the substrate (Heege *et al.* 2003). Indeed, some of the most frequent problems encountered when classifying benthic habitats in coastal waters are those associated with the confounding influence of the variable depth of the water column (Green *et al.* 1996; Mumby and Edwards 2000). In order to ameliorate this issue, a measurement of depth for each pixel is ideally required. Since the spatial resolution of the bathymetric data available to produce the digital elevation model for the SMR was not recorded at such a high spatial resolution, *i.e.* every 2.4 m, a simplified depth-correction procedure was initially undertaken for the entire set of SMR imagery (Lyzena 1978). Although this procedure has been used successfully in several other studies (e.g. Mumby *et al.* 1998; Mumby and Edwards 2000), it was unsuccessful in this case. This was due largely to the fact that the only pixels in the SMR image that could be reliably isolated in appropriate quantities, at variable depths and heterogeneous water qualities, were those representing pure sand. While pure sand pixels are certainly the easiest to distinguish from other benthic habitat types due to their highly reflective qualities, their values do not respond to changes in water depth in the same way as biotic substrate. This led to unacceptable inconsistencies in the classification of biosubstrate when the depth invariant coefficient was applied (Mumby and Edwards 2000).

In contrast, the Rottneest Island section of the SMR imagery contained sufficiently clear water and homogenous areas of macroalgae at various depths to facilitate the reliable application of the above depth correction procedure. This then enabled supervised classification of that section of the imagery to a finer scale (*i.e.* level 2, and in particular, seagrass *vs* macroalgae) of the benthic habitat classification framework. However, the benefits gained from correcting the reflectances of different benthic habitats by removing the influence of water depth, may have been outweighed by the resultant reduction in data dimensionality (*i.e.* from bands 1 and 2 to a single depth invariant band), which, in turn, may have limited the ability of the classification procedure to separate the spectra of those biotic habitats. Such issues would have contributed to the lower accuracies obtained for those maps. This problem was also highlighted by Mumby *et al.* (1998) for several other satellite images in which only one depth invariant band could be produced.

With respect to producing the map of the benthic habitats throughout the SMR at level 1 of the classification framework, the problems associated with variable water depth were best minimized by separating the images into sections that corresponded to particular depth ranges (*i.e.* 0-5 m, 5-10 m and 10-15 m), and classifying the habitats in each section separately. Thus, the unsupervised classification algorithm was applied to a reduced range of pixel values, and any errors associated with depth in the classified images were contained within a reduced area. Although several of these errors still occurred in the initial level 1 classification of the SMR (*e.g.* large groups of pixels in Cockburn Sound and around Rottnest Island that were incorrectly classified as biosubstrate), they were able to be corrected by contextual editing, *i.e.* editing in accordance with a visual comparison of the satellite imagery and field data. Contextual editing has been shown to vastly improve the accuracy of benthic habitat maps derived from satellite imagery in other studies in which basic depth corrective procedures are ineffective (Mumby *et al.* 1998). While this editing procedure only improved the accuracy of the level 1 benthic habitat classification of the SMR by 1-2% (data not shown), those areas of the map that were improved corresponded to some nearshore areas with high benthic habitat diversity and/or commercial and recreational fishing and are thus likely to be of particular importance to managers and researchers working in the region.

#### **4.4 Suggestions for future benthic habitat mapping of the SMR**

The results of this and other recent habitat mapping studies carried out in coastal waters (M. Harvey, unpubl.) suggest that the development of fine-scale and accurate benthic habitat maps, particularly over large spatial scales, requires a combination of mapping techniques. Thus, in order to develop such maps for the SMR, several different options, which will benefit from using the current broad-scale classification as a base, are suggested. However, before discussing these options, it is worthwhile addressing the benefits of employing a more precise method of image pre-treatment that has much greater potential than standard methods to remove the unwanted influence of variable water depth and quality from the original Quickbird imagery. Although expensive, and particularly for areas as large as the SMR, this recently developed method involves the use of an integrated, physically based processing chain to measure and correct the

imagery for biophysical parameters such as aerosols, sun glint, atmosphere, depth and water constituents, using the measured radiance at the sensor (Heege *et al.* 2003). Images corrected in this way prior to classification provide a considerably better basis for discerning benthic habitats at finer levels of discrimination, *i.e.* level 2 of the benthic habitat classification framework.

With respect to other mapping techniques besides those employed in the current study, a further and cost-effective possibility for producing accurate maps of finer scale benthic habitats is by employing predictive modeling techniques. Thus, various environmental measurements, which can be easily derived from the highly accurate digital bathymetric model that is a byproduct of the above water correction procedure, can be used in conjunction with the Quickbird spectral data to predict habitat occurrence over an entire area of interest based on known habitats in a subset of that area (e.g. De Maesschalck *et al.* 2000; Holmes *et al.* 2007). Finer-scale (levels 3-5) benthic habitat distinction may also be achieved using hyperspectral imagery and hydro-acoustic techniques, although they are likely to be useful only in particular parts of the SMR, *e.g.* particularly diverse areas, due to the high costs associated with acquiring this data.

In conclusion, the benthic habitat database produced in this study containing the broad-scale benthic habitat map, ground validation data, associated photographic samples and their percentage contributions of benthic habitats at successively finer levels of classification, provide managers and researchers working in this region with a sound basis for (1) developing fine-scale benthic habitat maps for the SMR (*i.e.* those based on levels 2-5 of the classification framework), (2) consistently identifying both unique and representative habitat types across the SMR at a range of scales that pertain to various levels of management or research and (3) incorporating existing spatially-explicit faunal assemblage data and designing further faunal sampling regimes. Such a basis will facilitate further research into ascertaining the relationships that exist between the marine environment and its biota, predicting the types of fauna that are likely to occur in any nearshore location and developing strategies for conserving biodiversity and managing the natural resources in the SMR.

The above tools will greatly contribute to achieving Resource Condition Targets CMR2 and CMR3 established by the Swan Catchment Council, *i.e.* the condition of

marine habitats and fauna, respectively in the SMR, as measured at representative sites be maintained and improved, by 2020. Moreover, it ensures that other important targets set by the Swan Catchment Council, *i.e.* determination of key indicator species (CMM3.1-MAT) and identification of 100% of priority marine habitats for protection (CMM2.1-MAT) are able to be reliably addressed.

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## APPENDIX 1

### ArcView 9.1 Benthic habitat database: List of component files.

N.B. All files were projected to UTM 50S, WGS84

Layer Title in ArcView Project	File Directory	File Type	Layer Description
SMR Level 1 Classification	SMR Project\Classifications\Level1\smr_0_15	ESRI Grid	Classification based on a k-means cluster analysis, originally carried in ENVI v3.4 on depth categorised Quickbird data.
Rottest Island Level 2 Classification (euclidean)	MR Project\Classifications\Level2\rotto_euclid	ESRI Grid	Supervised classification of seagrass and macroalgae for the Rottest Island section of the SMR using minimum distance algorithm (euclidean distance measure). Undertaken in ArcView 3.2. on depth corrected (modified Lyzenga, 1974) Quickbird data.
Rottest Island Level 2 Classification (mahalanobis)	SMR Project\Classifications\Level2\rotto_mahal	ESRI Grid	Supervised classification of seagrass and macroalgae for the Rottest Island section of the SMR using minimum distance algorithm (mahalanobis distance measure). Undertaken in ArcView 3.2 on depth corrected (modified Lyzenga, 1978) Quickbird data.
Rottest Bare Substrate Polygon	SMR Project\Level1_Class_Polys\FINAL_ROTTO_SAND_POLY.shp	Polygon Shapefile	Provided for display with the Rottest level 2 classifications
Rottest Island Land Polygon	SMR Project\Level1_Class_Polys\rotto_land_poly.shp	Polygon Shapefile	Provided for display with the Rottest level 2 classifications
Rottest Island Breaking Reefs Polygons	SMR Project\Level1_Class_Polys\rotto_reef_poly.shp	Polygon Shapefile	Provided for display with the Rottest level 2 classifications
SMR Polygon	SMR Project\SMR_shapefiles\swan_region_poly.shp	Polygon Shapefile	The Swan Marine Region polygon file
SMR 0-15 m Mapping Area	SMR Project\SMR_shapefiles\SMR_0_15_poly.shp	Polygon Shapefile	Areas within the SMR < 15 m depth
5km sampling grid	SMR Project\Field_sampling_regime\5kmgrid.shp	Polygon Shapefile	Grid system used to divide the SMR into large sampling units. Each grid is 5 x 5 km square.
Sampled grids	SMR Project\Field_sampling_regime\samplegrids.shp	Polygon Shapefile	Grids chosen for sampling from the 5 x 5 km grid sampling system
SMR field samples (level 1)	SMR Project\Field_samples\SMR_Level_1_field_samples.shp	Polygon Shapefile	Benthic habitat % contribution data for all field samples at level 1 of the benthic habitat classification framework. Samples are displayed as circles with variable radii, each determined by the positional error of the sample.

SMR field samples (level 2)	SMR Project\Field_samples\SMR_level2_field_samples.shp	Polygon Shapefile	Benthic habitat % contribution data for all field samples at level 2 of the benthic habitat classification framework. Samples are displayed as circles with variable radii, each determined by the position error of the sample.
SMR field samples (All Levels)	SMR Project\Field_samples\smr_all_levels.shp	Point Shapefile	Benthic habitat % contribution data for all field samples at each level of the benthic habitat classification framework. Each sample is displayed simply as the point at which it was located. * Further detail on the structure of this file is presented in Appendix 2.
Level 1 Accuracy Assessment Results	SMR Project\Accuracy_assessment\smr_0_15_SMRV1_Level_1_polygon_001\Results.shp	Point Shapefile	Results based on the error matrix that was constructed for the assessment of the level 1 benthic habitat classification. The legend categories refer to the results of matching pixels and samples, e.g. the bare_bare category infers that a pixel was classified as bare and its corresponding field sample was also bare .
SMR Imagery	SMR Project\SMR_image\test9.bil	Point Shapefile	The Quickbird imagery displayed as a 24 m resolution scaled mosaic.

## APPENDIX 2

### Field categories for the benthic habitat database layer “SMR field samples All levels (smr\_all\_levels.shp)”

Field Name	ArcView Field Name	Description
Record Number	RecNo	The record number within the database
Unique ID	UniqueID	The unique ID for each point that links it with it's photo
System Time	systemTime	System Time
GPS Time in UTC	gpsTimeUTC	GPS Time in UTC
Sample File	sampleFile	The file name of photographic sample
Transect tID	transectID	Transect identification number on day of acquisition
Sample Count	samp_count	The sample number of the photograph on day of acquisition
Latitude	latitude	Latitudinal coordinate for the photograph
Longitude	longitude	Longitudinal coordinate for the photograph
GPS Fix	gpsFix	GPS coordinates of photograph
GPS Number of Satellites	Num_satel	Number of satellites for gpsfix at time of photo-acquisition
GPS HDOP	gpsHDOP	Positional error of gpsfix at photo-acquisition
Water Depth	waterDepth	Depth of the water column in which the photograph was taken
Camera Depth	Cam_depth	Depth of the camera below the surface
Camera Height	Cam_height	Height of the camera above the sea floor
Field of View	FOV	Field of view of the photograph at its widest point
Number of points	NoPoints	No of points used to analyse the % contributions of each benthic substrate in the photograph
Area	Area	Benthic area captured in each photograph
Level 1 Classification	Level1	Indicates whether classification was achieved at level 1 of the benthic habitat classification framework (BHCF) 1=achieved, 2= not achieved
Unidentified Level 1	Unident1	% Unidentified benthic habitat at level 1 of the BHCF
Bio-substrate	Biosub1	% Bare substrate present in each photo
Bare substrate	Bare_sub1	% Biosubstrate present in each photo
Level 2 Classification	Level2	Indicates whether classification was achieved at level 2 of the benthic habitat classification framework (BHCF) 1=achieved, 2= not achieved

Unidentified Level 2	Unident2	% Unidentified benthic habitat in each photo
Macroalgae	Macroalga2	% Macroalgae present in each photo
Seagrass	Seagrass2	% Seagrass present in each photo
Coral	Coral2	% Coral present in each photo
Sponge	Sponge2	% Sponge present in each photo
Rhodoliths	Rhodolith2	% Rhodoliths present in each photo
Wrack	Wrack2	% Wrack present in each photo
Sand	Sand2	% Sand present in each photo
Rock	Rock2	% Rock present in each photo
Coral Rubble	Coral_rub2	% Coral Rubble present in each photo
Gravel	Gravel2	% Gravel present in each photo
Mud	Mud2	% Mud present in each photo
Level 3 Classification	Level3	Indicates whether classification was achieved at level 3 of the benthic habitat classification framework (BHCF) 1=achieved, 2= not achieved
Unidentified Level 3	Unident3	% Unidentified benthic habitat in each photo
Canopy Macroalgae	Can_macro3	% Canopy Macroalgae present in each photo
Mid-story Macroalgae	Mid_macro3	% Mid-Story Macroalgae present in each photo
Understory Macroalgae	Und_macro3	% Understory Macroalgae present in each photo
Straplike seagrass	Strap_sea3	% Straplike Seagrass present in each photo
Lignified seagrass	Lig_sea3	% Lignified Seagrass present in each photo
Foliose seagrass	Folio_sea3	% Foliose Seagrass present in each photo
Scleractian Coral	Scer_cora3	% Sceractinian Coral present in each photo
Sponge	Sponge3	% Sponge present in each photo
Rhodoliths	Rhodolith3	% Rhodoliths present in each photo
Wrack	Wrack3	% Wrack present in each photo
Sand	Sand3	% Sand present in each photo
Rock	Rock3	% Rock present in each photo
Coral Rubble	Coral_rub3	% Coral Rubble present in each photo
Gravel	Gravel3	% Gravel present in each photo
Mud	Mud3	% Mud present in each photo
Level 4 Classification	Level4	Indicates whether classification was achieved at level 4 of the benthic habitat classification framework (BHCF) 1=achieved, 2= not achieved
Unidentified Level 4	Undent4	% Unidentified benthic habitat in each photo

Ecklonia	Ecklonia4	% Ecklonia present in each photo
Sargassum	Sargassum4	% Sargassum present in each photo
Cystophora	Cystophor4	% Cystophora present in each photo
Scytothalia	Scytothal4	% Scytothalia present in each photo
Heterokontophyta	Heterokon4	% Heterokontophyta present in each photo
Chlorophyta	Chlorophy4	% Chlorophyta present in each photo
Rhodophyta	Rhodophyt4	% Rhodophyta present in each photo
Turf	Turf4	% Turf present in each photo
Coralline algae	Coral_alg4	% Coralline algae present in each photo
Posidonia	Posidonia4	% Posidonia present in each photo
Zostera	Zostera4	% Zostera present in each photo
Amphibolis	Amphib4	% Amphibolis present in each photo
Halophila	Halophila4	% Halophila present in each photo
Acropora corals	Acrop_cor4	% Acropora corals present in each photo
Non-Acropora	Non_acrop4	% Non-Acropora corals present in each photo
Alcyonacea_Soft Corals	Soft_cora4	% Alcyonacea (soft corals) present in each photo
Gorgonacea_Sea Fans	Sea_fan4	% Gorgonacea (sea fans) present in each photo
Sponge	Sponge4	% Sponge present in each photo
Rhodoliths	Rhodolith4	% Rhodoliths present in each photo
Wrack	Wrack4	% Wrack present in each photo
Sand	Sand4	% Sand present in each photo
Rock	Rock4	% Rock present in each photo
Coral Rubble	Coral_rub4	% Coral Rubble present in each photo
Gravel	Gravel4	% Gravel present in each photo
Mud	Mud4	% Mud present in each photo
Level 5 Classification	Level5	Indicates whether classification was achieved at level 5 of the benthic habitat classification framework (BHCF) 1=achieved, 2= not achieved
Unidentified Level 5	Undent5	% Unidentified benthic habitat in each photo
Ecklonia radiata	Ecklonia5	% Ecklonia radiata present in each photo
Sargassum	Sargassum5	% Sargassum present in each photo
Cystophora	Cystophor5	% Cystophora present in each photo
Scytothalia dorycarpa	Scytothal5	% Scytothalia present in each photo

Heterokontophyta	Heterokon5	% Heterokontophyta present in each photo
Chlorophyta	Chlorophy5	% Chlorophyta present in each photo
Rhodophyta	Rhodophyt5	% Rhodophyta present in each photo
Turf	Turf5	% Turf present in each photo
Articulated coralline	Artic_cor5	% Articulated coralline algae present in each photo
Encrusting coralline	Encr_cor5	% Encrusting coralline algae present in each photo
Posidonia australis	P_austral5	% Posidonia australis present in each photo
Posidonia sinuosa	P_sinuosa5	% Posidonia sinuosa present in each photo
Posidonia coriacea	P_coriac5	% Posidonia coriacea present in each photo
Zostera spp.	Zostera5	% Zostera present in each photo
Heterozostera tasmanica	Heter_tas5	% Heterozostera tasmanica present in each photo
Amphibolis griffithii	Amphib_gr5	% Amphibolis griffithii present in each photo
Amphibolis antarctica	Amphib_an5	% Amphibolis antarctica present in each photo
Halophila	Halophila5	% Halophila present in each photo
Acropora corals	Acrop_cor5	% Acropora corals present in each photo
Non-Acropora	Non_acrop5	% Non-Acropora corals present in each photo
Alcyonacea_Soft Corals	Soft_cora5	% Alcyonacea (soft corals) present in each photo
Gorgonacea_Sea Fans	Sea_fan5	% Gorgonacea (sea fans) present in each photo
Sponge	Sponge5	% Sponge present in each photo
Rhodoliths	Rhodolith5	% Rhodoliths present in each photo
Wrack	Wrack5	% Wrack present in each photo
Sand	Sand5	% Sand present in each photo
Rock	Rock5	% Rock present in each photo
Coral Rubble	Coral_rub5	% Coral Rubble present in each photo
Gravel	Gravel5	% Gravel present in each photo
Mud	Mud5	% Mud present in each photo