FAO Fisheries and Aquaculture Circular No. 1057 FIRF/C1057 (En)

ISSN 2070-6065

ESTIMATING REEF HABITAT COVERAGE SUITABLE FOR THE HUMPHEAD WRASSE, *CHEILINUS UNDULATUS*, USING REMOTE SENSING

Copies of FAO publications can be requested from:
Sales and Marketing Group
Office of Knowledge Exchange, Research and Extension
Food and Agriculture Organization
of the United Nations
E-mail: publications-sales@fao.org
Fax: +39 06 57053360
Web site: www.fao.org/icatalog/inter-e.htm

FAO Fisheries and Aquaculture Circular No. 1057 FIRF/C1057 (En)

ESTIMATING REEF HABITAT COVERAGE SUITABLE FOR THE HUMPHEAD WRASSE, *CHEILINUS UNDULATUS*, USING REMOTE SENSING

by

Axel Oddone
FAO Consultant
Rome, Italy

Roberta Onori
"La Sapienza" University of Rome
Rome, Italy

Fabio Carocci
Fisheries Management and Conservation Service
Fisheries and Aquaculture Department
Food and Agriculture Organization of the United Nations
Rome, Italy

Yvonne Sadovy
Department of Ecology and Biodiversity
University of Hong Kong
China, Hong Kong Special Administrative Region

Sasanti Suharti
Research Center for Oceanography
Indonesian Institute of Sciences
Jakarta, Indonesia

Patrick L. Colin
Coral Reef Research Foundation
Koror, Palau

Marcelo Vasconcellos
Institute of Oceanography
Federal University of Rio Grande
Rio Grande, Brazil

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2010

ISBN 978-92-5-106621-8

PREPARATION OF THIS DOCUMENT

The Napoleon fish (humphead wrasse) was listed in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II in 2004. Following listing, different efforts were directed towards developing approaches to assist range States in addressing CITES non-detriment finding requirements. In 2007 FAO published Fisheries Circular No. 1023 which elaborated a stock assessment method for estimating sustainable catch levels for the species in areas where estimates of reef area and fish densities are available. The lack of accurate estimates of reef areas suitable for the species was recognized as an important source of uncertainty for using the method in many range States. In view of this and of recent developments in the use of remote sensing techniques in mapping shallow water coral reefs, this study was commissioned to evaluate whether reliable estimates of humphead wrasse habitat coverage could be obtained using available satellite images. This study was funded by FAO regular programme and by the FAO Trust Fund Project (GCP/INT/987/JPN) "*CITES and Commercially-exploited Aquatic Species, Including the Evaluation of Listing Proposals*".

Oddone, A., Onori, R., Carocci, F., Sadovy, Y., Suharti, S., Colin, P. L., and M. Vasconcellos.
Estimating reef habitat coverage suitable for the humphead wrasse, *Cheilinus undulatus*, using remote sensing.
FAO Fisheries and Aquaculture Circular. No. 1057. Rome, FAO. 2010. 27p.

ABSTRACT

This study evaluates the use of satellite images for mapping shallow reef areas and the habitat of humphead wrasse. A method for mapping the suitable habitat for adult humphead wrasse is developed based on the location of reef edges on available Landsat images and on the application of a buffer area around the edges, where the probability of finding adult humphead wrasse is highest according to Underwater Visual Survey (UVS) data. The method is used to estimate the habitat coverage of the species in Indonesia, Malaysia and Papua New Guinea, three of the most important exporting countries of the species. The total estimated habitat coverage was 11 892 km^2 in Indonesia, 941 km^2 in Malaysia and 5 254 km^2 in Papua New Guinea. The estimates for Indonesia and Malaysia are approximately four times smaller than other available estimates of reef coverage for these countries, the difference being explained by the higher accuracy of the method used in the present study in identifying the location of shallow water fringing reefs. It is concluded that, for the purpose of estimating the suitable areas of humphead wrasse as a basis for defining population size and sustainable export quotas, the results obtained in the present study are more conservative and appropriate than previously available estimates of reef areas.

CONTENTS

TABLES

FIGURES

1. INTRODUCTION

Global and regional estimates of coral reef areas are of considerable value in different fields, including fisheries assessment, marine conservation and environmental change. Despite this, the available estimates of reef areas vary substantially, partly due to divergences in the definition of reef habitats but also because of lack of information about reef coverage and of cost-effective methods of reef mapping.

An innovative method for reef mapping has been proposed involving the use of available (free) Landsat satellite images of coastal areas and Geographical Information Systems. This method, so far used to produce maps of geomorphological classes of reefs in selected areas of the world (Andrefouet *et al*., 2004), has the potential to be used in the assessment of the coverage of reef fish habitat. This information is particularly needed in the assessment of reef associated fish stocks in data-limited areas. In this study remote sensing techniques are used to evaluate the habitat coverage of the humphead wrasse, *Cheilinus undulatus*. However, the method is expected to be widely applied to other tropical fish stock assessments and to influence the design of marine protected areas and other spatial measures for marine ecosystems conservation.

The humphead wrasse, *Cheilinus undulatus*, is the largest living member of the Labridae family, with a maximum size exceeding two metres and 190 kg (Sadovy *et al*., 2003). Its geographic range covers much of the Indo-Pacific. The species is not common, recorded maximum adult densities rarely exceeding 20 fish/10 000 m^2 and usually at least half this density (Sadovy *et al*., 2003). Small individuals are typically associated with high coral cover; larger fish are found singly or in small groups mainly on outer or deep reefs, seagrasses, steep slopes and passes, where they also spawn.

Humphead wrasse is a small but important part of the overall trade in live reef food fish. Although the fish is not even close to being the most important species in terms of volume in the China–Hong Kong Special Administrative Region (SAR) market, it is one of the highest in unit value. The total recorded international live trade in this species ranged from about 58 to 138 tonnes for the years 2000–2006. Although humphead wrasse occurs in the waters of 48 countries, the important suppliers of this fish to live trade are limited to a few countries in Southeast Asia and Papua New Guinea where a major percentage of their coral reef habitat occurs. In addition to its role in the live reef food fish trade, the humphead wrasse is valued for several reasons, especially for local food and for its role in dive tourism (Gillett, 2010).

The humphead wrasse was the first coral reef fish to be listed on CITES Appendix II (2004). Before issuing an export permit for a CITES Appendix II species, exporting countries must determine whether the volume of export will be detrimental to the survival of the species in the wild. A Non-Detriment Finding (NDF) requirement is therefore needed for countries exporting humphead wrasse. This requirement involves several facets, including a scientific basis for the level of removals. To this end Sadovy *et al*. (2007) developed a stock assessment approach for the humphead wrasse where an age-, sex- and size-structured population model is used to estimate an "optimal" exploitation rate for the species. Model outputs are combined with estimates of population densities, obtained from Underwater Visual Surveys (UVS), habitat size and fish removals (legal and illegal) to calculate a sustainable level of export. One of the key points of information needed in the approach is an estimate of the habitat area of the species, which is used to estimate population size from site-specific densities.

The objective of this study was first to evaluate whether remote sensing techniques could be used to provide a precise and cost-effective means of estimating the area coverage of shallow coral reefs. The second objective was to determine a methodology that enables the use of available satellite imagery and field data to estimate the coverage of reef areas suitable for the humphead wrasse. The methodology developed is finally used to estimate the approximate total area of coral reef habitat suitable for humphead wrasse in Indonesia, Malaysia and Papua New Guinea, three of the most important exporting countries of the species.

1.1 Applicability of satellite images to the mapping of coral reefs

The launch of the Landsat 1 satellite on 23 July 1972 opened the era of commercial Earth Observation. Since that year many different satellites, originating from different countries and carrying different sensors, began populating the sky and continuously monitoring the planet. Yet each satellite is unique in the characteristics of its sensors, built to satisfy certain specific applications. In this regard commercial satellites can be divided into four classes:

1. optical low resolution satellites
2. optical medium resolution satellites
3. optical high resolution satellites
4. radar satellites, with low to medium resolution

For the purposes of this study the radar sensors were not suitable, as their signals are not able to penetrate the water to allow the identification of reef areas, even though they have the great advantage of imaging through clouds, a continuous presence in tropical areas.

Optical low resolution satellites are generally equipped with multi-band sensors, yet their low resolution (in the range of 500–1 000 metres) does not give the required detail needed to define the habitat of a reef fish. High resolution satellites (2.5 to 0.6 metre resolution), on the other hand, are probably the best source of information, but their very small coverage (max 16.5 x 16.5 km images) in addition to their high cost make them an impractical solution for the mapping of large areas.

The best solution is to use medium resolution optical satellites, with a resolution in the range of 10–30 metres. Unfortunately almost all the satellites in this class are mainly designed for land applications (especially agriculture) and therefore have sensors designed to look more into the Near-Infrared range (0.75 to 1.4 micrometers) than into the visible range (0.38 to 0.75 micrometres), thus reducing their suitability for sea applications. As a matter of fact the French SPOT constellation, the Indian IRS constellation, the English DMC and the Japanese Terra/Aster sensors do not have a Blue band in their multispectral sensors, eliminating the ability to read information from water bodies. Figure 1 demonstrates how water reflection is almost zero in the Near-Infrared range, where vegetation has its peak of reflection.

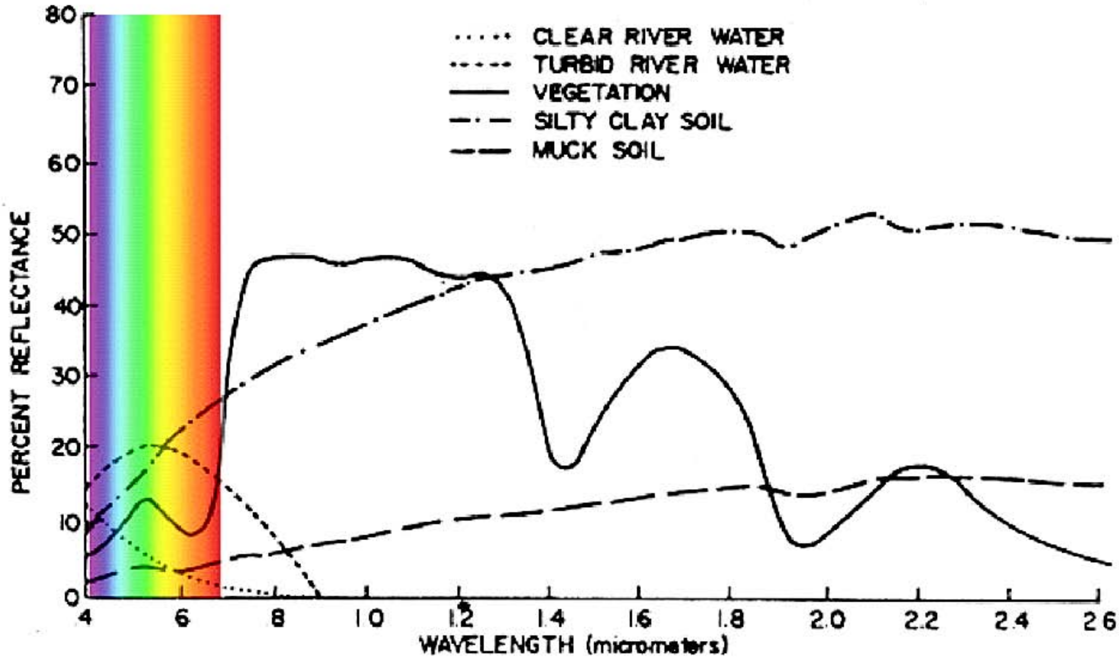

Figure 1: Examples of spectral signatures of different objects, i.e. the percentage of sun energy reflected at the different wavelengths of the electromagnetic spectrum (*modified from:* www.fao.org/docrep/003/W0615E/W0615E21.gif).

There is only one medium resolution mission that has always carried a sensor that can read information from the Blue band, and this is the long-running US Landsat project. This satellite has been the major source of satellite-based reef classifications in recent years, and although the two active satellites (Landsat 5 and Landsat 7) are facing some technical problems, they will continue to be the major source of detailed information from water bodies for many years to come.

It is expected that the ability to use satellite images to map coral reefs and other aquatic habitats and features will improve in the near future with the launching of new sensors. In particular the launch of new high resolution sensors with increased agility and higher acquisition rates (e.g. WorldView-2, launched in 2009, with an eight-band Multispectral sensor including a dedicated “Coastal band” in the range of 420–450 nm) will reduce the impact of their small swaths. In the next few years there will also be new medium resolution satellites (with Blue bands), including the English Rapid Eye constellation of four satellites at 6.5 metre resolution that will allow a daily revisit and the ESA’s Sentinel 2 constellation, that will guarantee a 5-day continuous monitoring of the whole Earth with a resolution up to 10 metres.

1.2 Some technical details of Landsat satellites

Landsat satellites have been operative since 1972, and at present there are two working satellites: Landsat 5, launched in 1984 and carrying the Thematic Mapper (TM) sensor, and Landsat 7, launched in 1999 and carrying an Enhanced version of the same sensor (ETM+). Both satellites are able to provide a 30-metre resolution multispectral image of the Earth every 16 days, covering a swath of about 180 km (Table 1).

Table 1: Technical details about the different sensors onboard the Landsat 5 and Landsat 7 satellites.

Band number	**Band type**	**Spectral range (μm)**	**TM (resolution m)**	**ETM+ (resolution m)**
1	Blue	0.45–0.52	30	30
2	Green	0.52–0.60	30	30
3	Red	0.63–0.69	30	30
4	NIR	0.76–0.90	30	30
5	NIR	1.55–1.75	30	30
6	TIR	10.42–12.50	120	60 (*)
7	SWIR	2.08–2.35	30	30
8	PAN	0.52–0.90		15

(*) = available in both High and Low gain

Unfortunately on 31 May 2003 the Landsat 7 experienced a major instrument anomaly (failure of the instrument's scan line corrector, SLC), and as a result is no longer operational. For this reason the old Landsat 5 is now the main source of data, and even if it has a reduced functionality due to some problems with the solar panels and a partial degradation of the sensor, after 23 years of activity it is still acquired by many stations all over the world. Note that Landsat 7 has an on-board memory that allows it to acquire images everywhere in the world through the United States Geological Survey (USGS) long-term acquisition plan, while Landsat 5 has no on-board memory and therefore is dependent on the availability of a receiving station, which means that it can only acquire images over the footprints of the available receiving stations (Figure 2).

In 1998 NASA decided to create a set of the best Landsat TM and MSS (Multispectral Scanner System) images available on a world-wide basis, and to make it available to the research community for free. This TM and MSS dataset has also been integrated with Landsat 7 ETM+ world coverage, created using images acquired around the year 2000, with the lowest possible cloud cover and geo-referenced with an error of about 50 m.

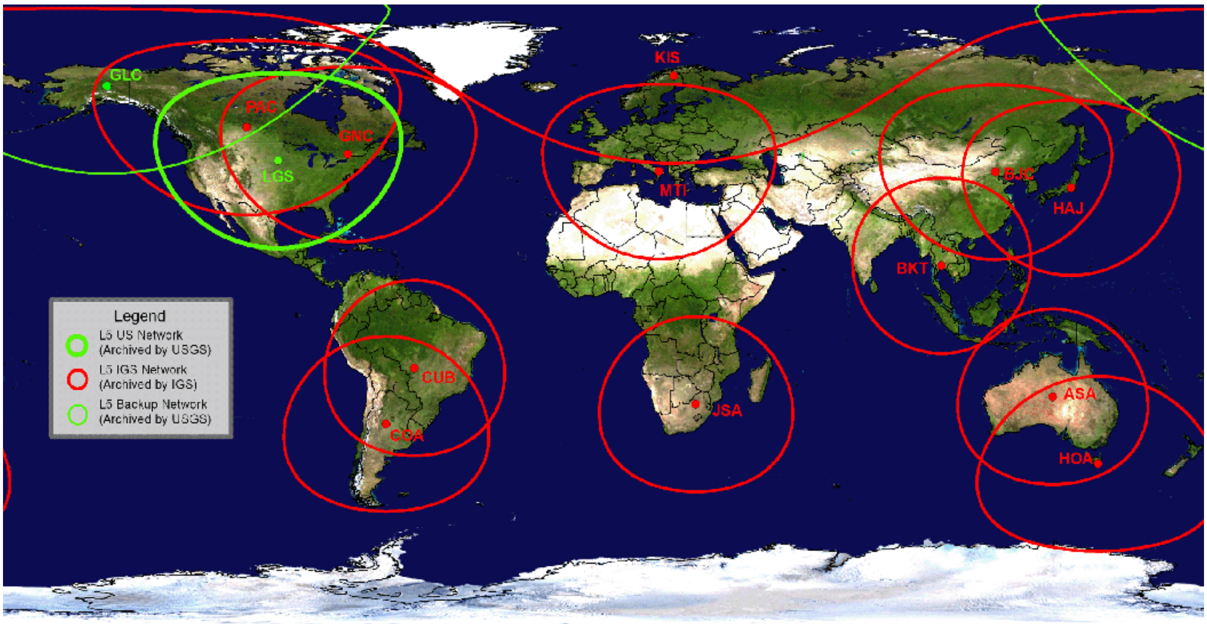

Figure 2: Map showing the extension of the footprints of the Landsat 5 receiving stations presently active all over the world (http://landsat.usgs.gov/about_ground_stations.php).

By using a consistent dataset of these multispectral Landsat 7 images acquired between 1999 and 2003, the Institute for Marine Remote Sensing at the University of South Florida is developing the first global uniform map of shallow coral reef ecosystems. This initiative, called Millennium Coral Reef Program, aims to highlight similarities and differences between reef structures on a scale never before considered by traditional work based on field studies (Sadovy, 2005). The project has included an unprecedented standardization of geomorphological structures for reefs around the world. The goal of the Program is “to provide a reliable, spatially constrained data set for biogeochemical budgets, biodiversity assessment, reef structure comparisons and also new high-quality information for reef managers about reef location, distribution and extent”. One limitation of the program with regard to the objectives of the present study is that it provides vector maps of geomorphological coral reef structures which are of little use in defining the reef habitat for humphead wrasse.

2. METHODOLOGY

The present study consisted of two phases. First a test study was conducted to evaluate whether Landsat 7 images could be used to identify the habitat of humphead wrasse in Indonesia. To perform this study a set of satellite images was collected for six areas in Indonesia that have been surveyed for humphead wrasse using UVS (Figure 3, Sadovy, 2005). The second phase of the study applied the methodology developed in the test phase to calculate the suitable habitat areas for humphead wrasse in Indonesia, Papua New Guinea and Malaysia.

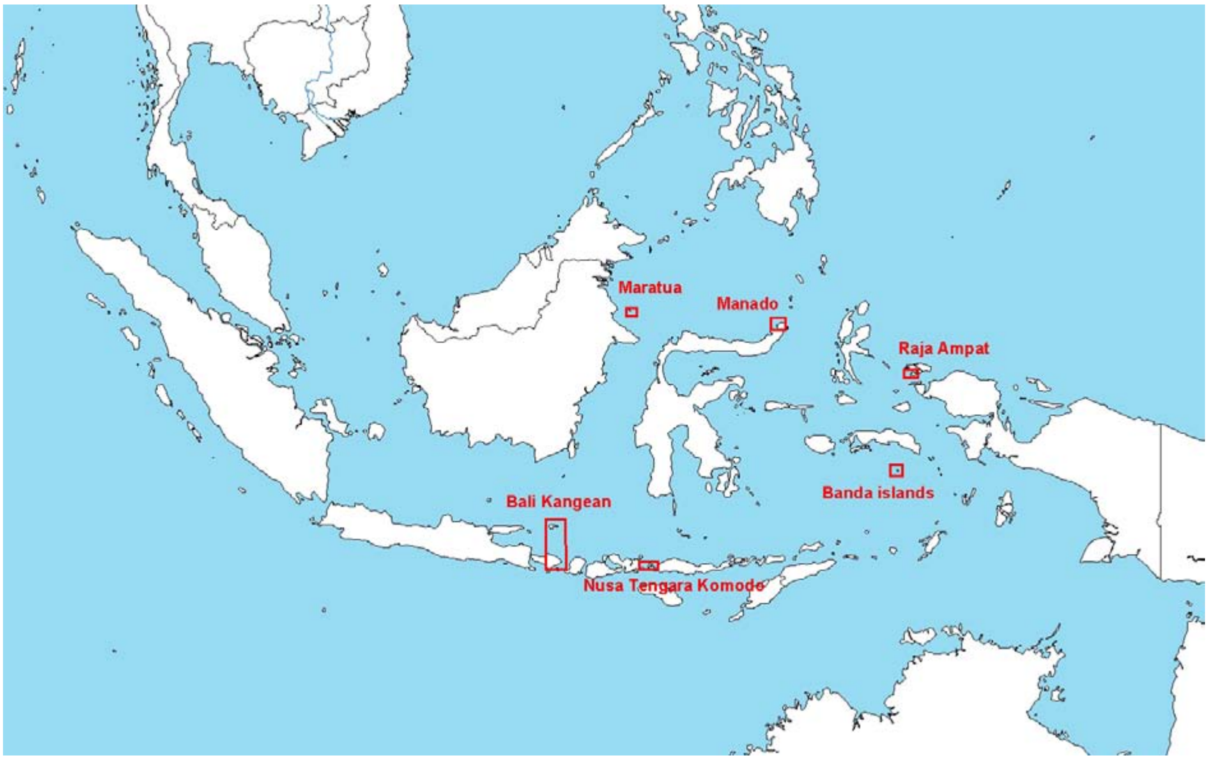

Figure 3: Map showing the extension of the six surveyed areas in Indonesia analysed in this study.

To perform the initial study, all the Landsat 7 images available in the Millennium Coral Reef website (http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl) over the six surveyed areas were downloaded. In total twelve Landsat 7 images were used (Table 2 and Figure 4). Every Landsat image is identified by three numbers that define it in a unique way:

- Track: this number refers to the satellite orbit and can be generalized as the "longitude" of the image.
- Frame: this number represents the reference scene along the orbit and can be generalized as the "latitude" of the image.
- Acquisition date: the obvious parameter that differentiates all the Landsat scenes acquired over the same area (i.e. same track and frame).

The Landsat images were imported into the ERDAS Imagine format, a format which allows a quick display thanks to the pyramid layer approach and which is fully compatible with ESRI ArcGIS, which was the main software used for this study.

Of the eight available bands (see Table 1) only four were imported and used in this study because of their suitability to the analysis of sea spaces: blue (1), green (2), red (3) and near infrared (4) bands. The images were generally displayed with a Natural Colour combination (RGB = 321) or with a False Infrared combination (RGB = 432) (Figures 5 and 6).

Table 2: List of the 12 Landsat 7 scenes used over the six surveyed areas. In the Banda Islands survey area there are two Landsat 7 scenes on the same track/frame (107-63). This is due to the fact that there were no cloud free images available, and therefore NASA provided the two best acquisitions available.

Track number	Frame number	Acquisition date
Test area: Bali Kangeam		
116	65	19 August 2000
116	66	19 August 2000
117	65	9 September 1999
Test area: Banda Islands		
107	63	6 July 2001
107	63	26 October 2001
108	63	11 August 2000
Test area: Manado		
111	59	18 July 2001
112	59	20 April 2001
Test area: Maratua		
116	58	6 August 2001
116	59	15 May 2000
Test area: Nusa Tengara Komodo		
114	66	20 July 2000
Test area: Raja Ampat		
108	60	26 September 1999

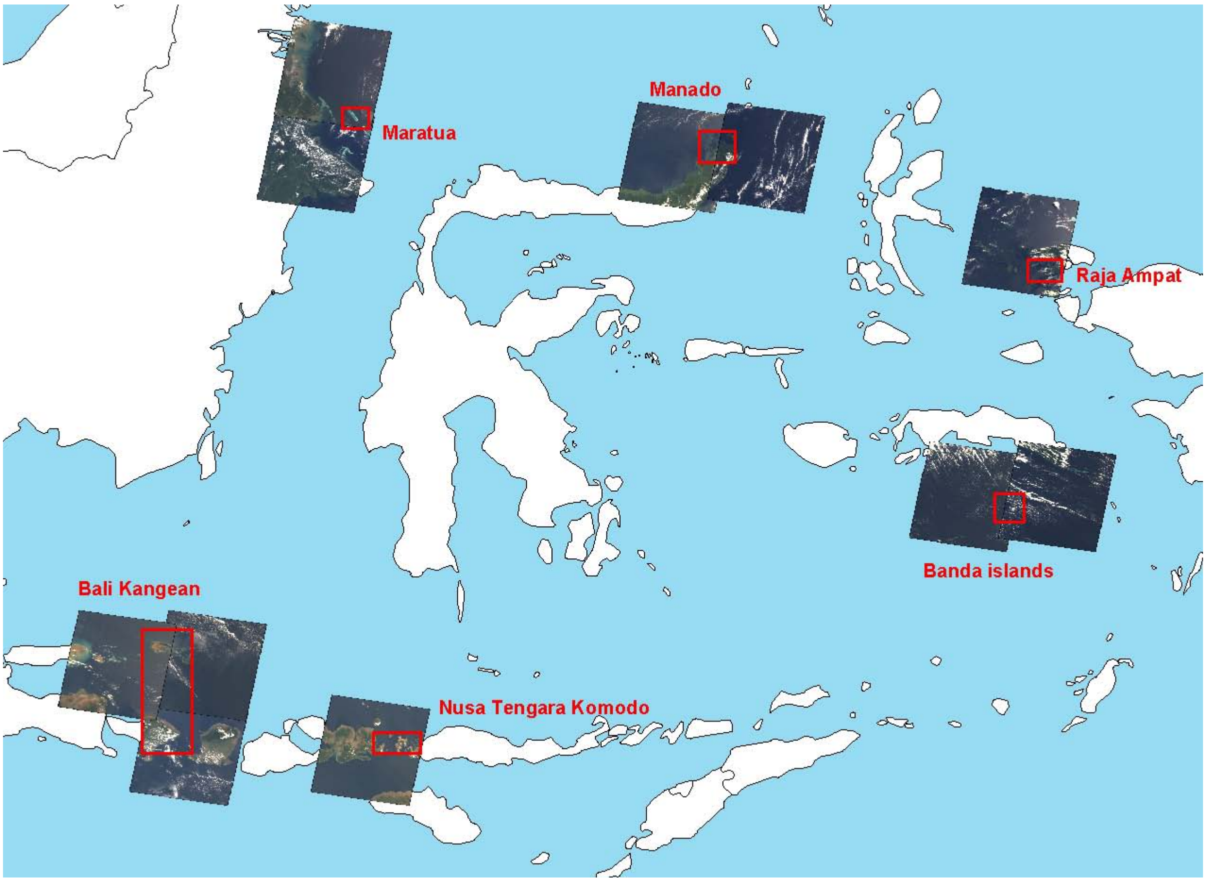

Figure 4: Map showing the 12 Landsat 7 scenes and the extension of the six test areas.

Figure 5: Landsat 7 image over the Maratua atoll displayed with a Natural Colour (RGB=321) band combination.

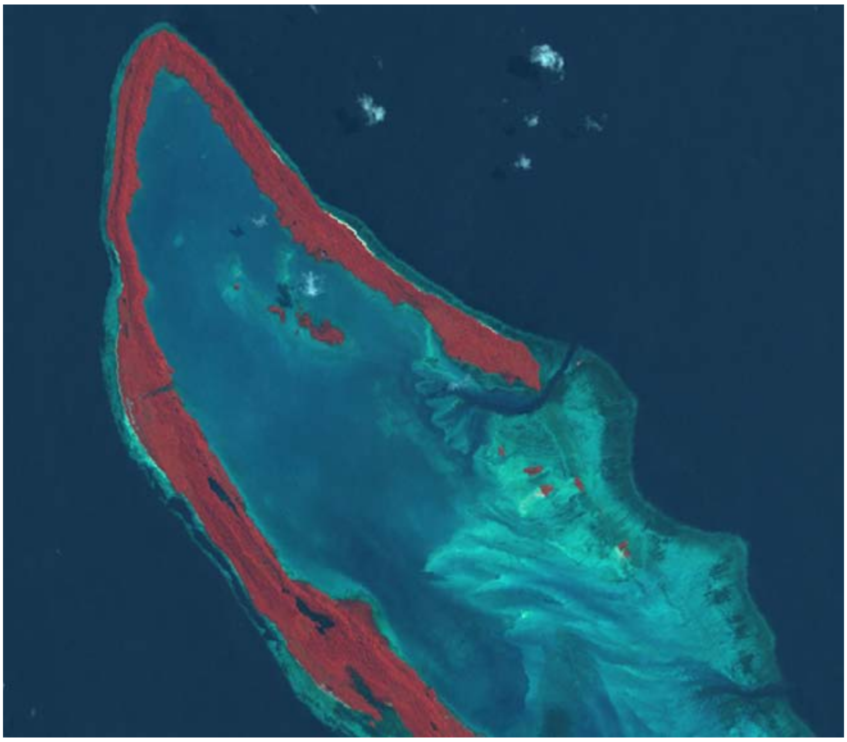

Figure 6: Landsat 7 image over the Maratua atoll displayed with a False InfraRed Colour (RGB=432) band combination; under this colour combination the vegetation becomes red because of the high reflection in the infrared range.

For comparative purposes, two other types of satellite images were obtained over the Maratua area: a SPOT-2 and a QuickBird scene (Figures 7 and 8 respectively). The SPOT-2 scene (provided by courtesy of SpotImage) was acquired on 17 July 2001 and is composed of three bands (green, red and near infrared) with 20 metre resolution. The QuickBird scene (provided courtesy of DigitalGlobe) was acquired on 8 December 2006 and is composed of two images: a Panchromatic image at 60 cm resolution and a four-band (blue, green, red and near infrared) multispectral image at 2.4 metre resolution. The geolocation accuracy of this product (Standard Ortho-Ready processing) is 23 metres (circular error, CE 90%). Using the algorithm created by Dr. Yun Zhang of the University of New Brunswick (available using PCI software), the two QuickBird images were merged creating a four-band pan-sharpened product at 60 cm resolution. All the SPOT and QuickBird images were also imported into the ERDAS Imagine format.

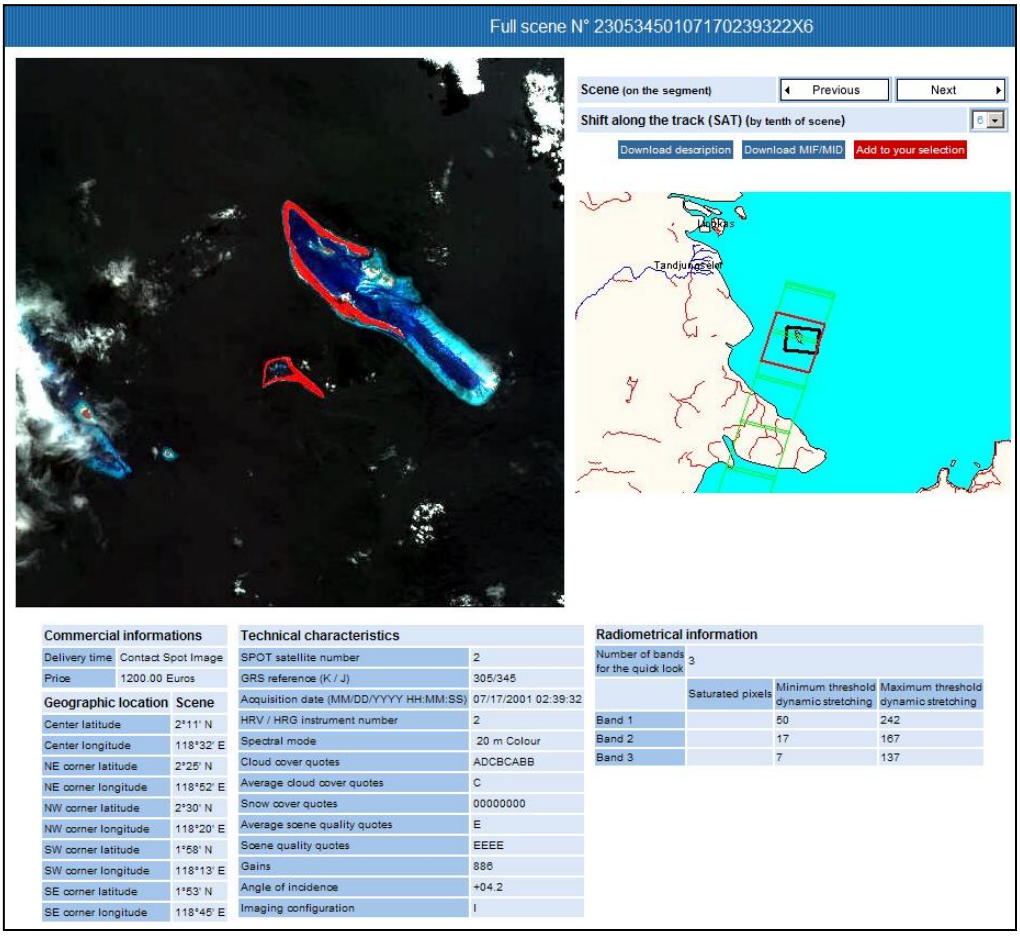

Figure 7: Technical details of the SPOT-2 satellite image of the Maratua area.

2.1 Ground surveys in Indonesia

Between 2005 and 2006 UVS were conducted in six areas of Indonesia to estimate humphead wrasse densities in areas with contrasting levels of fishing exploitation. The diving team used a floating GPS that allowed a detailed tracking of the diving paths (every 15 seconds the GPS systems recorded the position of the diver, with an expected accuracy of a dozen metres). All the GPS measured coordinates were transformed into Environmental Systems Research Institute, Inc. (ESRI) shape files, one for each survey area. The surveys were made in areas that showed all the typical aspects of the habitat of the humphead wrasse with a focus on adult habitat. Divers recorded the position of all humphead wrasse encountered during the surveys. Table 3 lists the dates of the surveys in each area and Figure 9 shows an example of a survey conducted in the Banda Islands.

Figure 8: QuickBird satellite image of the Maratua area.

2.2. Definition of the humphead wrasse habitat

Humphead wrasse is usually found in association with well-developed coral reefs (Sadovy *et al*., 2003). Juveniles occur in coral-rich areas of lagoon reefs, particularly among live thickets of staghorn *Acropora* sp. corals, in seagrass beds, murky outer river areas with patch reefs, shallow sandy areas adjacent to coral reef lagoons and in mangrove and seagrass areas inshore. Fish tend to move into deeper waters as they grow older and larger. Adults are more common offshore than inshore; their preferred habitat being steep outer reef slopes, reef drop-offs, passes and tops, channel slopes, where they also reproduce, and lagoon reefs to a depth of at least 100 m. They are typically found in association with well-developed coral reefs and may be somewhat sedentary, i.e. the same individuals may be seen along the same stretch of reef for extended periods. Indeed, many commercial dive sites have their "resident" humphead wrasse, a favourite species for divers in many areas. Population densities are never high, even in preferred habitats. For example, in unfished or lightly fished areas, adult fish densities may range from 2 to 20 (but rarely >10) individuals per 10 000 m^2 of reef (Sadovy *et al*., 2003). This is very low for a commercially targeted reef species and is more akin to densities of large terrestrial animals. In heavily fished areas, numbers can be up to ten times less than in unfished areas. In some countries the species has become rare due to overfishing (Sadovy *et al*., 2003).

Figure 9: Example of ground survey in the Banda Islands area overlaid on a Landsat Natural Colour image; yellow dots represent the GPS measurements of the area inspected by the survey specialists, while the red dots are the humphead wrasse spotting registered.

Table 3: Transects and dates of the UVS conducted in the six areas.

Area	Number of transects	Date
Bali Kangeam	32	22–28 June 2005
Banda Islands	69	3–8 October 2006
Manado	40	15–17, 19–21 and 23–25 July 2005
Maratua	61	22–24 and 26–27 September 2006
Nusa Tengara Komodo	33	6–11 April 2006
Raja Ampat	23	18–25 November 2005

Different attempts were made to automatically classify the fish habitat in the Landsat images. Using ESRI ArcGIS Image Analyst functions the images were classified using quantile and standard deviation breaks, cell statistics and slopes. In many cases, by fine-tuning the parameters, it was possible to identify the reef areas. However, because many other features in the image gave the same classification results as the coral reefs, it was very difficult and time-consuming to perform the extraction of the coral reef class. The presence of clouds, cloud shadows and small water reflections on sparse waves are additional critical aspects for the classification that precluded the use of a pre-defined masking. For instance, through an automatic edge detection algorithm (Figure 10) it was possible to find the edge areas between “coral reef and land” and between “coral reef and sea”, but also a lot of other edges between different objects in the image, like clouds, shadows, different vegetation, shoreline, etc. Another limitation is that the automatic procedure needs to be fine-tuned to every single Landsat image, as each one has a different radiometry, different sea structures and different weather conditions. Therefore it was concluded that such an automatic classification procedure, even if possible, would be time-consuming and not beneficial in terms of costs. A similar conclusion was also reached by the Millennium Coral Reef project (Andrefouet *et al*., 2004).

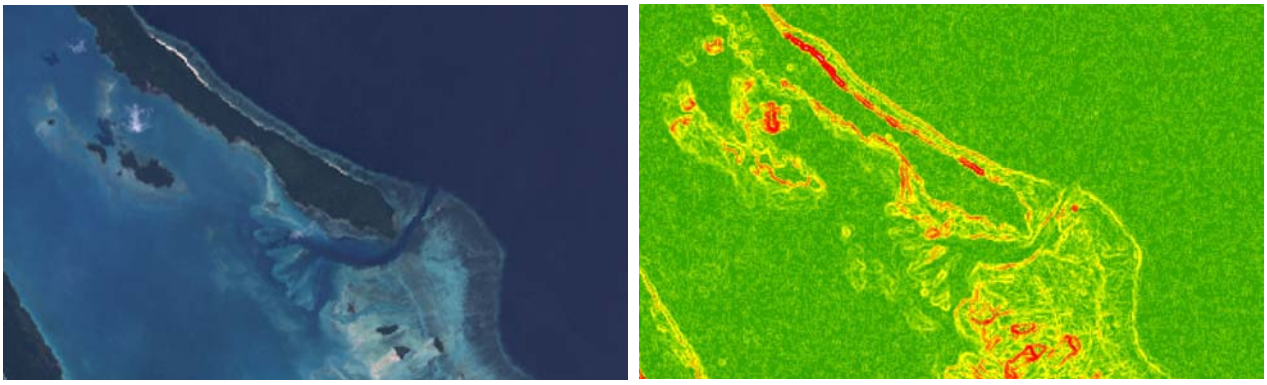

Figure 10: Example of an automatic slope definition of the Landsat image over Maratua atoll.

We also tried to use the GEOVIS and LCCS software developed by FAO's Africover project, but this did not give improved results and was more complicated to use and setup. Object-oriented classification software like eCognition may give better results, thanks to its ability to handle complex classification problems that require the consideration of local contextual information or other spatial data sets, but it has not been tried yet. Another practical method of assessing the habitat area of the humphead wrasse could be to use the maps of morphological reef types produced by the Millennium Coral Reef project, once they are completed (currently only a small area of Indonesia has been covered by the project).

Another important limitation in the use of Landsat images to assess the habitat area of humphead wrasse is that these images do not allow the identification of the external slope areas of the reefs, which is the common preferred habitat and spawning ground of adult humphead wrasse. Optical satellite images, even if they carry a multispectral sensor equipped with blue band, are not able to penetrate the water for more than five–six metres. For this reason they can be used to detect coral reefs only in shallow waters, but not in slope areas down to 100 m depths, where the fish is commonly found.

An empirical procedure was therefore used to map the habitat of the humphead wrasse. First, an operator manually draws the external borders of all the reef areas he is able to identify on the Landsat images (Annex 1 contains further information on basic procedure used to identify reef areas). Second, a fixed buffer zone is applied on both sides of the reef slope margins, thus including part of the reef habitat of young fishes, and the slope areas, habitat of adult fishes (Figure 11). The habitat extension is therefore calculated based on the area of the polygon formed by the buffer zone.

Potential sources of errors with the approach relate to the georeferencing accuracy of the images and to the ability of the operator to distinguish between dead and live coral and reef areas in different sea conditions. It should also be mentioned that the Landsat images available and used were six–eight years old (from 1999 to 2001), which means that the results do not necessarily reflect the current conditions of the reefs.

2.3 Definition of buffer area

Figure 12 shows a schematic representation of a typical barrier reef section, indicating the reef edge and the buffer area. It has to be said that the reef edges detected on the Landsat images are in reality the lines where the reef disappears from the Landsat image into the deep sea. This is not the end of the coral reef, but only the area where the reef is becoming too deep to be seen on a Landsat image (on average at five to six metres depth). If it is considered that the reef drops into the ocean with a 45° slope, a 100 metre buffer would cover an area to a depth of 100 metres (the limit of humphead distribution) on the offshore face of the reef. The 100 metre buffer towards the inside reef would cover the low water reef area.

Figure 11: Example of identification and manual vectorialization of reef edges and automatic buffering on the reef edges in the Maratua atoll.

As can be seen in Figure 13, in some cases the 100 metre buffer can be too big for islands with narrow fringing reefs, while in others it can be too small and underestimate the actual extent of reef areas. However, overall a buffer area of 100 metres seems to best fit the different morphological types of fringing reefs in Indonesia. The definition of a more complex buffer (e.g. asymmetrical on the two sides of the reef edge or customized for every single area) would simply create a more difficult and time-consuming procedure, the effects of which would probably not be significant in the overall definition of the habitat area. It must also be remembered that 100 metres on a Landsat image are equivalent to three pixels, which is almost the visual limit of detection of objects in a Landsat image.

2.4 Habitat classification using SPOT and QuickBird images

SPOT imagery, even if lacking a Blue band, allows for a good differentiation between coral reef areas and land/sea (Figure 14). However, the SPOT images are not available as orthorectified products (like the Landsat ones) and therefore their accuracy is an additional problem to be considered when choosing such a source of reference images.

Despite the slightly higher resolution of SPOT images (20 metres) compared to Landsat images (30 metres) they do not offer a substantial advantage considering the higher price (minimum 1 200 Euro versus approximately 500 Euro for a new Landsat scene) and the smaller area covered per frame (nine times smaller than a Landsat frame).

The very high resolution of a QuickBird scene, on the other hand, offers a perfect tool to help an operator define the limits of coral reef areas with precision (Figure 15). Yet the high price and very small scene size of QuickBird images (less than 100 times smaller than a Landsat), make them impractical for mapping reefs in large areas of the ocean.

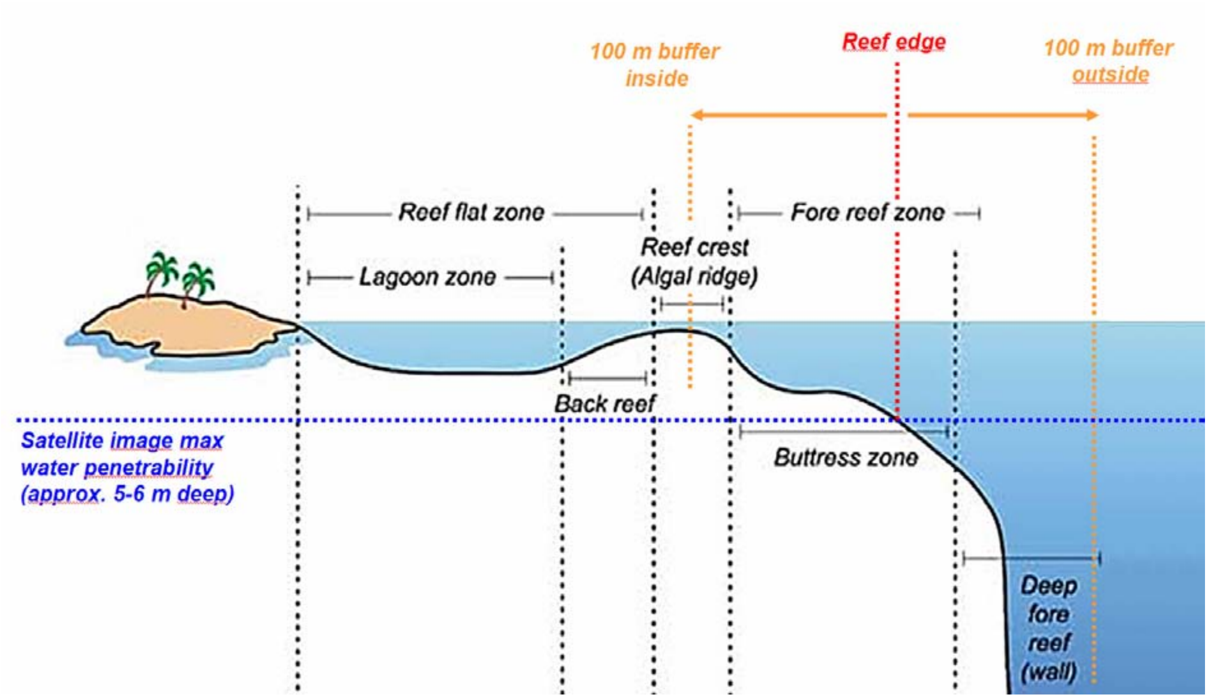

Figure 12: Section of barrier reef with indication of the reef edge and 100 metre buffer area (linear structures are not drawn to scale). In this example there is a steep reef wall, but this is not necessarily the norm.

Figure 13: Example of situations where a 100 m buffer overestimates (left) and underestimates (right) the coral reef area.

2.5 Evaluation of humphead wrasse habitat at country level

Following the empirical procedure defined above, the next phase of the study was to calculate the suitable adult habitat areas in Indonesia, Malaysia and Papua New Guinea. To perform this work we used 279 Landsat 7 scenes covering the area of interest (Figure 16). The scenes were downloaded from the Reefbase database (http://reefgis.reefbase.org/mapper.asp) and from the Global Land Cover facility of the University of Maryland (http://www.gcrmn.org). All scenes were acquired between 1999 and 2002 (Annex 2). The missing scenes in the grid shown in Figure 16 are either completely over land or in the sea areas where no coral reefs were identified.

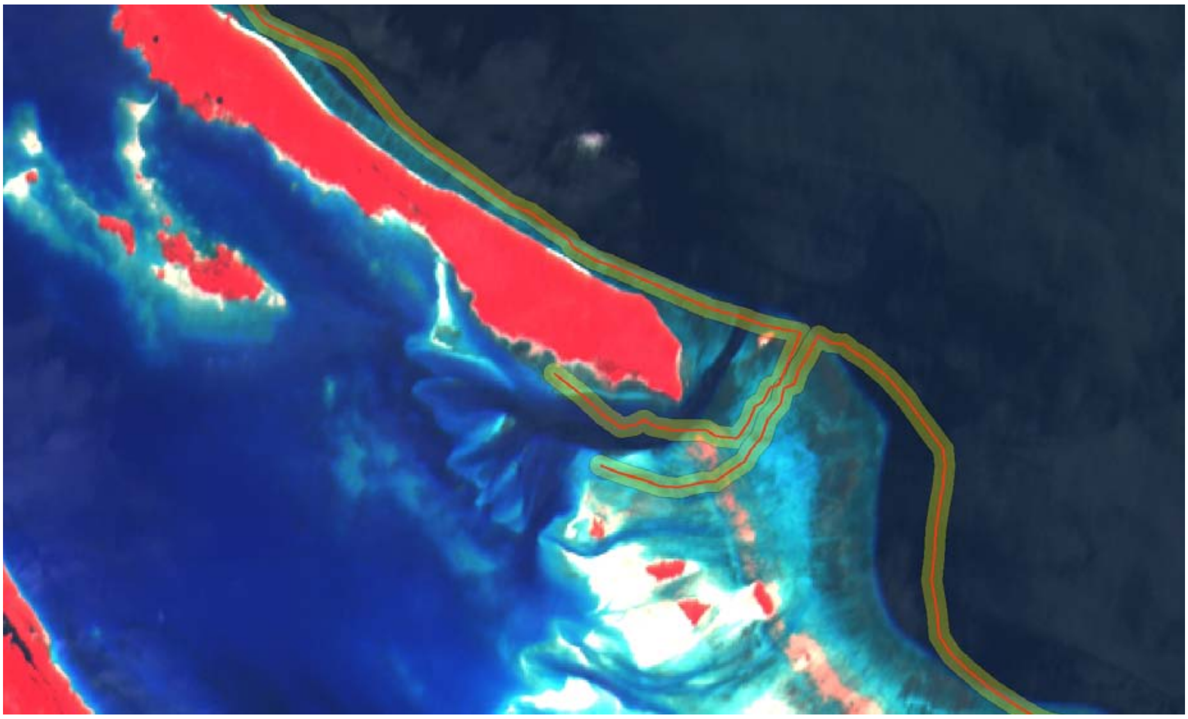

Figure 14: Overlay of the buffered habitat areas on the corresponding SPOT-2 satellite image, showing a shift due to the low geolocation accuracy of the SPOT image

Figure 15: Overlay of the bufferized habitat areas on the corresponding QuickBird satellite image.

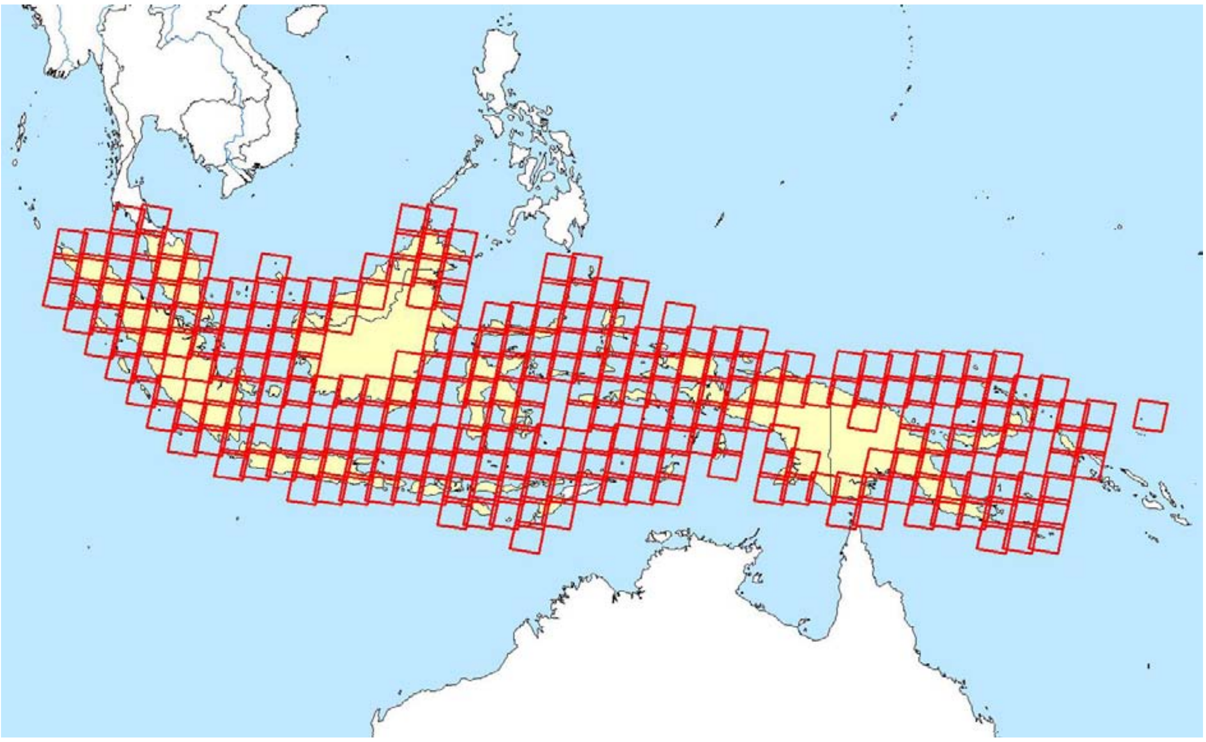

Figure 16: Grid of 279 Landsat 7 scenes used to calculate the humphead habitat areas in Indonesia, Malaysia and Papua New Guinea.

3. RESULTS AND DISCUSSION

The overlay of the habitat area defined by the reef edges and buffer zone with the actual location of humphead wrasse detected by the UVS in Indonesia indicated that overall the habitat areas accurately matched areas of fish occurrence (see example in Figure 17).

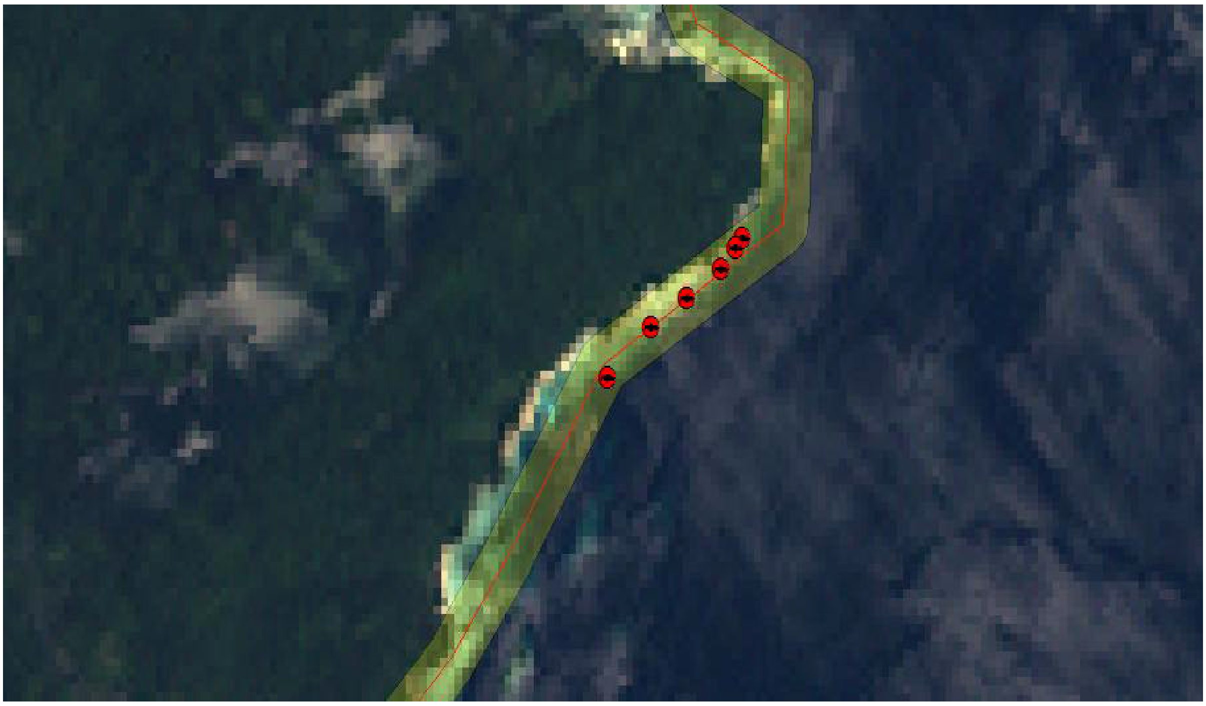

Figure 17: Example of habitat definition with humphead wrasse detected during the UVS in Indonesia.

Figure 18 and Table 4 show the position of 180 humphead wrasse detected during the surveys relative to the calculated position of reef edges. Results indicate that 96 percent of all the fishes are inside the 100 metre buffer zone. If the width of the buffer was reduced to 80 metres on each side of the reef edge the number of fishes inside the buffer zone would reduce to 92 percent. The accuracy of the method in determining humphead wrasse habitat can be deemed adequate, considering that only four fishes (2.2 percent of the total) were detected in areas that were not identified as reefs by the operator. Three of them were in areas where the resolution of the image did not allow the detection of reefs; the fourth was in an area covered with clouds.

The fishes detected were approximately symmetrically distributed around the reef edges (56 percent of the detected fishes were inshore and 44 percent offshore), indicating that the application of a symmetrical buffer (100 metres inside and outside the reef edges) was an adequate solution to the mapping of humphead wrasse habitat.

The total area of potential humphead wrasse habitat in the six test areas in Indonesia covered 838 km^2, distributed along 4 213 km of reef edges (Table 5).

Table 6 and Figures 19 to 21 show the results of the application of the method to Indonesia, Malaysia and Papua New Guinea. The total reef area suitable for humphead wrasse was 11 892 km^2 in Indonesia, 941 km^2 in Malaysia and 5 254 km^2 in Papua New Guinea. Previous estimates of reef areas were available only for Indonesia and Malaysia. Burke at al. (2002) estimated that the total reef areas in Indonesia covered 50 875 km^2 and in Malaysia 4 006 km^2. Both estimates are approximately four times larger than the habitat areas for humphead wrasse calculated in the present study for these countries. How can we reconcile these two independent results in view of the need to obtain accurate information about the humphead wrasse habitat area?

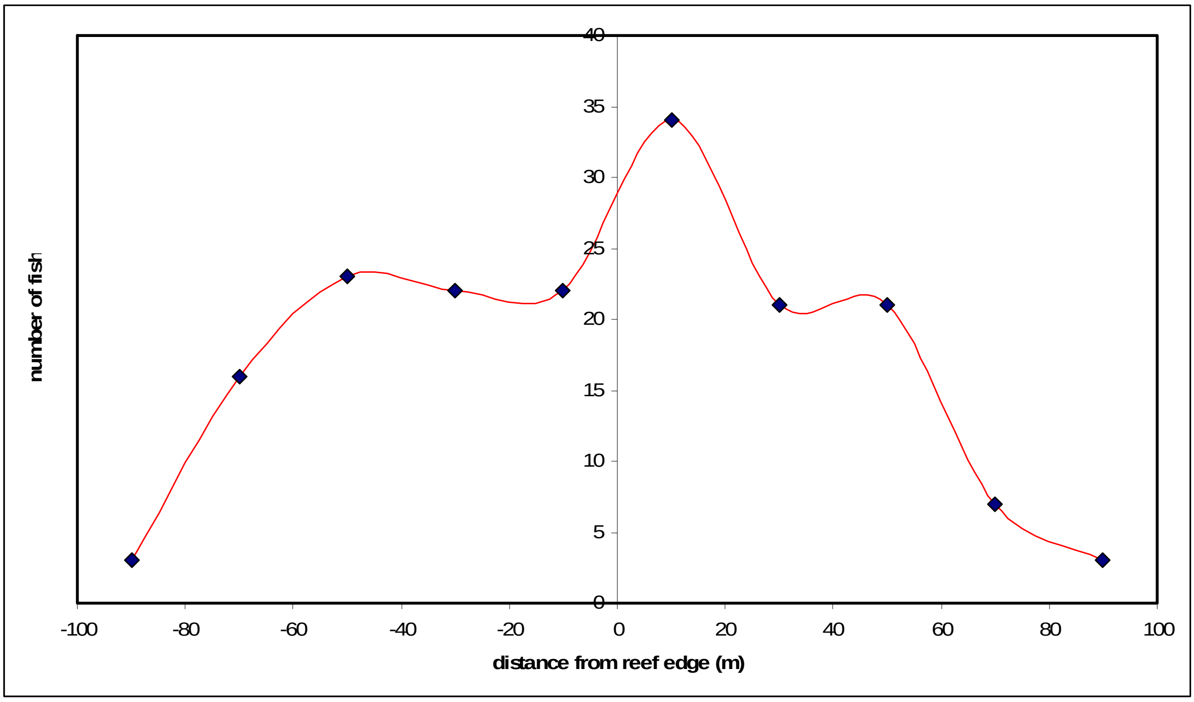

Figure 18: Distribution of humphead wrasse detected in UVS relative to the position of reef edge in the satellite images. A positive distance means that fish were located towards the open sea (slope area); a negative distance means that fish were detected in shallow reef areas.

Table 4: Position of humphead wrasse in buffer areas of different widths.

Distance from reef edge	Number of fishes towards the open sea	Number of fishes towards the internal reef	Total number of fishes
0–20 m	34	22	56
20–40 m	21	22	43
40–60 m	21	23	44
60–80 m	7	16	23
80–100 m	3	3	6
Outside buffer area	2	2	4
Fishes in areas where reef has not been detected			4
Total:	**78**	**88**	**180**

Table 5: Extension of suitable habitat areas for humphead wrasse in six test areas in Indonesia.

Survey area	Length of coral reef slopes	Area of potential habitat
Bali Kangeam	1093 km	218 km^2
Banda Islands	450 km	90 km^2
Manado	514 km	103 km^2
Maratua	880 km	173 km^2
Nusa Tengara Komodo	748 km	150 km^2
Raja Ampat	528 km	104 km^2

One simple explanation for the difference is that in the present study we focused only in the areas considered suitable for humphead wrasse, particularly the adults, while Burke, Selig and Spalding (2002) were interested in the whole reef area. It is therefore to be expected that the total humphead wrasse habitat area, as defined in the present study, would be smaller than the total reef area. However, looking in more detail at the method used by Burke, Selig and Spalding (2002) we concluded that part of the difference is explained by the methods used. The analysis performed by Burke, Selig and Spalding (2002) was based on grid cells with a one km resolution and the estimated reef areas are rounded to two significant digits (or the nearest 100 km^2). Figure 22 demonstrates the difference between the two methods used based on a test area in the Banda Islands, Indonesia: a) the method used in the present study is much closer to the real location of the fringing reefs; b) the resolution of the one km grid cells used by Burke, Selig and Spalding (2002) do not allow a precise mapping of the reefs in narrow continental shelves like those in Indonesia. In the example shown in Figure 22 the total area defined by the one km cells is 71 km^2, while the habitat area defined by our work is 11.3 km^2 or only 16 percent of the areas defined by Burke, Selig and Spalding (2002) as reefs. We therefore conclude that, for the purpose of estimating the suitable areas of humphead wrasse as a basis for defining population size and sustainable export quotas, the results obtained in the present study are adequate and more conservative than the previously available estimates of reef areas. The much smaller reef areas indicated in this study are also consistent with the considerably reduced coral reef areas indicated, on a global scale, by Andrefouet *et al*. (2004).

Table 6: Extension of humphead wrasse habitat area in Indonesia, Malaysia and Papua New Guinea calculated after the definition of reef edges and buffer areas on Landsat images.

Country	**Habitat area**
Indonesia	11 892 km^2
Malaysia	941 km^2
Papua New Guinea	5 254 km^2

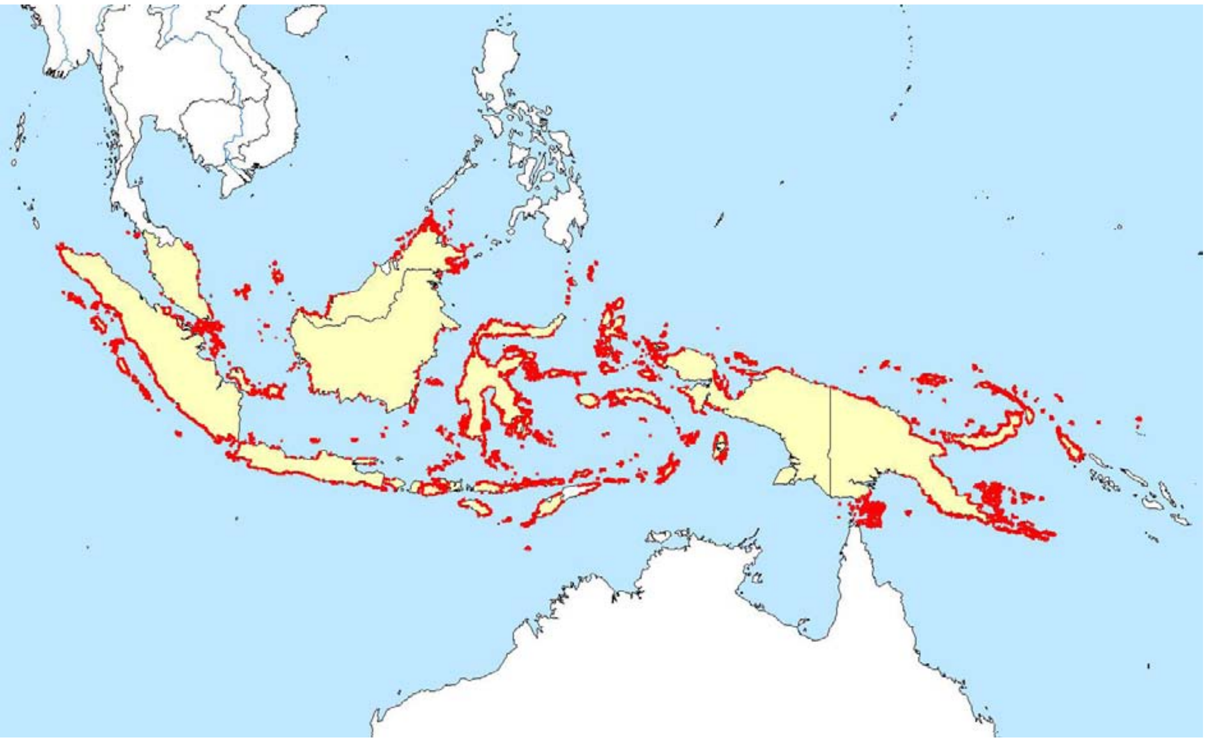

Figure 19: Humphead wrasse habitat area in Indonesia.

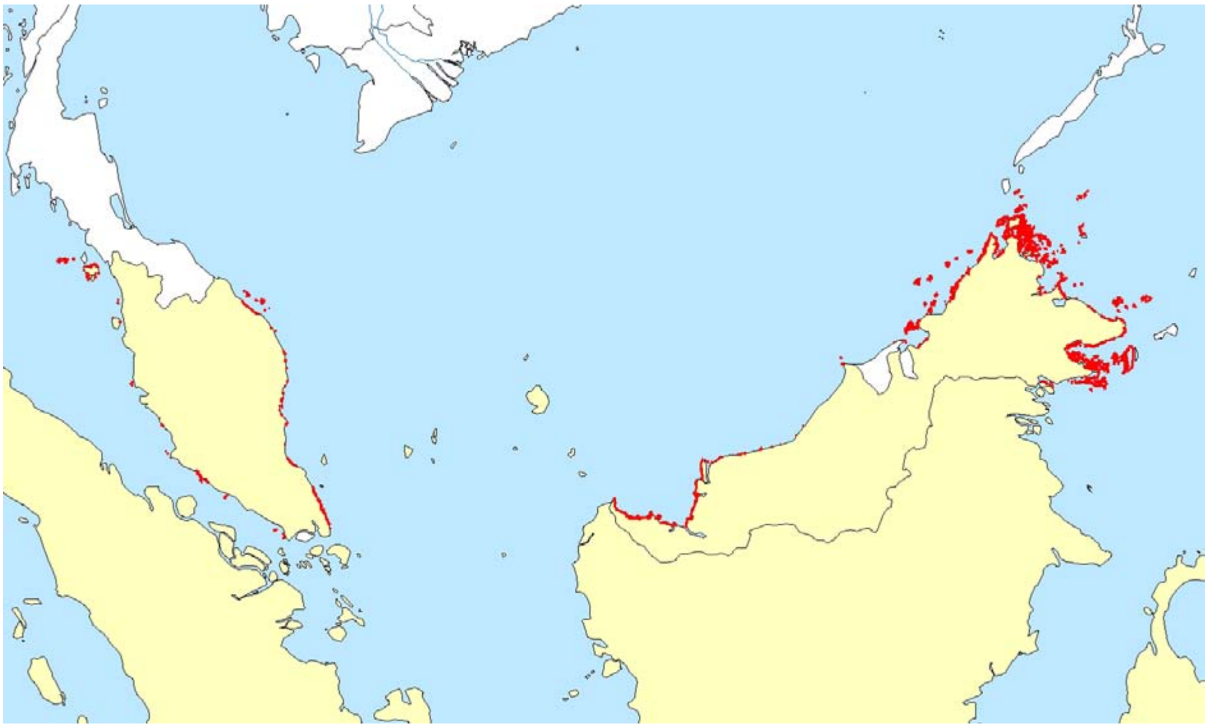

Figure 20: Humphead wrasse habitat area in Malaysia.

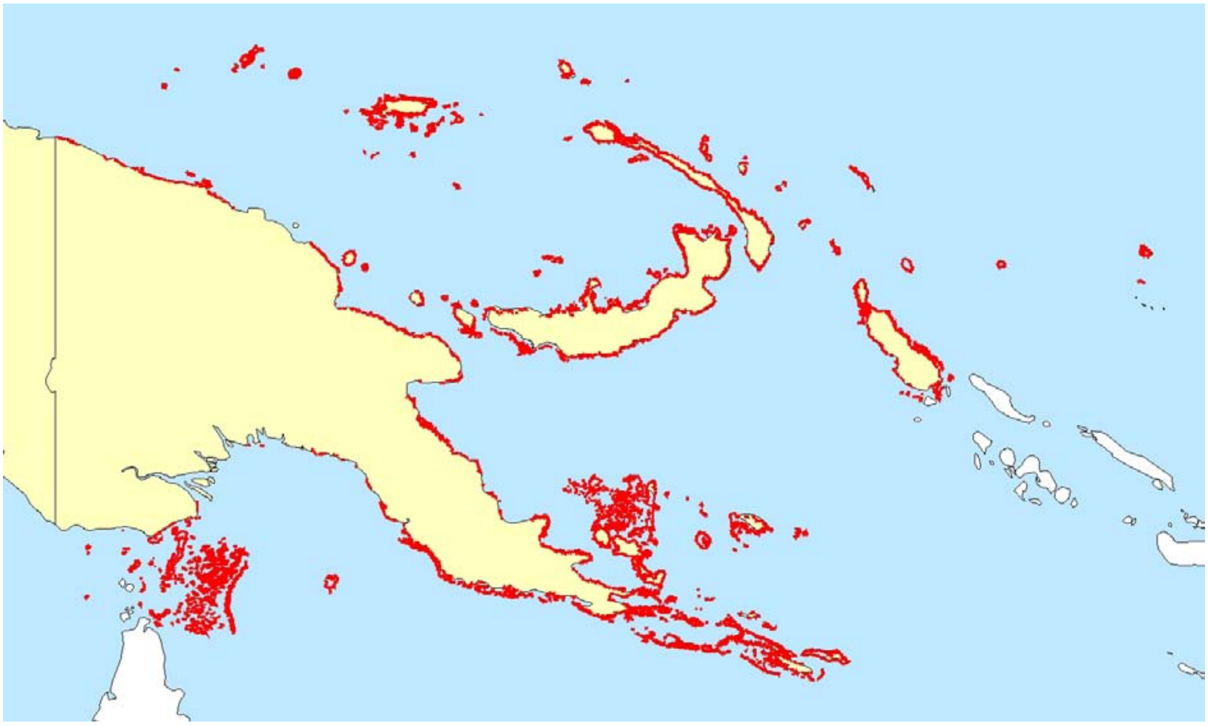

Figure 21: Humphead wrasse habitat area in Papua New Guinea.

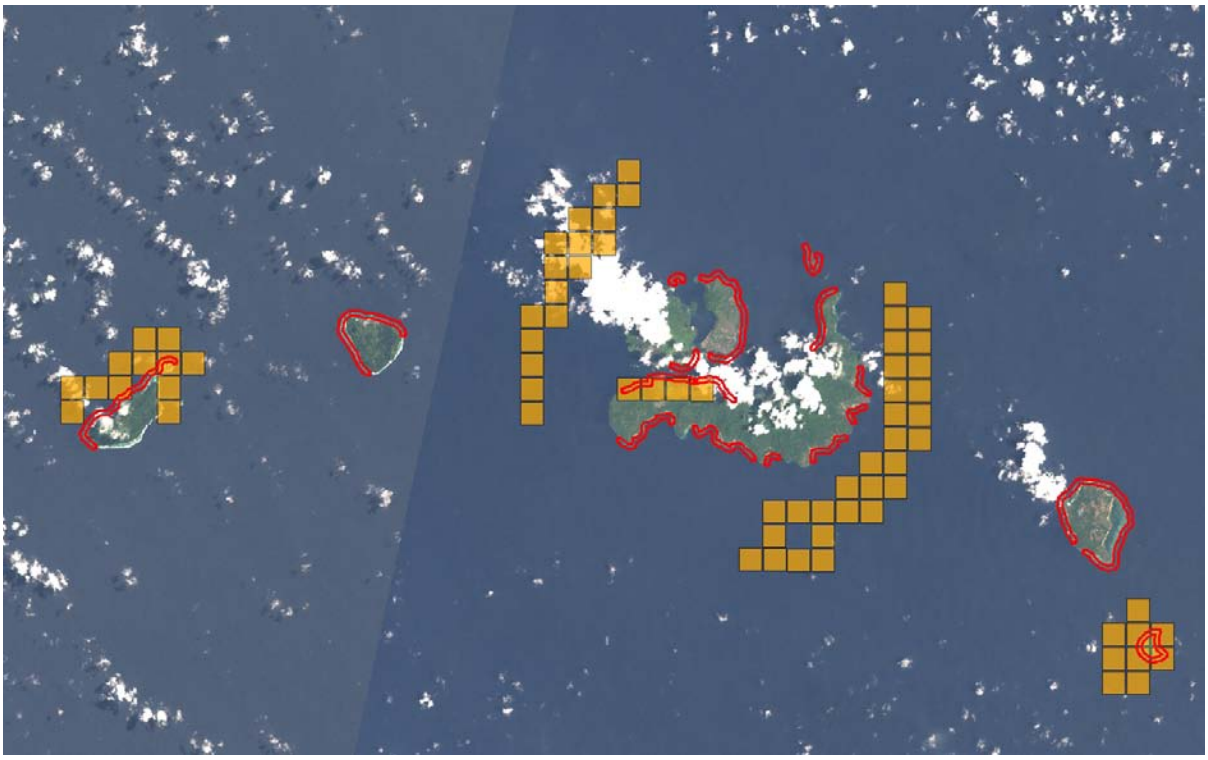

Figure 22: Humphead wrasse in reef habitat areas in the Banda Islands, Indonesia: comparison between current study (red outlines) and previous estimations (orange squares) by Burke, Selig and Spalding 2002

3.1 Some issues related to the application of the method

The case study recognised some main issues and challenges related to the above approach to mapping. In relation to the remote sensing analysis, they are concerned with aspects such as:

i. reef areas that are not well defined or are too small to be detected in a Landsat image;
ii. areas close to river mouths where the discharge of sediments affects the ability to visualize structures below the surface (although areas with high turbidity are naturally unsuitable for coral reefs);
iii. the difficulty in discriminating between live and dead coral;
iv. GIS worker's experience in RS image analysis (some experience is helpful).
v. habitat mapping, which can be complicated and time-consuming, especially for large and complex areas like Indonesia,

It is also likely that in reality humphead wrasse distribution would be affected by factors other than the position of the edge of the reef. These include the availability of food, wave strength and height, existence of algae, etc. Nonetheless, the study presents a simple, though effective, methodology that could couple the use of remote sensing images with the analytical capabilities of GIS.

3.2 Concluding remarks

The use of Landsat satellite images appears to be an objective way to detect coral reefs, and the habitat of reef-associated species, such as the humphead wrasse, over large sea areas. At present there is no automatic procedure to extract information about reef areas from Landsat images; a considerable level of manual work is required to perform the analysis. The habitat mapping can be a complex and time-consuming process, especially for large and complex areas like Indonesia, Malaysia and Papua New Guinea, where there are different coral structures and variable atmospheric conditions and sea status. The skill of the operator in having a clear understanding of photogrammetric coral reef detection in a 30 m resolution Landsat image is also a crucial aspect, and further tests and in-situ analysis may show some level of discrepancy with the results obtained. Nonetheless, overall, we are confident that the habitat areas estimated in this study are much more accurate than those previously used to estimate the population size of humphead wrasse (e.g. Sadovy *et al*., 2007).

Satellite images are an independent source of objective information that can be instrumental in identifying habitat areas in a relatively rapid and cost effective way. They also offer a continuous source of information in time and space that could be used to monitor the impact of human activities on these habitats. In this regard, further developments could be made to use satellite images to investigate the impact of common stressors on coral reefs habitats, such as:

- large human settlements in coastal areas;
- the intensity of land runoff and the siltation of coastal waters caused by both human and natural impacts;
- areas of heavy ship movements (e.g. the Malacca strait near Singapore) where the risk of oil spills is higher;
- impact of natural phenomena on the coral reefs (e.g. typhoons and tsunamis).

4. REFERENCES

Andrefouet, S., Muller-Karger, F.E., Robinson, J.A., Kranenburg, C.J., Torres-Pulliza, D., Spraggins, S.A. and Murch, B. 2006. Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space. Proceedings of tenth International Coral Reef Symposium, Okinawa, Japan. 28 June–2 July 2004. pp. 1732–1745. (http://www.reefbase.org/resource_center/publication/icrs.aspx)

Burke, L., Selig, E. and Spalding, M. 2002. Reefs at risk in Southeast Asia. World Resources Institute in collaboration with the United Nations Environment Programme–World Conservation Monitoring Centre, the WorldFish Center and the International Coral Reef Action Network. 76 p. (http://www.wri.org/publication/reefs-risk-southeast-asia)

Gillett, R. 2010. Monitoring and managing the humphead wrasse, *Cheilinus undulatus*. FAO Fisheries Circular. No. 1048. Rome, FAO 62 p.

Sadovy, Y. 2005. Napoleon fish (humphead wrasse), *Cheilinus undulatus*, trade in southern China and underwater visual census survey in southern Indonesia. IUCN Groupers & Wrasses Specialist Group. 26 p.

Sadovy, Y., Kulbicki, M., Labrosse, P., Letourneur, Y., Lokani, P. and Donaldson, T.J. 2003. The humphead wrasse, *Cheilinus undulatus*: synopsis of a threatened and poorly known giant coral reef fish. Reviews in Fish Biology and Fisheries. Kluwer Academic Publishers. 13: 327–364.

Sadovy, Y., Punt, A., Cheung, W., Vasconcellos, M., Suharti, S. and Mapstone, B.D. 2007. Stock assessment approach for the Napoleon fish, *Cheilinus undulatus*, in Indonesia – A tool for quota-setting for data-poor fisheries under CITES Appendix II Non-Detriment Finding requirements. FAO Fisheries Circular. No. 1023. Rome, FAO. 71 p.

APPENDIX 1

Short guidelines to detect reef areas in Landsat images

To detect coral reef areas in Landsat medium resolution images we must use both resolutions of a remote sensing image: radiometric and geometric.

Coral reef areas are structures that are found under a few metres of clean sea water, therefore it is fundamental to use the Blue band of the Landsat sensor, which has the highest water penetration. Typical band combinations to be used for coral reef detection are the Natural Colors (RGB = 321) or False Infrared Colors (RGB = 421). The 421 combination has an additional advantage, as it clearly indicates the outer vegetation areas (red), while the 321 combination is better for public display, as it has the natural look that people generally expect (see figure 23).

Figure 23: When loading these images into a software like ESRI ArcGIS, particular care should be taken to apply the correct colour stretching, as the colour automatically applied by the software generally gives very light colours, which are not the best for photo interpretation. In ESRI ArcGIS we generally applied a 4–5 standard deviation, which gives a darker and well contrasted image. The black background values (Red=0, Green=0, Blue=0) must be set to transparent.

The Landsat images have a pixel resolution of 30 metres, so we will not be able to detect very small coral reef areas. The Landsat 7 satellite also has a 15 metre panchromatic band which could be used to pan-sharpen the multispectral images and get colour images at 15 metre resolution, but unfortunately the water penetrability of these images would be slightly reduced as the Pan band ranges from Blue to Near InfraRed. In addition to that, the typical pan-sharpening algorithms do not work well in images such as those over Indonesia, where the most part of the scene is covered by a uniform value (the blue sea). For this reason we suggest using only the first four bands at a 30 metre resolution.

At this point to detect the coral reef areas we simply need to look at the images and try to see these very characteristic structures; hereafter some tips:

- Coral reef areas have a light blue colour, which is generally very well differentiated from the dark blue colour of the sea.
- There are three kinds of coral reef areas (fringing, barrier and atoll, see Figure 24); to properly identify the typology of reef, carefully study their position compared to the generally vegetated ground areas out of the water.
- Coral reefs have some very typical, “circular” structures, and they generally smooth the structure of rough coastlines.
- If along the coast there are white areas, these are generally rocky coasts with crashing waves and are unlikely to have reef formations (see figure 25 below as an example).

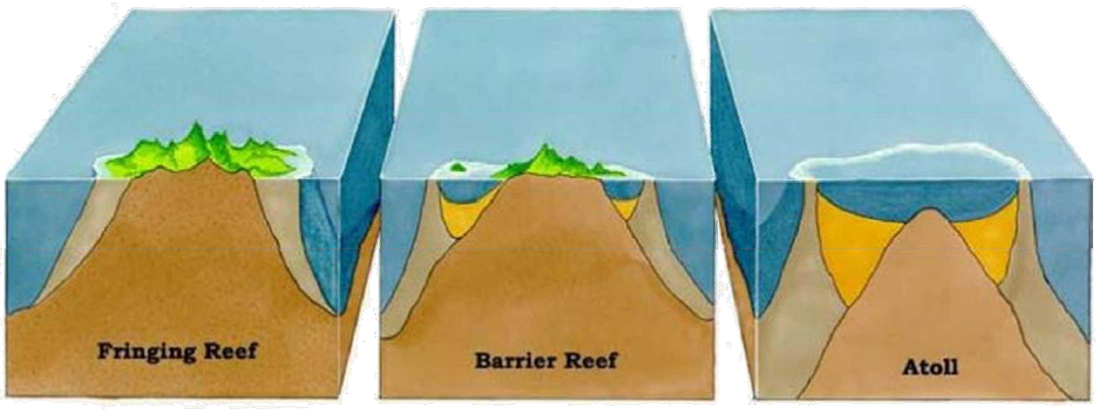

Figure 24: The three stages of coral reef formation - fringing, barrier, and atoll (*Source*: www.marinebio.net/marinescience/04benthon/crform.htm).

Figure 25: Example of a rocky coast from the study area.

APPENDIX 2

List of the Landsat 7 scenes used for this study

PATH	ROW	DATE	UTM ZONE	PATH	ROW	DATE	UTM ZONE
P088	R063	29/05/2001	57	P097	R066	20/10/2001	55
P090	R063	02/02/2000	57	P098	R061	04/09/1999	55
P090	R064	28/08/2000	57	P098	R062	28/01/2001	55
P090	R065	11/09/1999	57	P098	R065	17/05/2000	55
P091	R063	16/06/2000	56	P098	R066	01/03/2001	54
P091	R064	02/05/2001	56	P098	R067	07/07/2001	54
P091	R065	24/01/2000	56	P099	R061	21/03/2000	54
P091	R066	24/01/2000	56	P099	R062	09/04/2001	54
P091	R067	24/01/2000	56	P099	R063	27/07/2000	54
P091	R068	24/01/2000	56	P099	R066	19/01/2001	54
P092	R062	09/09/1999	56	P099	R067	30/07/2001	54
P092	R063	04/04/2000	56	P100	R061	18/09/1999	54
P092	R066	25/09/1999	56	P100	R062	18/09/1999	54
P092	R067	05/02/2002	56	P100	R066	25/10/2001	54
P092	R068	11/10/1999	56	P101	R062	25/10/2001	54
P093	R062	27/04/2000	56	P101	R065	26/08/2000	54
P093	R063	13/05/2000	56	P101	R066	10/08/2000	54
P093	R064	13/05/2000	56	P102	R061	08/11/2001	54
P093	R065	14/07/1999	56	P102	R062	02/10/1999	54
P093	R066	16/05/2001	56	P102	R064	07/02/2000	54
P093	R067	02/09/2000	56	P102	R065	16/05/2001	53
P093	R068	02/09/2000	56	P102	R066	16/05/2001	53
P094	R061	18/01/2002	56	P103	R061	08/08/2000	53
P094	R062	17/03/2000	56	P103	R062	08/08/2000	53
P094	R063	09/09/2000	56	P103	R063	07/05/2001	53
P094	R064	02/04/2000	56	P104	R060	22/02/2001	53
P094	R066	08/08/2000	55	P104	R061	31/08/2000	53
P094	R067	31/01/2001	55	P104	R062	27/05/2000	53
P095	R061	06/02/2000	55	P104	R063	17/11/1999	53
P095	R062	06/02/2000	55	P104	R064	17/11/1999	53
P095	R063	07/01/2001	55	P104	R065	03/09/2001	53
P095	R064	10/01/2002	55	P105	R060	25/08/2001	53
P095	R065	10/01/2002	55	P105	R061	08/07/2001	53
P095	R066	10/01/2002	55	P105	R062	08/07/2001	53
P095	R067	22/10/2001	55	P105	R063	13/11/2001	53
P096	R061	14/01/2001	55	P105	R064	13/11/2001	53
P096	R062	08/10/1999	55	P106	R060	28/05/2001	53
P096	R064	08/09/2000	55	P106	R061	23/04/2001	53
P096	R065	03/03/2001	55	P106	R062	01/11/2000	53
P096	R066	03/03/2001	55	P106	R063	03/02/2000	53
P096	R067	09/07/2001	55	P106	R064	22/12/2001	52
P097	R061	20/02/2000	55	P106	R065	22/12/2001	52
P097	R062	20/02/2000	55	P106	R066	01/09/2001	52
P097	R063	20/02/2000	55	P107	R059	05/10/1999	52
P097	R064	17/10/2000	55	P107	R060	06/07/2001	52
P097	R065	20/10/2001	55	P107	R061	28/02/2001	52
P108	R061	13/07/2001	52	P113	R067	29/09/1999	51

PATH	ROW	DATE	UTM ZONE	PATH	ROW	DATE	UTM ZONE
P108	R062	13/07/2001	52	P114	R059	21/06/2001	51
P108	R064	11/08/2000	52	P114	R060	21/06/2001	51
P108	R065	11/08/2000	52	P114	R061	24/08/2001	51
P108	R066	11/08/2000	52	P114	R062	21/08/2000	51
P109	R058	21/08/2001	52	P114	R063	21/08/2000	50
P109	R059	17/05/2001	52	P114	R064	20/09/1999	50
P109	R060	24/10/2001	52	P114	R065	20/09/1999	50
P109	R061	21/08/2001	52	P114	R066	20/07/2000	50
P109	R062	21/08/2001	52	P114	R067	20/07/2000	50
P109	R063	18/08/2000	52	P115	R060	24/05/2000	50
P109	R064	18/08/2000	52	P115	R061	31/08/2001	50
P109	R065	18/08/2000	52	P115	R062	11/05/2001	50
P109	R066	18/08/2000	52	P115	R064	11/09/1999	50
P110	R058	10/10/1999	52	P115	R065	11/09/1999	50
P110	R059	24/05/2001	52	P115	R066	13/09/2000	50
P110	R060	13/11/2000	52	P116	R056	09/12/2000	50
P110	R061	13/11/2000	52	P116	R057	18/09/1999	50
P110	R062	09/08/2000	52	P116	R058	06/08/2001	50
P110	R063	05/05/2000	52	P116	R059	15/05/2000	50
P110	R065	26/10/1999	51	P116	R060	27/02/2001	50
P110	R066	08/09/1999	51	P116	R061	16/04/2001	50
P110	R067	08/09/1999	51	P116	R062	05/07/2001	50
P111	R057	04/09/2001	52	P116	R063	31/03/2001	50
P111	R058	10/04/2000	52	P116	R064	19/08/2000	50
P111	R059	18/07/2001	51	P116	R065	19/08/2000	50
P111	R060	18/07/2001	51	P116	R066	19/08/2000	50
P111	R061	18/07/2001	51	P117	R055	06/05/2000	50
P111	R064	29/06/2000	51	P117	R056	09/09/1999	50
P111	R065	29/06/2000	51	P117	R057	26/06/2001	50
P111	R066	14/08/1999	51	P117	R058	26/06/2001	50
P111	R067	17/09/2000	51	P117	R061	26/08/2000	50
P111	R068	29/04/2001	51	P117	R062	22/03/2001	50
P112	R057	19/05/2000	51	P117	R063	22/03/2001	50
P112	R058	19/05/2000	51	P117	R064	09/05/2001	50
P112	R059	20/04/2001	51	P117	R065	09/09/1999	50
P112	R060	13/10/2001	51	P117	R066	12/07/2001	50
P112	R061	13/10/2001	51	P118	R055	05/09/2001	50
P112	R062	13/12/2000	51	P118	R056	02/10/1999	50
P112	R063	06/05/2001	51	P118	R057	25/02/2001	50
P112	R064	09/07/2001	51	P118	R062	16/07/2000	50
P112	R065	08/09/2000	51	P118	R063	01/06/2001	49
P112	R066	27/09/2001	51	P118	R064	01/06/2001	49
P112	R067	27/09/2001	51	P118	R065	01/06/2001	49
P113	R059	17/10/2000	51	P118	R066	20/08/2001	49
P113	R060	16/07/2001	51	P119	R057	10/07/2001	49
P113	R061	08/04/2000	51	P119	R058	10/07/2001	49
P113	R062	21/01/2001	51	P119	R062	15/01/2001	49
P113	R063	02/09/2001	51	P119	R063	09/09/2000	49
P113	R064	29/09/1999	51	P119	R064	09/09/2000	49
P113	R065	29/09/1999	51	P119	R065	27/08/2001	49
P113	R066	29/09/1999	51	P119	R066	21/06/2000	49

PATH	ROW	DATE	UTM ZONE	PATH	ROW	DATE	UTM ZONE
P120	R058	01/07/2001	49	P127	R056	31/05/2001	47
P120	R059	31/08/2000	49	P127	R057	20/09/2001	47
P120	R062	13/08/1999	49	P127	R058	31/05/2001	47
P120	R064	01/07/2001	49	P127	R059	26/04/2000	47
P120	R065	28/04/2001	49	P127	R060	26/04/2000	47
P120	R066	13/08/1999	49	P127	R061	15/07/2000	47
P121	R058	26/11/2000	49	P127	R062	31/05/2001	47
P121	R059	18/05/2000	49	P128	R055	20/04/2001	47
P121	R060	22/06/2001	49	P128	R056	17/01/2002	47
P121	R061	22/06/2001	49	P128	R057	27/12/1999	47
P121	R062	23/06/2001	49	P128	R058	02/02/2002	47
P121	R063	24/06/2001	49	P128	R059	09/07/2001	47
P121	R064	25/06/2001	49	P128	R060	09/07/2001	47
P121	R065	05/09/1999	49	P128	R061	09/07/2001	47
P122	R058	21/02/2001	49	P129	R055	22/02/2001	47
P122	R059	17/11/2000	49	P129	R056	22/02/2001	47
P122	R060	13/06/2001	49	P129	R057	22/02/2001	47
P122	R061	13/06/2001	49	P129	R058	14/06/2001	47
P122	R062	13/06/2001	48	P129	R059	13/07/2000	47
P122	R064	15/07/2001	48	P129	R060	13/07/2000	47
P122	R065	12/05/2001	48	P130	R056	05/08/2000	47
P123	R057	19/05/2001	48	P130	R057	05/08/2000	47
P123	R058	28/02/2001	48	P130	R058	05/08/2000	47
P123	R059	19/07/2000	48	P130	R059	31/01/2002	47
P123	R060	25/01/2000	48	P131	R056	08/05/2000	46
P123	R061	03/09/1999	48	P131	R057	12/06/2001	46
P123	R062	14/04/2000	48	P131	R058	02/12/2000	46
P123	R063	15/04/2000	48				
P123	R064	07/08/2001	48				
P123	R065	07/08/2001	48				
P124	R058	26/05/2001	48				
P124	R059	29/11/1999	48				
P124	R060	23/05/2000	48				
P124	R061	15/12/1999	48				
P124	R062	13/07/2001	48				
P124	R063	13/07/2001	48				
P124	R064	05/04/2000	48				
P125	R058	17/09/1999	48				
P125	R059	28/04/2000	48				
P125	R060	01/09/1999	48				
P125	R061	01/09/1999	48				
P125	R063	16/08/1999	48				
P125	R064	16/08/1999	48				
P126	R056	08/05/2001	48				
P126	R057	08/07/2000	48				
P126	R058	08/07/2000	48				
P126	R059	03/01/2002	48				
P126	R060	21/05/2000	48				
P126	R062	25/08/2000	47				
P126	R063	22/04/2001	47				

ISBN 978-92-5-106621-8 ISSN 2070-6065

9 789251 066218

I1706E/1/08.10