

4 Research and Developments of Case Studies: (TO-ASIST Steps 1 - 3)

4.1 Introduction

It is appropriate at this stage to look at several research case studies, each designed to develop methods that can deliver the necessary information to the lay-user or transfer the appropriate technology to the operational community. The three case studies represent smaller research components of an overall strategy to monitor the health of Port Phillip Bay specifically, although the techniques developed would be transportable to other situations. Much of sections 4.3 and 4.4 come from a technical report submitted to the Port Phillip Bay Environmental Study (Rollings et al. 1993, Rollings et al. 1994). Each of these sections carries a table detailing my contribution to each activity and hence those part to which I can claim for this thesis. At the end of each sub-chapter we will look at the techniques developed, the technical problems faced with each and assess their suitability for development as a TO-ASIST.

4.2 Port Phillip Bay Environmental Study – A project in need of information (TO-ASIST Step 1).

Port Phillip Bay (PPB) is an almost enclosed, shallow marine embayment located in south-eastern Australia in the state of Victoria. In addition to harbour facilities, it forms an important recreational, commercial and industrial resource and receives a variety of urban and industrial wastes from the nearby cities of Melbourne and Geelong. The Bay has a surface area of approximately 1,950 km² with a single entrance to Bass Strait at its southern end. Over 50% of the Bay has a depth of less than 14 m, with a maximum of 22 m in the central basin. Tides in the Bay are predominantly semi-diurnal with a mean amplitude at the entrance of approximately 1 m (MMBW and FWD, 1973). The surrounding catchment (approximately 9800 km²) is of low relief, with the result that water currents and movements are significantly affected by wind. Bottom sediments are generally sandy at the shoreline and grade into fine clays in the centre of PPB (MMBW and FWD, 1973). The major freshwater

inputs to the Bay are the Werribee Treatment Farm and the Yarra River, however the annual inflow from these and other sources is approximately equal to annual surface evaporation, maintaining salinity to that of normal seawater. The residence time of water in the Bay varies from about two weeks in the southern segment to about twelve months in the northern segment (Longmore et al. 1990).

Although much data has been collected on Port Phillip Bay (PPB) since the First Environmental Study of PPB (1969-1971), monitoring and research activities have not been well coordinated (CSIRO 1992a:6). There is a need for a new assessment of the status of PPB, particularly with respect to nutrients and toxicants. The current PPB Environmental Study (PPBES), commissioned by Melbourne Water and managed by CSIRO, was announced in June 1991.

The general aim of the PPB Environmental Study is to determine the environmental status of PPB in relation to nutrients and toxicants and to provide a basis for the long-term management of point-source and diffuse inputs. Fundamental to addressing this broad aim is an understanding of the distribution and abundance of phytoplankton and benthic habitats at the spatial and temporal scales operating in PPB. The PPB project provided an ideal opportunity to research the application of state-of-the-art technology to NRM. Consequently, certain aspects of the project feature in this thesis.

4.3 Benthic Assemblage Mapping - Research Case Study 1 (TO-ASIST Steps 2-3)

Benthic assemblage mapping involves the recognition of groups of macrophytes, macroalgae and substrate types. The information is useful for assessing the health of an area as well as assessing that area's potential to cycle nutrients and toxicants.

This case study was initiated to research the suitability of digitally enhanced aerial photography, air-borne multispectral remote sensing and satellite multispectral remote sensing (SPOT) for mapping the distribution of benthic habitats in Port Phillip Bay (PPB). This project was officially part of this Ph.D. although my contribution to each aspect of this project was mostly in the area of project design, processing and analysis of the spatial data sets (Table 4-1). Other sections of the final report detailing field operations have been summarised in this thesis, the entire report is included in Appendix 2.

Table 4-1 Percentage contribution claimed for research case study 1.

Component of Research Case Study	Approximate Contribution
Project design for field component	20
Project design for remote sensing component	80
Writing literature review for field mapping methods	10
Writing literature review for spatial techniques	70
Field work for ground truth and accuracy assessment	10
Field work for remote sensing	90
Analysis of field data	30
Processing and analysis of remotely sensed data	90
Classification of remotely sensed data	80
GIS processing and analysis	100
Final analysis	80
Report writing	50

4.3.1 Introduction

Previous maps of benthic habitats within PPB were acquired using air-photo interpretation (Brown et al. 1980, Bulthuis 1981, Watson 1979), direct observations from a submersible towing system (Brown et al. 1980), diving along selected transects (Axelrad 1986, Bulthuis 1981, Watson 1972, 1979), spot-diving intercepts of a grid (Denning et al. 1986) and overboard grab sampling (Hope-Black 1971, Seedsman and Marsden 1980, Womersley 1966). Several of these methods were often used in a single study. These studies focused on different benthic habitats, occurred in markedly different environments and produced varying results in terms of uncertainty of location. The limitations of these procedures are well documented and reviewed by MeRVaL (1993a). No single method or combination of methods has been recommended for the purpose of mapping the distribution of benthic habitats within PPB.

There has been widespread application of multi-spectral remote sensing for the purpose of mapping benthic habitat distribution. Satellite remote sensing has been used to map the distribution of seagrass in Corner Inlet, Victoria (Allen and Ellis 1990), the Great Sandy Strait, Queensland (Lennon and Luck 1990) and Lake Macquarie, New South Wales (Monaghan and Williams 1988), a coral reef environment off New Caledonia (de Vel and Bour 1990), benthic habitats off the Dominican Republic (Luczcovich et al. 1993), and coral atoll environments in Kiribati (Rollings and Coops 1993). In a feasibility study of the use of Landsat TM and SPOT imagery to map benthic vegetation in PPB, Allen (1991) concluded that both data sources had the ability to delineate benthic features in shallow water, but were of limited value in the absence of concurrent ground truth information.

Airborne multispectral imaging was developed over 20 years ago, but there have been relatively few attempts to utilise such data for mapping the distribution of benthic marine habitats. Several studies have compared the efficacy of multispectral satellite and airborne imagery for mapping seagrass distribution in Moreton Bay, Queensland (Greenway and Fry 1988) and Corner Inlet, Victoria (Allen and Ellis 1990). Both studies indicated that airborne scanners show the greatest capacity for assessing change in composition and structure within vegetated benthic habitats due to their

higher spatial and spectral resolution. This led Allen (1991) to consider that such mapping techniques were applicable to PPB.

4.3.2 Research Questions

Research Question 1: Can a remote technique(s) be developed that can reliably map benthic assemblages in the waters of Port Philip Bay?

Research Question 2: To what depth can these techniques operate?

Research Question 3: What are the requirements to make these techniques operational?

4.3.3 Study Sites

Two study sites were investigated during the course of the study; Indented Head - St Leonards and Mornington (Figure 4-1). Preliminary investigations (a combination of aerial reconnaissance, the study of time series aerial photography and *in situ* observation) suggested that the study sites differed markedly with respect to their benthic flora and fauna, substrate type, water depth, turbidity regime and operating conditions. In all, the two study sites are representative of the environments in PPB (Rollings et al. 1993).

Indented Head - St Leonards

This study area is situated between Indented Head and St Leonards, on the Bellarine Peninsula. The area extends offshore 2,800 m to the north and 2,200 m to the east. The site is shallow (3 m - 8 m) and has predominantly soft substrate. Sediments are a combination of medium to coarse sands and fragmented shell. The bedrock of the Indented Head headlands is Pliocene ferruginous sandstone (Black and Mourtikas 1992) and the Inner Governor and Outer Governor Reefs most likely represent offshore remnants of this same rock type.

The Indented Head - St Leonards region is subject to the predominant southerly currents emanating from the Heads region (Black and Mourtikas 1992) and exhibits no net loss or gain of sediments (Bird 1990). The Indented Head - St Leonards site

falls within the southeastern zone of PPB which has been reported to have high levels of light penetration (EPA 1983).

Mornington

The Mornington study site includes the region between Schnapper Point and Shag Rock. The area extends offshore 150 m to the north and 650 m to the south. The coastline includes rugged cliffs, which fall away to water depths approaching 6 m at the shoreline. The area includes the deepest water investigated during the study (typically 5 m - 13 m); water depth grades deeper on the eastern side of the Bay as compared to the western side (Brown and Davies 1991). The headlands are composed of resistant Pliocene laterite, which separates the small bays and crescent shaped beaches of sand or cobble (Black and Mourtikas 1992). This rock type extends seawards forming several large offshore reefs (Hope-Black 1971).

The Mornington region is subject to net water movement from the north (Coleman et al. 1991). Wind direction components reported by MMBW and FWD (1973) leave this site particularly exposed to a high degree of disturbance and wave action in both summer and winter. Black and Mourtikas (1992) demonstrated that beach alignment in this area is at equilibrium with prevailing weather patterns and the shape of the Bay. Mornington falls within the southeastern zone of PPB which has been reported to have high (marginally lower compared to Indented Head - St Leonards) levels of light penetration (EPA 1983).

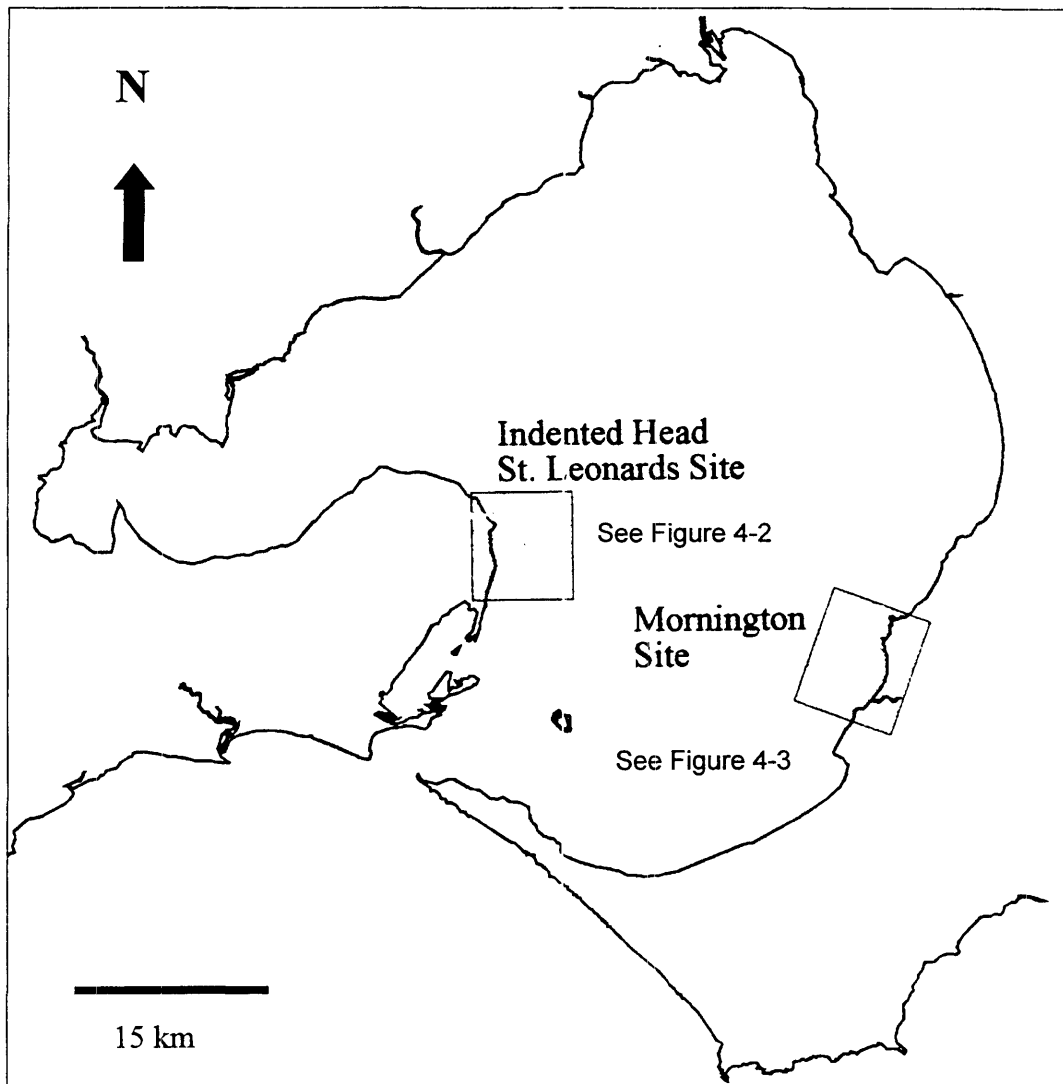


Figure 4-1 Map of PPB indicating benthic mapping sites (after Rollings et al. 1993).

4.3.4 Method - Field Investigations

Melbourne Water Corporation (MWC), under the leadership of Dr B. Light, undertook all field investigations for benthic mapping including the development of the Dominant Assemblage Assessment Protocol (DAAP) as described below. Preliminary site assessment and the development of all methodology took place between February 15 and March 12, 1993. Poor visibility and operating conditions resulted in minimal data collection between March 12 and the end of April. Final field trials at the study sites, excluding the field validation procedure, were undertaken at Mornington on May 19 and at Indented Head - St Leonards on May 17 and 20.

Dominant Assemblage Assessment Protocol (DAAP)

A principal objective of the field trials was to develop a benthic assemblage assessment protocol that would generate meaningful and interpretable information to categorise benthic habitats in PPB. Key criteria considered in its development were:

- (a) the ability to assess large areas;
- (b) time efficiency;
- (c) cost efficiency; and
- (d) safety of personnel and equipment (Rollings et al. 1993).

Total plant cover for each benthic assemblage was estimated from a four-point cover scale (< 5 % - bare substrate; 6-30 % - low; 31-70 % - medium; >70 % - high) devised from preliminary observations of a representative number of assemblages at each site.

The underlying substrate type was determined for each assemblage. Categories used were sand, shelly sand, cobbly sand, bouldery sand and reef.

Benthic assemblages were assessed on the basis of four criteria: dominant plant assemblage, total plant cover, dominant animal assemblage, and substrate type.

Collection of Field Data

Three methods of data acquisition were developed. Each method involved a data recording and position-fixing component. The three methods were largely determined by the physical features and safety considerations (personnel and equipment) of the locations being mapped. All diving (SCUBA) operations were conducted in accordance with the Australian commercial diving standard - AS 2299. The three methods of data acquisition - offshore deep water, offshore shallow water and near-shore shallow water - were named according to the environment in which they could be applied. Figure 4-2 and Figure 4-3 illustrate the benthic ground truth transects traversed at Indented Head - St Leonards and Mornington respectively using these procedures. (Rollings et al. 1993).

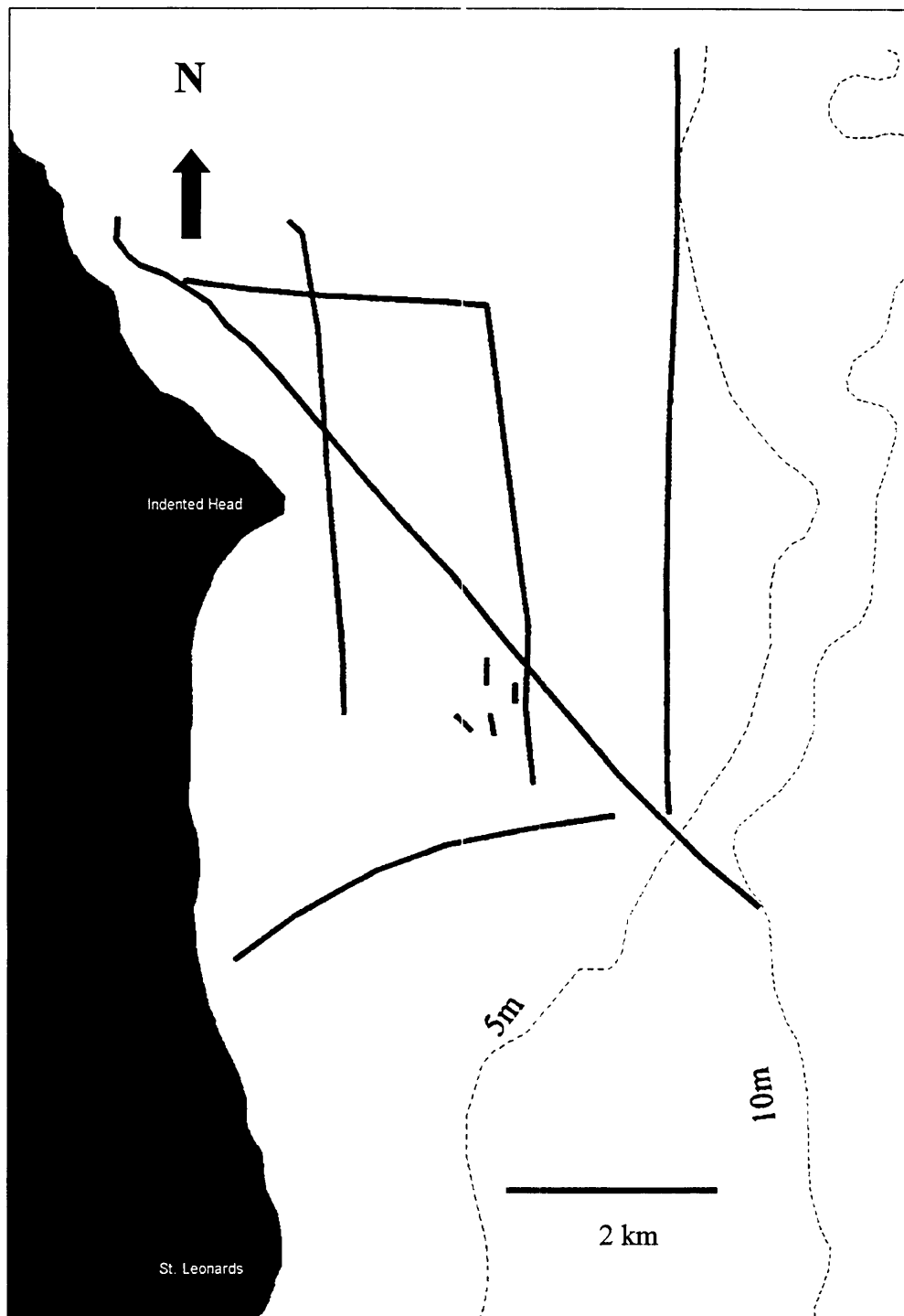


Figure 4-2 Indented Head - St Leonards ground truth transects (after Rollings et al. 1993).

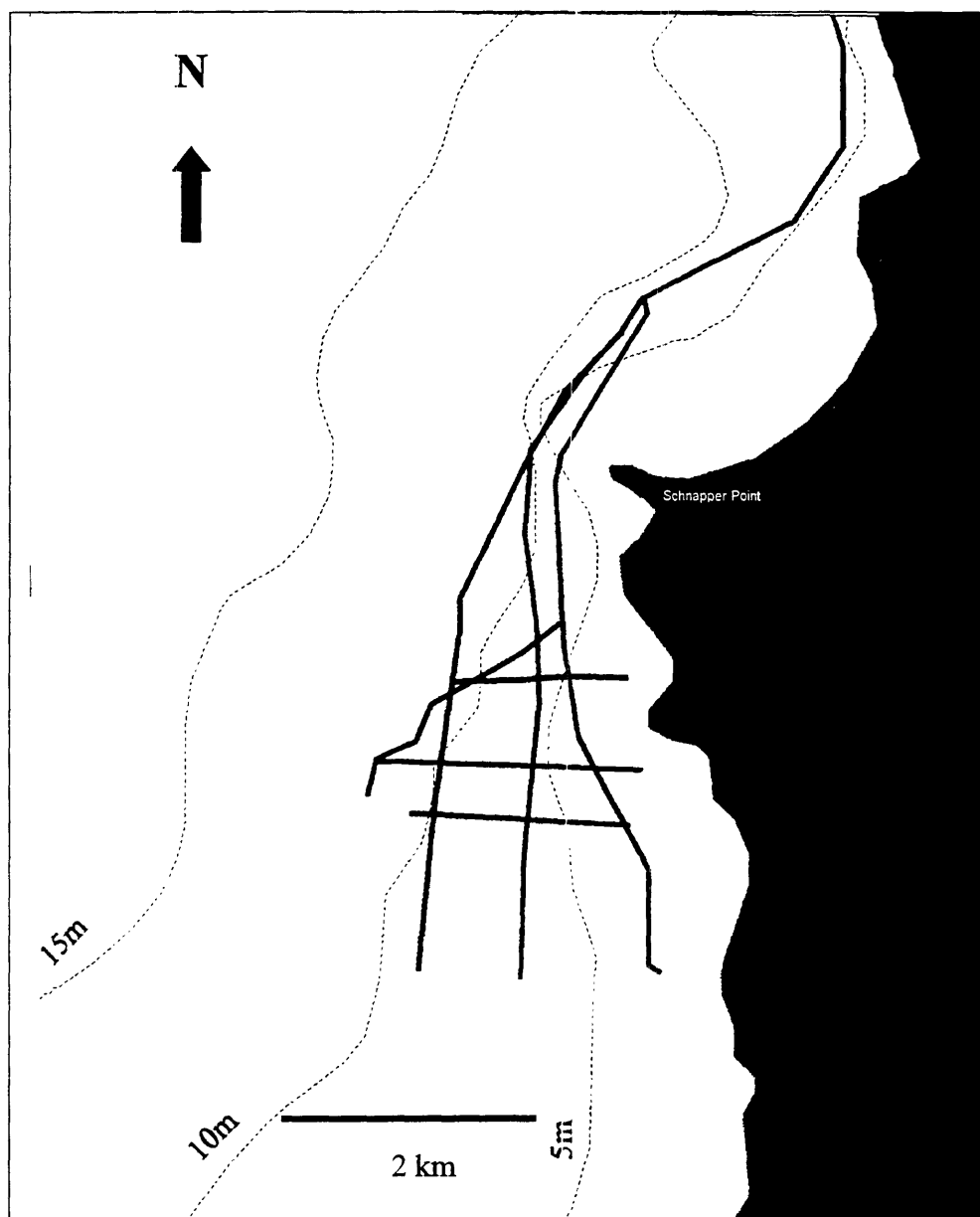


Figure 4-3 Mornington ground truth transects (after Rollings et al. 1993).

Off-shore deep water method

A deep-water (3-14 m) submerged sled method was developed to cover large areas of benthos rapidly. The procedure employed two people (driver and observer) on a sled that was towed behind a boat along pre-determined transects. A surveillance camera enclosed in a purpose-built waterproof housing was hard-wired to a monitor/video recorder on-board the vessel, providing a permanent data record. The VCR provided

a means to record voice communicated observations from the divers. Position fixing was provided by a real-time differentially corrected global positioning system (GPS). While being towed along transects, the divers estimating the benthic assemblages used the DAAP to “call” what they saw which was also recorded for later analysis.

Off-shore shallow water method

Shallow offshore water with irregular bathymetry precluded the use of the submersible sled. In this environment an observer was stationed on the bow of the vessel and called the boundary between assemblages according to the DAAP when bottom-visibility was appropriate. A series of short (< 300 m) transects positioned perpendicular to the benthic feature were traversed slowly. Position fixing was facilitated by differential GPS

Near-shore shallow water method

Close proximity to the shoreline and shallow water made the use of a large vessel and submersible sled unnecessary in this environment. Observations were made by snorkelers along transects. Transects approximately 500 m in length were projected and marked with a series of weighted buoys deployed from an inflatable craft. The observer snorkeled along the length of each transect assisted by a second person who acted as a scribe. Position fixing was facilitated by an electronic distance measure (EDM) procedure. Boundaries between benthic assemblages were “called” according to the DAAP, a prism locator was raised and the fix made and recorded by the EDM operator.

Data Processing of Field Data

All data were extracted from video and field logs and entered into a PC based spreadsheet. Field data were later entered into a GIS. Dominant plant assemblages, dominant animal assemblages and dominant plant / animal assemblages were tabulated as a function of environment (off-shore deep water, off-shore shallow water, near-shore shallow water), site (Indented Head - St Leonards, Mornington) substrate (soft, hard) and cover (< 5 % - bare substrate; 6-30 % - low; 31-70 % - medium; >70 % - high).

Field Validation Procedure – post image classification

A field validation procedure was developed and undertaken for each image classification. A 250 m spaced grid based on the AMG was overlain on the image and grid intercept coordinates for field checking were recorded. In addition, a series of representative habitat classes was selectively targeted, based on classification uncertainty and/or water depth, and coordinates recorded. All coordinates were entered into differential GPS as way-points, systematically located and spot-dived. A total of 46 coordinates were field validated at Indented Head - St Leonards. A further 16 coordinates were validated at Mornington.

4.3.5 Method - Remote Sensing

Four sources of remotely sensed imagery were assessed for their utility in mapping benthic habitats in PPB. These were:

- (a) Colour aerial photography;
- (b) Daedalus 1268 airborne thematic mapper;
- (c) Compact Airborne Spectrographic Imager (CASI); and
- (d) SPOT multispectral satellite imagery.

Acquisition of Images

A search of archived aerial photography was undertaken at VicImage, the State government supplier of maps and aerial photography. Two series of 1:25 000 colour aerial photography were selected for interpretation based on their clarity and depth penetration. The photography incorporated the Indented Head - St Leonards site only. Details of the aerial photography are presented in the full PPB report in Appendix - 2.

The Daedalus Airborne Thematic Mapper (DATM) 1268 is an 11 channel digital scanner recording in the visible (0.42 - 0.75 μm), near infrared (0.75 - 1.05 μm),

shortwave (or middle) infrared (1.55 - 2.35 μm) and thermal infrared (8.5 - 13.0 μm) regions of the EMS. It has a variety of settings (mirror speed, scan rate, as well as aircraft velocity and altitude) which need to be selected for a given mission, and to define the scale and spatial resolution of the product. To minimise the complexity of this choice, standard combinations of altitude, airspeed and mirror speed are normally provided. In addition to these geometric settings, the DATM has variable gain settings on each channel. These are often defined by experience and depend on the target features and the environmental conditions. The DATM has been utilised in studies of water quality in inland water bodies such as Lake Mokoan (Jupp et al. 1993) and has been applied to seagrass mapping at Corner Inlet (Allen and Ellis 1990).

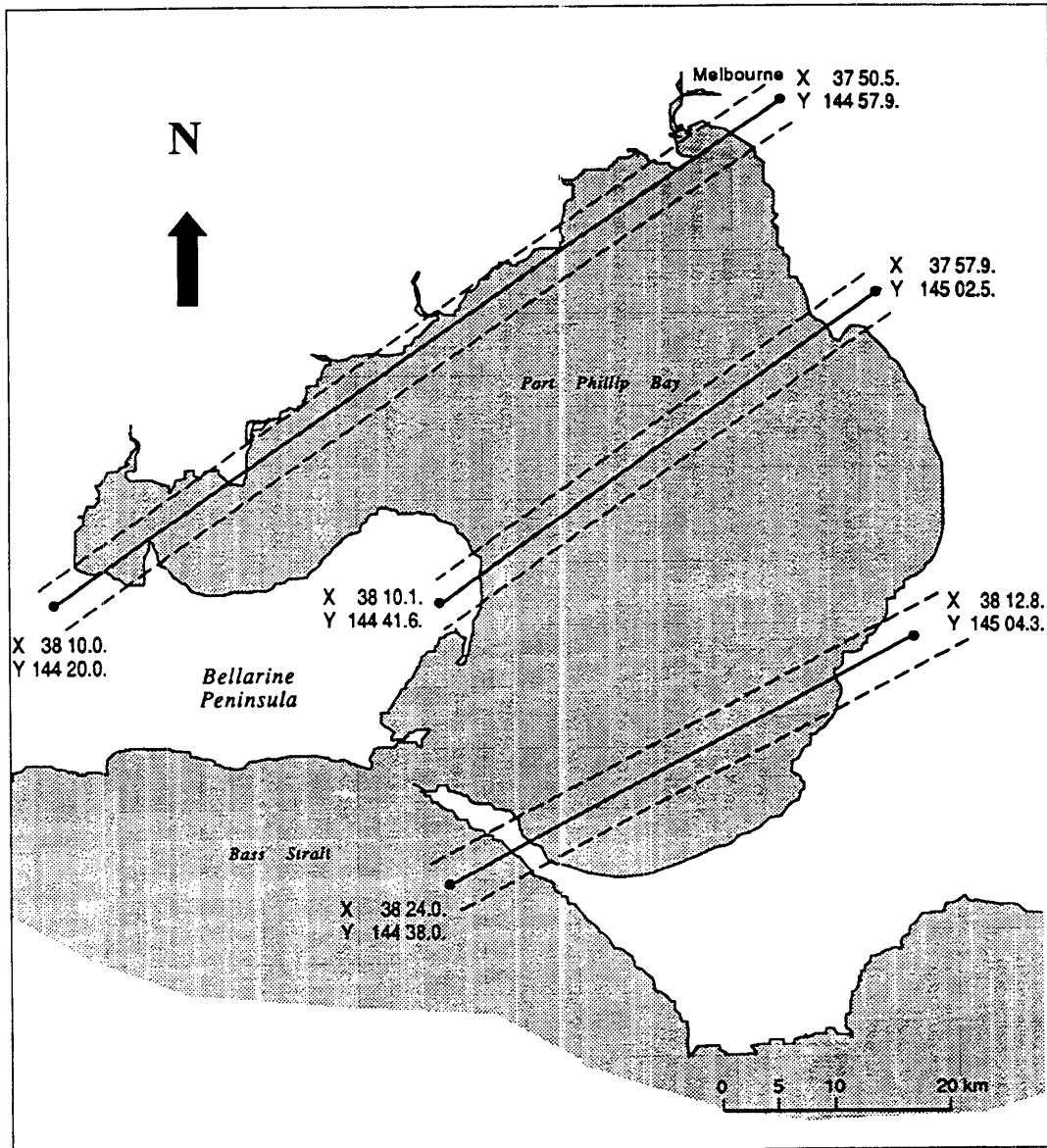
The CASI is an imaging spectrometer developed by ITRES Research (Canada). CASI was brought to Australia during the summer of 1992/3 to allow researchers to collect data on areas of interest and to become acquainted with the fine-resolution spectrometric data it acquires. The instrument operates in imaging mode with up to 15 programmable bands or spectrometer mode with 288 bands (intervals of 1.8 nm, limited spatial array). It has been used in oceanographic, agricultural, land-use, forestry and environmental impact applications in Europe, the Caribbean and North America, and more recently in Australia over Lake Mokoan (north east Victoria) and the Hawkesbury River (north of Sydney), (Jupp et al. 1993).

Both the Daedalus and CASI scanners acquire multi-spectral imagery that can be analysed using computer-based image processing methods. With appropriate information on the atmospheric conditions during the flight, the scanners provide measurements of the spectral distribution of radiation leaving the water as well as (in the case of the DATM), the temperature of the surface. Such measurements enable water bodies to be characterised based on their physical properties such as turbidity, light penetration, colour and surface temperature thus providing useful information for scientists and managers.

Airborne scanner data acquisition took place on the 12th of March, 1993 after three failed attempts due either to cloud cover or poor operating conditions on PPB.

Imagery was planned to be acquired between 1100 and 1300 and entailed simultaneous imaging by both the CASI and the Daedalus scanners. Flights were timed to coincide with late morning low tide in order to minimise the depth of water over benthic features. Flights were also planned to maintain a solar elevation angle of less than 60 degrees (to avoid sunglint) and such that the aircraft would fly directly into or away from the sun (thus avoiding across-track effects). Operational considerations meant however, that imaging was actually undertaken between 1357 and 1604 when the geometry of the sun and the aircraft were not at an optimum configuration.

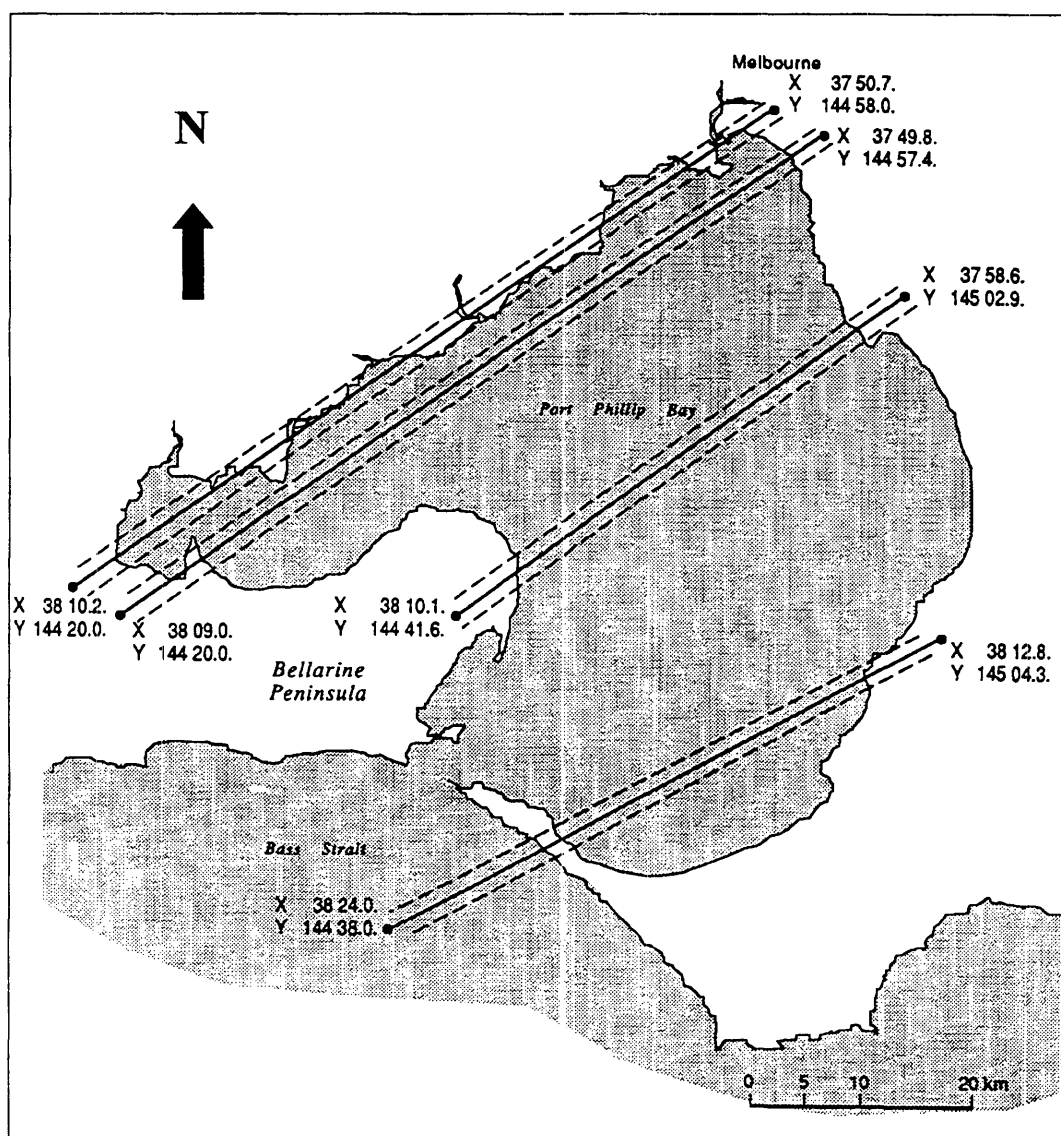
The Daedalus 1268 was flown by Air Target Services, Nowra aboard a Lear Jet. An altitude of 13,200 ft above sea level provided a 10 m pixel and a 5 km swath. The scanner imaged along three planned flight lines totalling 163 km. The central run (Run 2) incorporated the Indented Head - St Leonards site, and the southern-most run (Run 1) incorporated the Mornington site (Figure 4-4). A third run (Run 3) was flown for the chlorophyll modelling research reported in chapter 4.4



Useable swath width is 4000 m. X,Y coordinates indicate latitude and longitude of the start and finish points for each run.

Figure 4-4 Daedalus 1268 flight lines for PPB project (from Rollings et al. 1993).

The CASI was flown aboard a Cessna by CSIRO Office of Space Sciences and Applications (COSSA). An altitude of 10 500 ft provided a 5 m pixel and a 2.5 km swath. This scanner imaged along four flight lines in spatial mode and one flight line in spectral mode, totalling 231 km (Figure 4-5).



Useable swath width is 2000 m. X,Y coordinates indicate latitude and longitude of the start and finish points for each run.

Figure 4-5 CASI flight lines for PPB case study (from Rollings et al. 1993).

Image bandwidths for the CASI and Daedalus, flight logs, including solar elevation and azimuth angles, tide heights at the study areas; wind speed and cloud conditions on the day of the overpass are given in Rollings et al. (1993) included in Appendix 2.

A programming request for SPOT data acquisition was placed with Spot Imaging Services, Sydney for the period 2nd January to 28th June, during which 12 multispectral images (which were at least partially cloud free and potentially useable) were acquired. The image acquired on 13 January 1993 was selected for analysis.

Image Processing and Analysis

Data import

The Indented Head - St Leonards aerial photographs were scanned into a digital, raster data format using a flatbed colour scanner (*Model JX-450*, Sharp, Japan) at a resolution of 150 dots per inch. This provided the finest pixel resolution of all datasets while being acceptable for interpretation and maintaining a manageable dataset in terms of size.. The scanned images were stored in a standard band-interleaved-by-file data structure supported by the scanning software (QSCAN II) and read into microBRIAN using a generic import facility.

The Daedalus imagery was received on a single 2.3 Gbyte exabyte tape. These data were read using an Apollo based system at the Australian Antarctic Division. Once downloaded onto disk, the Daedalus images were imported into microBRIAN using the Daedalus import facility (DATM2MB).

CASI data was supplied on five 2.3 Gbyte exabyte tapes. These images were then loaded onto the Sun workstation disk at RMIT. The difficulty reading these tapes suggests a problem with the ITRES software in producing the tar format. Other CASI users have experienced this difficulty (Jupp, pers. comm. 1993). CASI images were imported into microBRIAN using the PCI import facility (PCI2MB). The SPOT image was supplied on a single 2.3 Gbyte exabyte tape and loaded onto the RMIT system. The image was loaded into microBRIAN using a generic import facility.

Field data (position, dominant plant assemblage, total plant cover, dominant animal assemblage, substrate type, water depth) were imported into ARC/INFO as point coverage's and presented as an overlay on the imagery.

Image rectification

Digital data sets were rectified to the Australian Map Grid, Zone 55 using standard microBRIAN rectification procedures based on terrestrial derived ground control only. Ground control points were scaled off 1:2 500 plan maps supplied by Melbourne Water Corporation and the Geelong District Water Board. Rectification

model root mean square (rms) and predictive errors are tabulated and are given in Rollings et al. (1993) included in Appendix 2.

Each digital dataset was resampled to the geographic boundaries of the benthic study areas. A list of the image files produced and their respective pixel sizes are summarised in Table 4-2.

Table 4-2 Rectified images and corresponding pixel size for PPB case study.

Platform/Sensor	Pixel Size (m)
Daedalus 1268	5
CASI	5
Aerial Photography – Indented Head	1.8
Spot	10

A series of randomly selected points were used to test image derived pixel locations to true location as determined from 1:2 500 maps. The position residuals of these points are summarised in Rollings et al. (1993) included in Appendix 2. A further analysis of the rectification of airborne scanner imagery in areas of little or no ground control was undertaken using the Daedalus 1268 imagery. This analysis is presented in Appendix 2.

Image Processing and Enhancement

All land was masked from the study area images in microBRIAN. Linear contrast stretches and logarithmic stretches were applied depending on the individual image characteristics. Based on field data and visual interpretation, bands that appeared to be noise dominated or offered poor water column penetration were eliminated from further analysis. A series of band ratios were performed on each image in order to minimise inter-band correlation. The principal component transformation algorithm in microBRIAN was applied to the imagery as a data compression and exploration technique. The land masked images, ratioed images and the principal component images were further enhanced and displayed in ARC/INFO (using a 24 bit colour, RasterOps display board).

Image Interpretation

Colour aerial photography - on screen interpretation

The digitally enhanced Indented Head - St Leonards colour aerial photography was interpreted using traditional photo-interpretive procedures based on colour, tone, texture, shape and location. The enhanced images were displayed in ARC/INFO using a system equipped with a 24 bit colour board, which enabled maximum contrast to be achieved. The field data were then overlain and displayed according to the dominant assemblage, total plant cover substrate type and depth. An interpretive key was developed and the entire image interpreted for benthic features by drawing boundaries around discernible assemblages using the mouse.

Image Classification

Processed and enhanced images were used as a guide for supervised training in microBRIAN. Figure 4-6 shows a map of PPB indicating image subsets (aerial photographs, Daedalus, CASI and SPOT) used in dominant benthic assemblage classification at Indented Head - St Leonards and Mornington. Training areas were selected based on dominant assemblage, total plant cover, substrate type and depth. Standard microBRIAN classification routines utilising a minimum distance algorithm were then applied. In areas where the field data poorly matched interpretable features, an unsupervised classification approach was used. The minimum distance classifier was chosen because it was found that the information classes generated by training were more spherically distributed than elongate, as commonly encountered in terrestrial systems. MicroBRIAN also has a very complete set of indicators to judge the statistical significance of class separability.

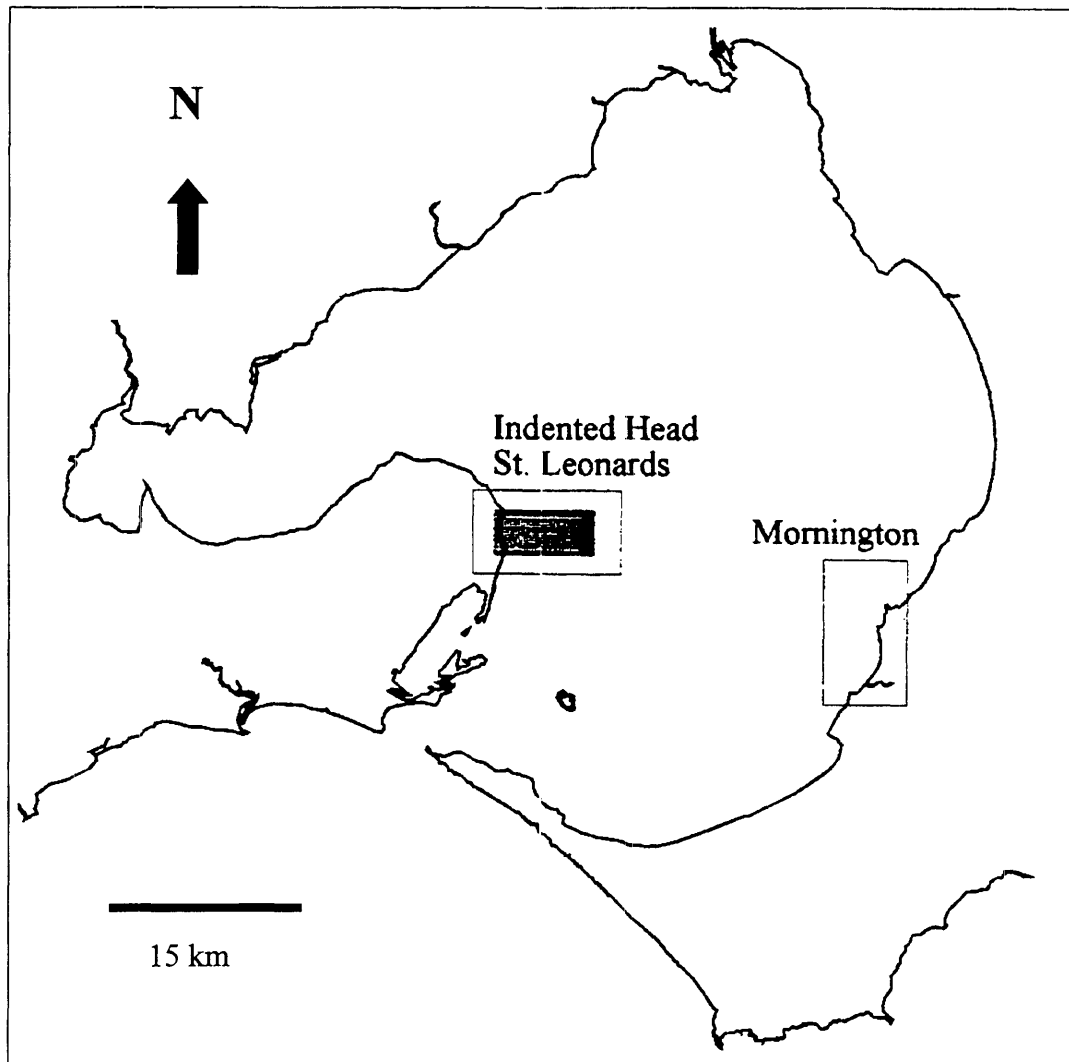


Figure 4-6 Location of images used in Research Case Study 2 (after Rollings et al. 1993). Black inset at Indented Head site represents coverage of aerial photography.

Map Production and Verification

Plots were produced on a Colour Electrostatic Plotter (Raster Graphics, T.G.A, Australia) for each interpretation at each study area. These plots and the ground verification procedure are described in the section 4.3.4. The results of the field exercise were subsequently used to construct error matrices in order to gauge the thematic accuracy of each spectral class.

The spectral separability of two class means in a classification procedure is difficult to quantify. Often, supervised training is attempting to divide a continuous multi-spectral space into meaningful information classes. MicroBRIAN provides a statistic

that may be used to give an indication of spectral separability and the significance of this separation. However, it is the final accuracy assessment via a confusion matrix that is the ultimate test of the accuracy of a class (Jupp pers. comm. 1993). A confusion matrix is used in remote sensing not only to give an estimate of the accuracy of a classification but also the direction of that error. A confusion matrix assesses a set of randomly selected pixels and compares its classification compared to ground data. If a misallocation occurs, the class into which it was incorrectly placed is recorded. The direction of errors can then be determined. An error of commission indicates a pixel was allocated to a class when it is in fact not a member of that class. An error of omission results when a pixel is not allocated to a class when it is a member of that class. Errors of omission and commission are useful as they give an indication as to the direction of the error that can then be compared with the classes position in the canonical variate crossplot. A Ward's incremental sum of squares test was used to gauge whether the spectral separation of classes was statistically significant (CSIRO 1992b). Non significant classes were merged.

Data Import into ARC/INFO GIS

Classification files produced in microBRIAN were exported to ERDAS using a standard export facility. Classes were grouped according to dominant plant assemblage and cover, and the classification files recoded according to this new schema. The ERDAS files were then converted into GRID format and a raster to vector conversion was applied.

4.3.6 Results - Field Investigations

Off-shore deep water environments

A total of 12 dominant benthic plant assemblages was identified in the offshore deep water environments at Indented Head - St Leonards and Mornington (Table 4-3).

Table 4-3 Dominant plant assemblages for off-shore deep water environments (after Rollings et al. 1993).

Indented Head - St Leonards (IH-SL) and Mornington. Soft substrate includes sand, shelly sand, and interstitial spaces within cobbly sand. Hard substrates include all hard surfaces within cobbly sand, bouldery sand and reef.

Total plant cover categories: B = bare substrate (<5%), L = low (6-30%). M = medium (31-70%), H = high (>70%). P denotes dominant benthic assemblage is present.

Benthic plant assemblage Dominant plant component	IH-SL								Mornington							
	Soft				Hard				Soft				Hard			
	B	L	M	H	B	L	M	H	B	L	M	H	B	L	M	H
<i>Caulerpa</i>	-	P	P	P	-	-	-	-	-	P	P	P	-	-	-	P
Filamentous red algae	-	-	-	-	-	-	-	-	-	P	-	-	-	P	P	P
<i>Giffordia</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Heterozostera</i>	-	-	P	P	-	-	-	-	-	-	-	-	-	-	-	-
<i>Sargassum</i>	-	-	-	-	-	P	P	P	-	-	-	-	-	P	P	P
<i>Caulerpa</i> /Filamentous red algae	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	P
<i>Caulerpa</i> /Heterozostera	-	P	P	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Caulerpa</i> /Sargassum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	P
Filamentous red algae/Sargassum	-	-	-	-	-	-	-	-	-	-	-	-	-	P	P	P
<i>Sargassum</i> /Ecklonia	-	-	-	-	-	-	-	P	-	-	-	-	-	-	-	-
<i>Caulerpa</i> /Filamentous red algae/Sargassum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	P
<i>Caulerpa</i> /Sargassum	-	-	-	-	-	-	-	P	-	-	-	-	-	-	-	-

Off-shore shallow water environment

Three dominant benthic plant assemblages were identified in the offshore shallow water environment at the Indented Head - St Leonards site. All were substrate specific, with *Caulerpa* being associated with soft substrate and *Sargassum* and *Caulerpa* / *Sargassum* being associated with hard substrate (Table 4-4). *Caulerpa* had total cover values ranging from low to medium whereas *Sargassum* had total cover values ranging from medium to high. *Caulerpa* / *Sargassum* exhibited total cover > 70 % (high). Two assemblages were specific to hard substrate whereas a single assemblage was specific to soft substrate (Table 4-4). The dominant benthic assemblage comprising *Caulerpa* / *Sargassum* exhibited total plant cover > 70 %.

Table 4-4 Summary of benthic assemblage composition in the off-shore, shallow water environment at Indented Head - St Leonards (after Rollings et al. 1993).

Soft substrates include sand, shelly sand and interstitial spaces within cobbly sand. Hard substrates include all hard surfaces within cobbly sand, bouldery sand and reef.

Total plant cover categories: B = bare substrate (<5%), L = low (6-30%). M = medium (31-70%), H = high (>70%).

P denotes dominant benthic assemblage is present.

Dominant plant assemblage	Soft				Hard			
	B	L	M	H	B	L	M	H
<i>Caulerpa</i>	-	P	P	-	-	-	-	-
<i>Sargassum</i>	-	-	-	-	-	-	P	P
<i>Caulerpa/Sargassum</i>	-	-	-	-	-	-	-	P

4.3.7 Results - Remote Sensing Analysis

Colour Aerial Photography

Digital Air Photograph Interpretation

A total of 82 distinct polygons were classified in the enhanced aerial photograph of Indented Head - St Leonards, of which ten discernible classes were identified (Table 4-5). In terms of frequency of occurrence and areal extent, *Caulerpa* was the most dominant class whereas *Ecklonia* was the least dominant class. Eight classes comprised benthic flora whereas two classes (bare substrate, deep water) comprised neither flora nor fauna. No classes were identified on the basis of benthic fauna. Within the vegetated classes, five dominant plant assemblages were identified. Three assemblages (*Caulerpa*, *Sargassum*, *Caulerpa* / *Heterozostera*) exhibited more than one cover value whereas two assemblages (*Heterozostera*, *Ecklonia*) were specific to a single total plant cover. Among the vegetated classes, *Caulerpa*, *Heterozostera* and *Caulerpa* / *Heterozostera* were difficult to distinguish from one another, whereas *Ecklonia* and *Sargassum* were more easily discernible.

Table 4-5 Classification/Interpretation summary for dominant plant assemblages for scanned photography, CASI and SPOT at Indented Head - St Leonards (after Rollings et al. 1993).

Total plant cover categories: B = bare substrate (<5%), L = low (6-30%). M = medium (31-70%), H = high (>70%).

Areas are expressed in 10⁴ m².

Dominant plant assemblage	Aerial photography				CASI				SPOT			
	L	M	H	Total	L	M	H	Total	L	M	H	Total
<i>Caulerpa</i>	114.9	38.3		153.2	90.7	26.30	8.60	125.6				57.06
<i>Ecklonia</i>				0.951				0.97				9.11
<i>Heterozostera</i>				3.730		2.67	4.01	6.68				16.37
<i>Sargassum</i>		0.136	0.132	0.268				5.55				21.74
<i>Caulerpa/Heterozostera</i>		11.35	3.027	14.38								
Bare Substrate			80.92				47.32					132.93
Other (areas not classified)			18.1				87.01					39.31
Total			272.20				273.18					276.65

Classification Accuracy

Compilation of a confusion matrix for the interpreted aerial photograph of Indented Head - St Leonards compared to field verified assemblages demonstrates that all classes that were represented suffered either errors of omission or commission (Table 4-6). When summarised into errors of omission and commission it is apparent that insufficient points were used for three of the five classes (Table 4-7).

Table 4-6 Confusion matrix for aerial photography interpretation at Indented Head - St Leonards with dominant assemblage assessment protocol derived classes (from Rollings et al. 1993).

BAAP = Benthic Assemblage Assessment Protocol. Mean class separation is significant at the 90% confidence limit. Based on thirty randomly selected points.

As interpreted	Bare	<i>Caulerpa</i>	<i>Caul./Sargassum</i>	<i>H-zostera</i>	<i>Sargassum</i>	<i>Ecklonia</i>	Total
----------------	------	-----------------	------------------------	------------------	------------------	-----------------	-------

BAAP							
Bare	4	4					8
<i>Caulerpa</i>	1	12		2			15
<i>Caul./Sarg</i>			0				0
<i>H-zostera</i>		1		0			1
<i>Sargassum</i>		1	2		1		4
<i>Ecklonia</i>						2	2
Total	5	18	2	2	1	2	30

Table 4-7 Error summary for aerial photograph interpretation at Indented Head - St Leonards (from Rollings et al. 1993).

Assemblage	Omission %	Commission %
Bare	50	10
<i>Caulerpa</i>	20	33
Seagrass *	100	100
<i>Sargassum</i> *	25	0
<i>Ecklonia</i> *	-	-

* Based on 5 pixels or less.

CASI Indented Head - St Leonards

Image Classification

The output from the CASI classification of Indented Head - St Leonards is consistent with field data and shows that benthic assemblages are dominated by *Caulerpa* (Figure 4-7). A total area of 2.727E+06 m² was classified in the CASI image of Indented Head - St Leonards. Unclassified areas totalled < 7 % of the total image. A cross-plot of canonical variates axes one and two for 18 discernible information classes in the CASI image shows that class separation was very good (Figure 4-8). Twelve classes comprised benthic macrophytes whereas five classes contained no flora. A single deep water class was also classified.

Of the 2 classes comprising benthic macrophytes, four dominant plant assemblages were identified, two of which (*Caulerpa* and *Heterozostera*) exhibited more than a single cover value. From six *Caulerpa* classes, five grouped closely in multispectral space and exhibited a gradient in total plant cover. The sixth *Caulerpa* class appeared somewhat anomalous in having similarity with *Heterozostera*, suggesting that this class may in fact be a macroalgae / seagrass mix. Two *Ecklonia* classes exhibited distinct spectral characteristics, as did two *Sargassum* classes. Five bare substrate classes exhibited poor similarity due to varying concentrations of

pigment in the sediments. These classes appear spectrally distinct from all other classes excluding low cover *Caulerpa*.

Caulerpa was the dominant macrophyte plant assemblage in terms of cover, whereas *Ecklonia* was the least dominant (Table 4-5). Low cover *Caulerpa* was the most dominant vegetated class whereas high cover *Heterozostera* was the least dominant.

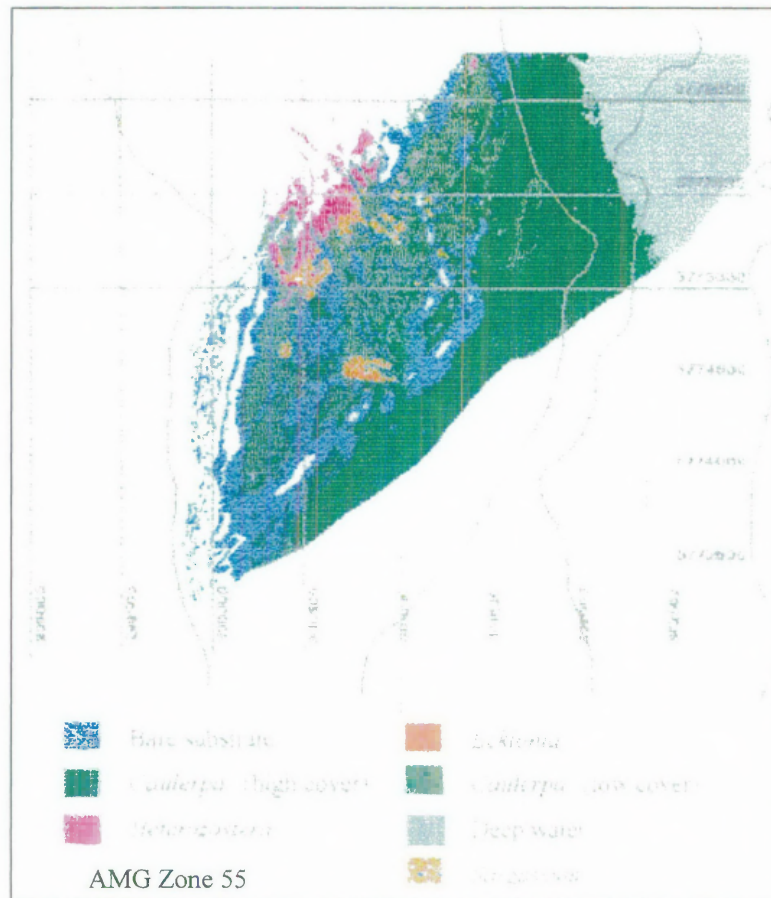


Figure 4-7 CASI classification at of Indented Head - St Leonards (from Rollings et al. 1993).

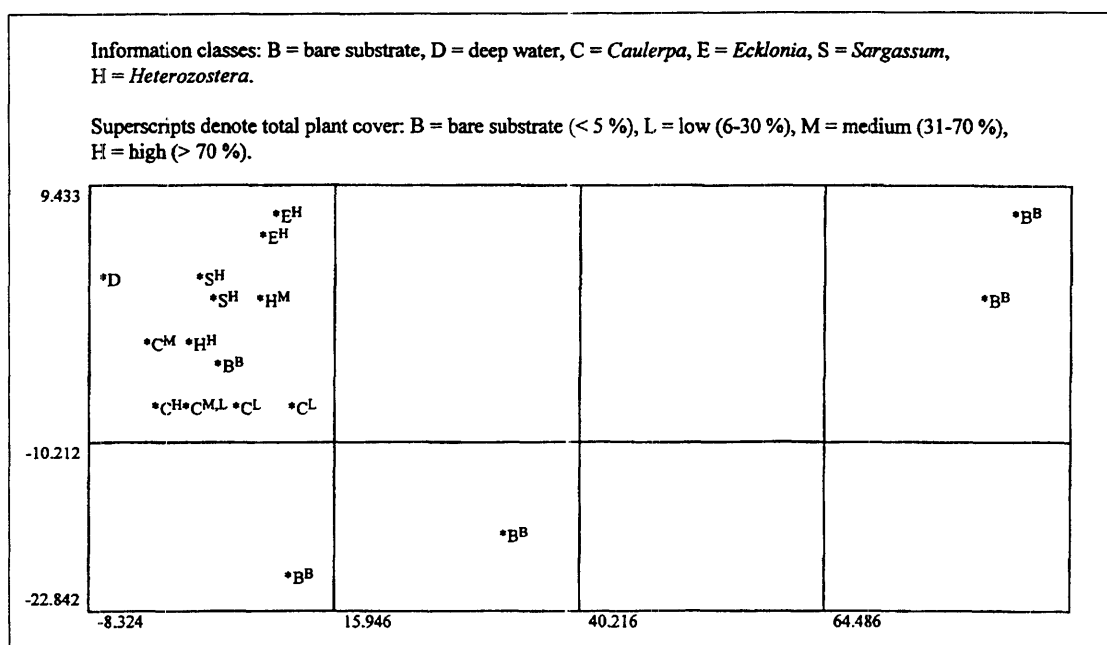


Figure 4-8 Canonical variates plot for CASI at Indented Head - St Leonards (from Rollings et al. 1993).

Classification Accuracy

Table 4-8 shows a confusion matrix based on 43 randomly selected points from the classified CASI image of Indented Head - St Leonards, compared to field verified assemblages. Following analysis of the Ward's statistic (Table 4-9) non-significant classes were merged (Table 4-10). A confusion matrix was also generated with the BAAP classes simplified and different cover values in each class merged (Table 4-11). Errors of omission and commission varied from 0 - 80%, although assessment of three classes was made on insufficient pixels (Table 4-12). During training of the Indented Head - St Leonards image, mixed assemblages were not trained as classes. Mixed assemblages were left to the classification routine to see where they would be allocated (Table 4-13). For CASI, mixed classes were invariably allocated to one of the members of the mixed class. SPOT however did not always allocate mixed classes to a member class (Table 4-13).

Table 4-8 Classification assessment for CASI at Indented Head - St Leonards, with dominant assemblage assessment protocol derived classes (after Rollings et al. 1993).

Numbers in cells refer to field site locations as found in the PPB Historical Database.

		Class number													
		Assemblage as classified													
		Cover													
		Depth/Substrate													
Assemblage (BHA Protocol)	Cover	1. Bare.	2. Bare	3. <i>Caul.</i>	4. <i>Caul.</i>	5. <i>Caul.</i>	6. <i>Caul.</i>	7. <i>H-zost.</i>	8. <i>H-zost.</i>	9. <i>Sarg.</i>	10. <i>Sarg.</i>	11. <i>Caul.</i>	12. Bare	13. <i>Caul.</i>	16. <i>Eck.</i>
		-	5m	-	-	-	-	-	-	reef	boulder	2	- shallow	-	-
Bare sand			7, 8F, 3A, 3B				21, 6H					21		61	
<i>Caulerpa</i>	3								4						
<i>Caul./Fil. red algae</i>	2		11	8H	4L	15, 2L			16, 3L			8E, 7E			
"	3			9G	17			4F, 3G	5, 2K					6J, 4K	
"	4														
<i>H-zostera/Sarg.</i>	3									6					
<i>Sargassum</i>	1							3F							
"	2									18					
"	3									7H	8 (cobble sand)				
"	4														

Table 4-8 cont.															
<i>Sarg./Fil. red algae</i>	2									9					
"	3														
<i>Caul./Fil. red algae</i> <i>/Sarg.</i>	2	10					6G								
"	3														
"	4					13									
<i>Sarg./Caul</i>	1		11												
"	2														
"	3								14						
<i>H-zostera/Fil. red</i> <i>algae</i>	2	6F						12							
"	3													5L	
"	4														
<i>Fil. red algae</i>	2		7I	9H, 8I										7J	
"	3														
<i>Ecklonia</i>	4														1A, 1B

Table 4-9 Suggested Class Mergings for Classification Statistics Using Ward's Incremental Sum of Squares Sorting for CASI Classification at Indented Head (from Rollings et al. 1993).

Ward's statistic shown in **bold** represent those that are statistically significant.

Suggested Classes to Merge		New Class	Ward's Statistic ($\alpha = 17.275$ at 90% conf. limit.)
9 - Sargassum	10 - Sargassum	Sargassum	1.106
3 - Caulerpa 2	4 - Caulerpa 4	Caulerpa 2/3	3.987
6 - Caulerpa 2	13 - Caulerpa 3	Caulerpa 2/3	4.850
5 - Caulerpa 3	8 - Seagrass	Caulerpa 2/3	5.303
1 - Bare	6 - Caulerpa 2	Bare	13.733
1 - Bare	11 - Caulerpa 2	N.A.	25.091
5 - Caulerpa 3	14 - Deep Water	N.A.	46.542
1 - Bare	3 - Caulerpa 3	N.A.	58.978
7 - Seagrass 3	9 - Sargassum 4	N.A.	68.067
15 - Ecklonia	16 - Ecklonia	N.A.	87.267
5 - Caulerpa 3	7 - Seagrass 3	N.A.	136.243
1 - Bare	2 - Caulerpa 2	N.A.	204.203
17 - Bare	18 - Bare	N.A.	254.658

N.A. = not applicable

Table 4-10 Confusion matrix for classified CASI image of Indented Head, compared to field verified assemblages – non-significant, similar classes merged.

Numbers in cells refer to field site locations as found in the PPB Historical Database (from Rollings et al. 1993).

		Class number Assemblage as classified Cover Depth/Substrate									
Assemblage (BAA Protocol)	Cover	1.+ 6 Bare	2. Bare	3. + 4. <i>Caul.</i>	5. + 8. <i>Caul.</i>	7. <i>H.zost</i>	+ 10. <i>Sarg.</i>	11. <i>Caul.</i>	12. Bare	13. <i>Caul.</i>	16. <i>Eck.</i>
		-	-	2/3	3	3	4	2	-	-	-
		-	5m	-	-	-	-	-	shallow	-	-
Bare sand		21, 6H	7, 8F, 3A, 3B					21		61	
<i>Caulerpa</i>	3				4						
<i>Caul./Fil. red</i>	2	11		4L, 8H	2L, 3L, 15, 16			8E, 7E			
“	3			9G, 17	2K 5	3G, 4F				6J, 4K	
“	4										81
<i>H-zostera/Sarg.</i>	3						6				
<i>Sargassum</i>	1					3F					
“	2						18				

Table 4-10 cont.

“	3						7H, 8				
“	4										
<i>Sarg./Fil. red algae</i>	2						9				
“	3										
<i>Caul/Fil. red algae/Sarg.</i>	2	6G, 10									
“	3										
“	4				13						
<i>Sarg./Caul.</i>	1		11								
“	2										
“	3				14						
<i>H-zostera/Fil. red algae</i>	2	6F				12					
“	3									5L	
“	4										
<i>Fil. red algae</i>	2		7I	9H, 8I						7J	
“	3										
<i>Ecklonia</i>	4										1A, 1B

Table 4-11 Classification assessment for CASI at Indented Head - St Leonards, with dominant assemblage assessment protocol derived classes (from Rollings et al. 1993).

BAAP = Benthic Assemblage Assessment Protocol. Mean class separation is significant at the 90% confidence limit.

Assumptions: BAAP categories of *Caulerpa*/Filamentous red algae/*Sargassum* have been included in either the *Caulerpa* or Bare class. The Filamentous red algae category has been included in the *Caulerpa* class.

As interpreted	Bare	<i>Caulerpa</i>	<i>H-zostera</i>	<i>Sargassum</i>	<i>Ecklonia</i>	Total
----------------	------	-----------------	------------------	------------------	-----------------	-------

BAAP						
Bare	8	2				10
<i>Caulerpa</i>	2	17	2			21
<i>H-zostera</i>	1	2	1	1		5
<i>Sargassum</i>			1	4		5
<i>Ecklonia</i>					2	2
Total	11	21	4	5	2	43

Table 4-12 Errors of Omission and Commission for simplified CASI classification of Indented Head - St Leonards.

Assemblage	Omission %	Commission %
Bare	20	26
<i>Caulerpa</i>	19	19
<i>Seagrass</i> *	80	75
<i>Sargassum</i> *	20	20
<i>Ecklonia</i> *	0	0

Note: Based on 5 pixels only.

Table 4-13 Allocated Classes for Mixed Assemblages not Trained during classification - Indented Head - St Leonards Image (from Rollings et al. 1993).

Field Assemblage	As Classified by CASI	As Classified by SPOT
<i>Caulerpa/Heterozostera</i>	- <i>Caulerpa</i> - <i>Heterozostera</i>	- <i>Caulerpa</i> - <i>Heterozostera</i> - Bare
<i>Caulerpa/Sargassum</i>	- <i>Caulerpa</i> - <i>Sargassum</i>	- <i>Caulerpa</i> - Bare
<i>Caulerpa/Heterozostera/Sargassum</i>	- <i>Sargassum</i> - <i>Caulerpa</i> - Bare	- <i>Sargassum</i> - <i>Caulerpa</i> - Bare
<i>Heterozostera/Fil.Red</i>	- <i>Heterozostera</i>	- <i>Heterozostera</i>
<i>Sargassum/Ecklonia</i>	- <i>Sargassum</i> - <i>Caulerpa</i> - Bare	- <i>Ecklonia</i> - <i>Caulerpa</i> - Bare

CASI - Mornington

Image Classification

The distribution of benthic assemblages at Mornington based on the classification of CASI imagery is shown in Figure 4-9. The image was divided into 18 information classes representing all assemblages identified in the BAAP, including mixed assemblages.

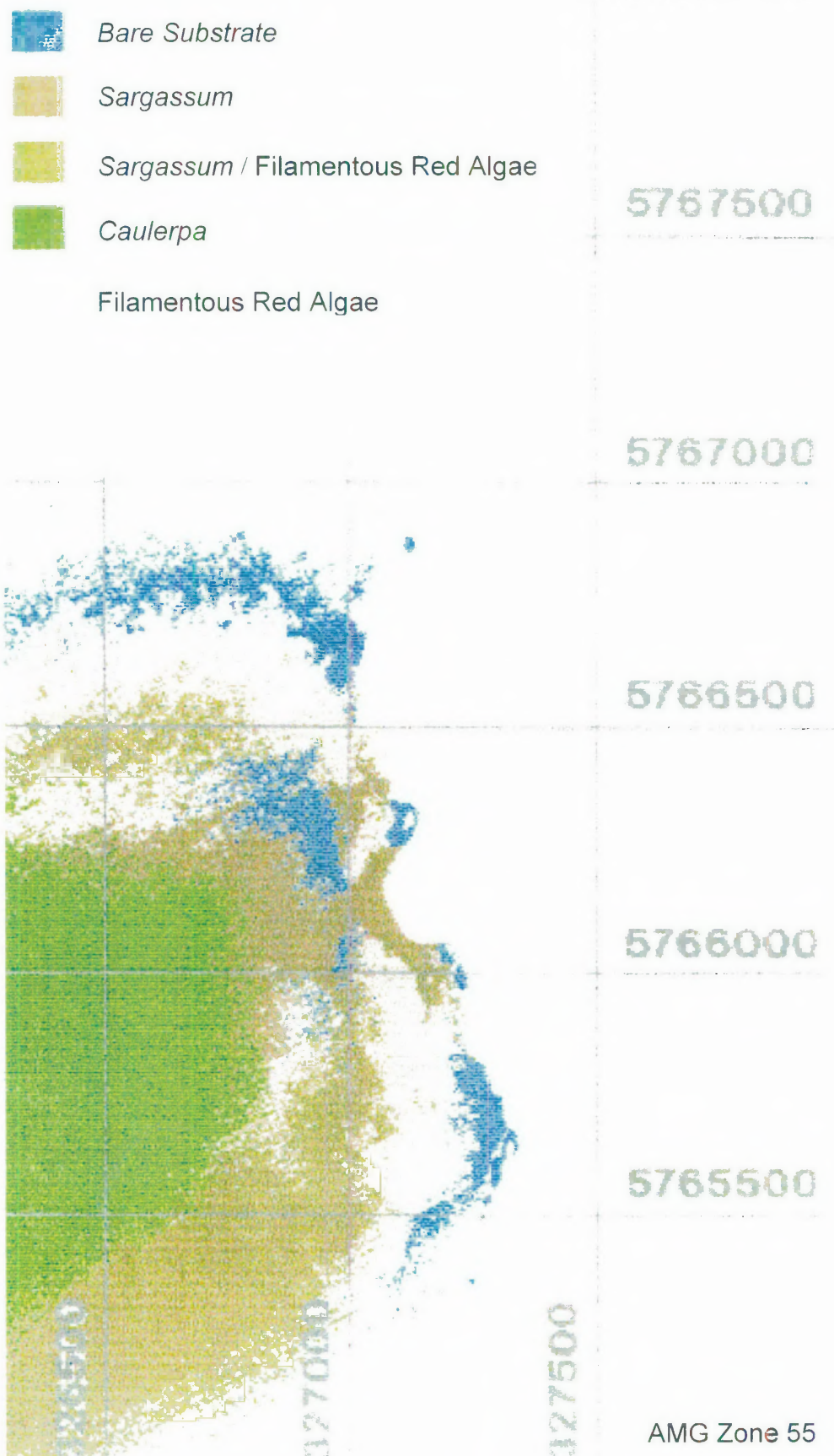


Figure 4-9 Classification of CASI image for Mornington (after Rollings et al. 1993).

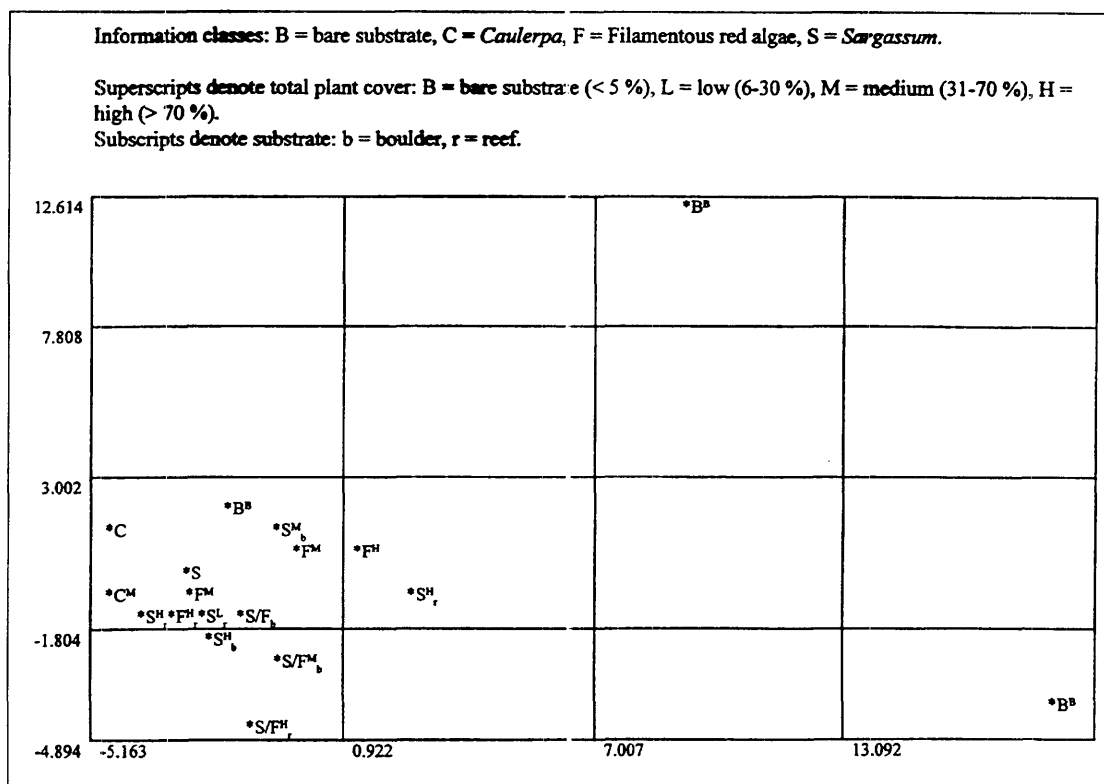


Figure 4-10 Cross plot of canonical variates axes for classification of CASI for Mornington (from Rollings et al. 1993).

Classification Accuracy

Of the sites tested, a confusion matrix shows that mainly Filamentous red assemblages were encountered despite *Caulerpa* being the dominant cover-type (Table 4-14 and Figure 4-9). Many of the *Caulerpa* beds occurred in deeper water and might have been inadvertently under-represented due to diving restrictions. Of seventeen defined classes, five are spectrally separable according to the Ward's statistic (Table 4-15).

Table 4-14 Confusion matrix for CASI classification over Mornington study site (from Rollings et al. 1993).

Numbers in cells refer to field site locations as in the PPB Historical Database.

		Class number Assemblage as classified Cover Depth/Substrate															
Assemblage (Benthic Assessment Protocol)	Cover	1. <i>Sarg.</i> - 4 boulder	2. <i>Sarg.</i> - 4 reef	3. <i>Sarg.</i> - 3 boulder	4. <i>Sarg.</i> or <i>Caul.</i> 2 boulder	5. <i>Sarg.</i> - 4 reef, shallow	6. <i>Caul.</i> - 2 -	7. <i>Caul.</i> - 3 -	8. Fil. red - 3 shallow	9. Fil. red - 4 deep	10. Fil. red - 4 deep	11. Fil. red 3 deep	12, 17, 18. Bare - -	13. <i>Sarg./</i> Fil. red 4 reef	14. <i>sarg./</i> Fil. red 2 reef	15. <i>Sarg./</i> Fil. red 3 boulder	16. <i>Sarg./</i> Fil. red 2 boulder

Bare substrate									8				35				11, 38
Fil. red algae	1								36						1		
"	2							33	34, 38					2			
"	3						5						29		4		
"	4											12					
<i>Caul</i> /Fil red algae	4								14								
<i>Sarg</i> /Fil. red algae	4																
<i>Sarg</i> /Fil. red/Fil. green algae	4	20 (4.5m, boulder															

Table 4-15 Suggested Class Mergings for Classification Statistics Using Ward's Incremental Sum of Squares Sorting for CASI Classification at Mornington (from Rollings et al. 1993).

Ward's statistic shown in **bold** are statistically significant.

Suggested Classes to Merge		New Class	Ward's Statistic ($\alpha = 17.275$ at 90% conf. limit.)
11 - Fil Red 3	14 - Sarg.Fil Red 2 on reef	Fil Red 3	0.490
* 10 - Fil Red 4	16 - Sarg Fil Red 2 on boulder	Fil Red 3	1.378
* 8 - Fil Red 3	9 - Fil Red 4	Fil Red 2	1.420
10 - Fil Red 4	11 - Fil Red 3	Fil Red 4	1.623
* 6 - Caul 2	7 - Caul 3	Caul 3	1.901
* 3 - Sarg 3 on boulder	12 - Bare	Sarg 3	2.358
* 2 - Sarg 4 on reef	4 - Sarg or Caul 2 on boulder	Sarg 4	3.195
* 2 - Sarg 4 on reef	6 - Caul 2		3.859
3 - Sarg 3 on boulder	8 - Fil Red 3	Fil Red 2/3	6.398
* 10 - Fil Red 4	15 - Sarg Fil Red 3 on boulder	Sarg Fil Red 3	6.723
* 1 - Sarg 4 on boulder	5 - Sarg 4 on reef	Sarg 4	8.216
* 3 - Sarg 3 on boulder	10 - Fil Red 4	Fil Red 4	14.816
2 - Sarg 4 on reef	3 - Sarg 3 on boulder	N.A.	17.549
2 - Sarg 4 on reef	13 - Sarg Fil Red 4 on reef	N.A.	30.239
1 - Sarg 4 on boulder	2 - Sarg 4 on reef	N.A.	55.567
17 - Bare	18 - Bare	N.A.	229.930
1 - Sarg 4 on boulder	17 - Bare	N.A.	697.567

N.A. = not applicable

* likely to be spectrally separable, based on observation and canonical variates cross plot.

SPOT (Indented Head – St Leonards only)

Image Classification

The distribution of benthic assemblages at Indented Head-St Leonards, as classified using SPOT imagery show the benthic assemblages to be dominated by bare substrate and seagrass (Figure 4-11). A total area of $2.77\text{E}+10^6 \text{ m}^2$ was classified in the SPOT image of Indented Head - St Leonards. Non-cartographic or unclassified areas totalled less than 14 % of the classified image. Five classes comprised benthic macrophytes whereas five classes showed no flora. A single deep-water class was also classified.

Of the five classes comprising benthic macrophytes, four dominant plant assemblages were identified. Five bare substrate classes exhibited poor similarity due to varying concentrations of pigment in the sediments. These classes appear spectrally distinct from all other classes. *Sargassum*, *Ecklonia* and deep water grouped closely together but were spectrally distinct from all other classes (Figure 4-12).

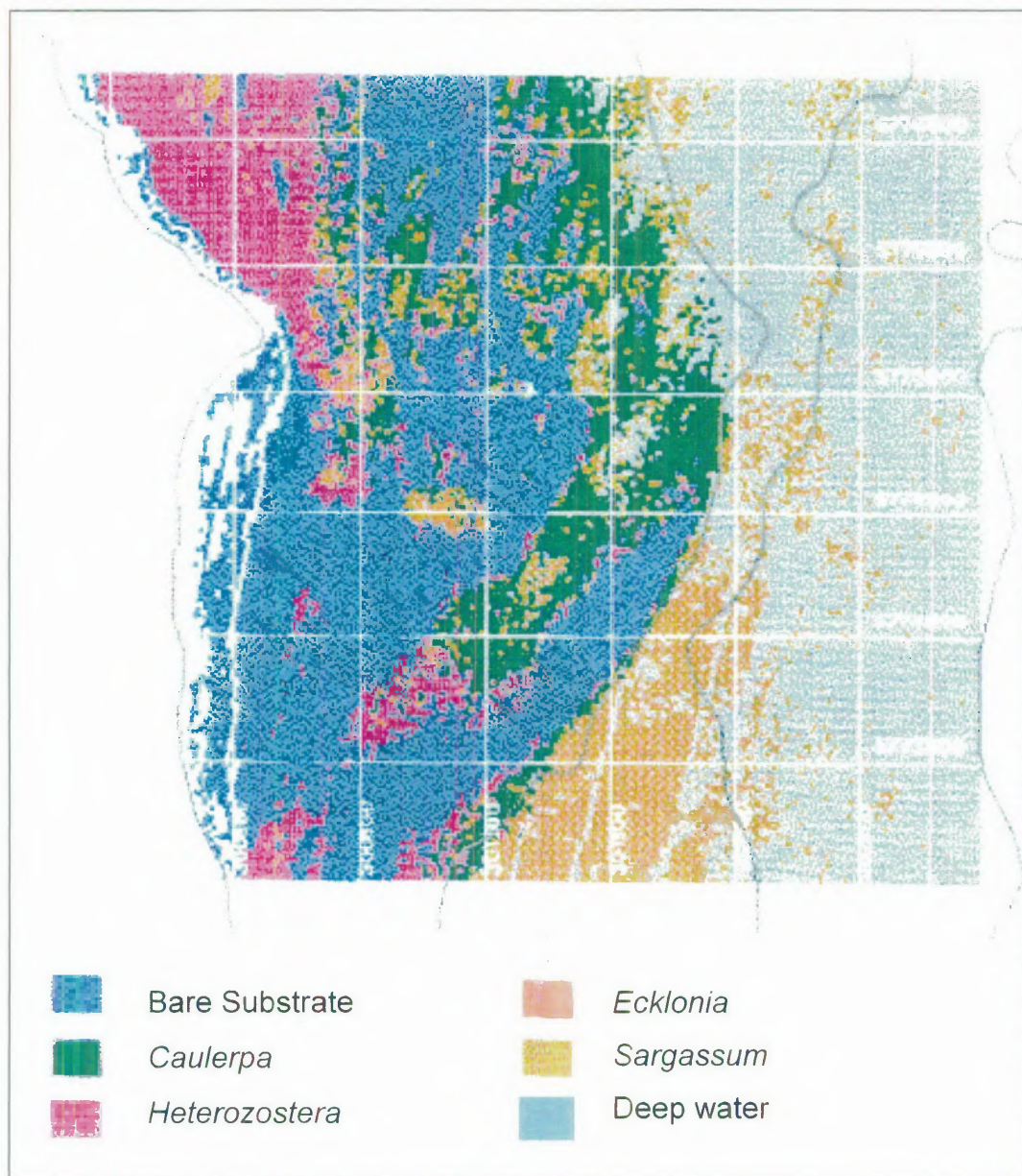


Figure 4-11 Classification of SPOT image for Indented Head-St. Leonards (from Rollings et al. 1993).

Results of the SPOT classification indicate that *Caulerpa* was the most dominant macrophyte plant assemblage, in terms of cover, whereas *Ecklonia* was the least dominant (Table 4-5). Low cover *Caulerpa* was the most dominant vegetated class whereas high cover *Heterozostera* was the least dominant.

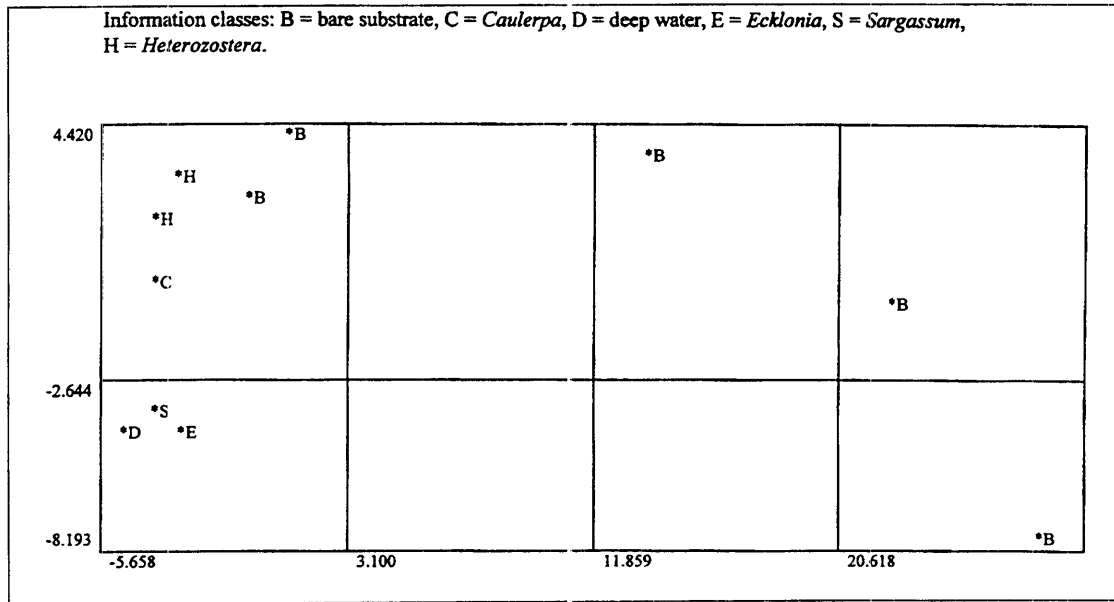


Figure 4-12 Cross-plot of canonical variates axes one and two for 11 discernible information classes classified in the SPOT image at Indented Head – St Leonards (from Rollings et al. 1993).

Classification Accuracy

A confusion matrix based on 43 randomly selected points from the classified SPOT image of Indented Head - St Leonards reveals that substantial errors have occurred with perhaps the exception of bare substrate (Table 4-16). Of the 10 defined classes, 7 are statistically significant (Table 4-17). Statistically insignificant classes were merged (Table 4-18). It was evident that classification by SPOT was imprecise according to the BAAP so the cover variants of the standards were merged (Table 4-19). Subsequently, a summary of the classification errors suggests that bare substrate and *Caulerpa* can be mapped to an acceptable accuracy (80%) while other classes were grossly in error (Table 4-20). The need to generalise the benthic classes to this degree indicates that SPOT cannot perform reliably in this environment.

Table 4-16 Confusion matrix based on randomly selected points from the classified SPOT image of Indented Head - St Leonards, compared to field verified assemblages.

Numbers in cells refer to field site locations as found in the PPB Historical Database (from Rollings et al. 1993).

		Class number Assemblage as classified Cover Depth/Substrate							
Assemblage (BAA Protocol)	Cover	1. Bare	2. Bare	3. <i>Caulerpa</i> 3	4. <i>H-zostera</i> inshore	5. <i>H-zostera</i> offshore	8. Deep Water	9. <i>Ecklonia</i>	10. 1. <i>Sargassu</i> <i>m</i> - hard
Bare sand		2,6H,7,3B, 2I,6I	8F	31a					2G
<i>Caulerpa</i>	3								
<i>Caul./Fil.red algae</i>	2	11	7E, 8E	15,16		8H	2L(6.3m), L(6.1m), 4L(6.5m)		
”	3			72K,3G,4F,6J,5,17					4K(5.4m)
“	4								

Table 4-16 cont.									
<i>H-zostera</i> /Sarg.	3								6
<i>Sargassum</i>	1	3F							
“	2								
“	3							18	
“	4	7H		31b					8
<i>Sar.</i> /Fil.Red algae	2	6F							
“	3								9
Caul/Fil.red/ <i>Sarg</i>	2	6G							
“	3	10							
“	4			13					
<i>Sarg.</i> /Caul	1			11					
“	2								
“	3								14
<i>H-zostera.</i> / Fil.red	4						12		
Fil.red algae	2			7I			5L(6.9m)		
“	3			7J,9H					81
<i>Ecklonia</i>	4								

Table 4-17 Suggested Class Mergings for Classification Statistics Using Ward's Incremental Sum of Squares Sorting for SPOT Classification at Indented Head - St Leonards (from Rollings et al. 1993).

Ward's Statistic in **bold** are significant (from Rollings et al. 1993).

Suggested Classes to Merge		New Class	Ward's Statistic ($\alpha = 4.605$ at 90% conf. limit.)
9 - Ecklonia	10 - Sargassum	Sargassum	1.540
4 - Seagrass	5 - seagrass	Seagrass	3.688
8 - Deep Water	9 - Ecklonia	Deep Water	3.744
1 - Bare	2 - Bare	N.A.	4.965
3 - Caulerpa	8 - Deep Water	N.A.	8.024
1 - Bare	4 - Seagrass	N.A.	27.383
6 - Bare	11 - Bare	N.A.	33.621
1 - Bare	3 - Caulerpa	N.A.	68.985
6 - Bare	7 - Bare	N.A.	149.573
1 - Bare	6 - Bare	N.A.	1283.193

Table 4-18 Confusion matrix based on randomly selected points from the classified SPOT image of Indented Head - St Leonards, compared to field verified assemblages – non-significant classes merged (from Rollings et al. 1993).

Numbers in cells refer to field site locations as found in the PPB Historical Database.

		Class number Assemblage as classified Cover Depth/Substrate					
Assemblage (Benthic Assessment Protocol)	Cover	1. Bare - -	2. Bare - -	3. <i>Caulerpa</i> 3 -	4. + 5. <i>H-zostera</i> . - -	8. Deep water - -	9. + 10. 10. <i>Sargassum</i>
Bare sand		2, 6H, 7 3B, 2I, 6I	8F	31a			2G
<i>Caulerpa</i>	3						
<i>Caul./Fil.Red.</i>	2	11	7E, 8E	15, 16	8H	2L (6.3m), 3L (6.1m), 4L (6.5m)	
<i>Caul/Fil Red</i>	3			2K, 3G, 4F, 6J, 5, 17			4K (5.4m)
"	4						
<i>H-zostera/Sarg.</i>	3						6
<i>Sargassum</i>	1	3F					
"	2						

Table 4-18 Cont.							
“	3						18
“	4	7H		31b			8
<i>Sarg/Fil.red</i>	2	6F					
“	3						9
<i>Caul/Fil.red</i> <i>algae/Sarg</i>	2	6G					
“	3	10					
“	4			13			
<i>Sarg./Caul</i>	1			11			
“	2						
“	3						14
<i>H-zostera/ Fil.red</i> <i>algae</i>	2						
“	3						
“	4					12	
<i>Fil. red algae</i>	2			7I		5L (6.9m)	
“	3			7J, 9H			81
<i>Ecklonia</i>	4						

Table 4-19 Confusion matrix based on randomly selected points from the classified SPOT image of Indented Head - St Leonards, compared to field verified assemblages – non significant classes merged – BAAP classes simplified (from Rollings et al. 1993).

Mean class separation is significant at the 90% confidence limit.

As interpreted	Bare	<i>Caulerpa</i>	<i>H-zostera</i>	<i>Sargassum</i>	<i>Ecklonia</i>	Deep (>5m)	Total
----------------	------	-----------------	------------------	------------------	-----------------	------------	-------

BAAP							
Bare	9	1		1			11
<i>Caulerpa</i>		11	1				12
<i>H-zostera</i>			0	1		1	1
<i>Sargassum</i>		2		3			5
<i>Ecklonia</i>							0
Deep (>5m)				1		4	5
Total	9	14	1	6	0	5	35

Table 4-20 Errors of Omission and Commission for SPOT classification of Indented Head - St Leonards (from Rollings et al. 1993).

Assemblage	Omission %	Commission %
------------	------------	--------------

Bare	18	0
<i>Caulerpa</i>	8	21
Seagrass *	100	100
<i>Sargassum</i> *	40	50
<i>Ecklonia</i> *	-	-
Deep Water	10	10

* Based on 5 pixels or less.

4.3.8 Summary of Benthic Mapping Results

Aerial photography was capable of delineating five dominant plant assemblages whereas CASI and SPOT imagery were limited to four. All three data sources could detect bare substrate. Conversely, all three data sources failed to resolve benthic fauna. As a proportion of total image area, aerial photography classified a greater amount of vegetation (63%) compared to CASI (50%) and SPOT (38%). CASI imagery demonstrated the greatest potential to discriminate variation in benthic plant assemblage cover (density) whereas SPOT imagery exhibited the least potential. A synopsis of information on dominant plant assemblage classification / interpretation for the three data sources is presented in Table 4-21. The maximum depth at which CASI could distinguish benthic features was 12 m at the Mornington site. SPOT was restricted to 5 m based on the Indented Head –St Leonards site.

Table 4-21 Synopsis of capability to map dominant plant assemblage for the four data sources (from Rollings et al. 1993).

C= Caulerpa, C/Hz= Caulerpa/Heterozostera, C/S= Caulerpa/Sargassum, C/S/Hz= Caulerpa/Sargassum/Heterozostera, Hz= Heterozostera, E= Ecklonia, S= Sargassum, B= Bare Substrate.

Y= Yes mapping possible, N= No mapping not possible, P= Mapping may be possible, 10m?= Can technique satisfy 10 m accuracy requirement?

Assemblage	C	C/Hz	C/S	C/S/Hz	Hz	E	S	S/E	B	10 m ?
------------	---	------	-----	--------	----	---	---	-----	---	--------

Data Source										
Aerial Photo	Y	P	P	P	Y	Y	Y	P	Y	Y
CASI	Y	P	P	P	Y	Y	Y	P	Y	Y
SPOT	Y	P	P	P	Y	P	P	P	Y	P
Daedalus	N	N	N	N	N	N	N	N	Y	N

Table 4-22 Suggested mappable assemblages at Mornington (from Rollings et al. 1993).

Assemblage	Comments
Caulerpa	Generally well discriminated, cover variations possible?
Filamentous Red	As water gets deeper becomes confused with Sarg/Fil Red on reef, cover variation evident in shallower water.
Sargassum	Well discriminated when in a pure stand.
Bare Substrate	Highly variable due to microbial mats?
Sarg/Fil Red mix	Below medium cover becomes confused with filamentous red in deep water.

4.3.9 Discussion of Benthic Mapping

The benthic mapping techniques described here are a result of the innovative application of state of the art technology from the areas of satellite positioning, underwater data recording and airborne remote sensing. Results obtained from this study illustrate the accuracy (in terms of horizontal position) and detail (in terms of spatial resolution) of data generated by such procedures when applied to mapping large areas of benthos in PPB.

Field Investigations

Benthic data derived from field investigations form the basis for comparison with the remotely sensed imagery. The three methods of *in situ* data acquisition used in this study (viz. submersible sledding using scuba/hookah - GPS, bow viewing - GPS and snorkeling - EDM) were largely dependent on the physical environment being mapped in each instance. All four procedures were based on an established protocol for assessing benthic assemblages. Fundamental to all four procedures is a method of observation and a method of position fixing.

Benthic assemblage assessment protocol

The benthic assemblage assessment protocol used in all three field methods proved adequate for separating dominant plant and animal assemblages. These data proved excellent as ground truth information for image training and accuracy assessment. During image training, the cooperative approach between those who collected field data and those who processed images proved invaluable.

Remote Sensing

Aerial Photography - Indented Head - St Leonards

Softcopy Interpretation

An on screen, visual assessment of the digitally enhanced aerial photography revealed that benthic features could be more easily distinguished than via interpretation of

conventional hard copy aerial photography. In particular, fine spatial detail was evident even at the relatively coarse scanning resolution of 150 dpi. The technique is reliant on skilled interpreters and is subject to varying degrees of inconsistency between images and between interpreters unless a well designed standard key is used (Wolf 1983). This technique has the disadvantage of not offering stereo viewing that is often helpful for discriminating similar assemblages at differing depths. This problem can be overcome with the use of the latest softcopy digital photogrammetric workstations but at a considerable addition to the time required for interpretation.

Classification of aerial photography was considered to be too time consuming as the radiometric calibration between photographs and within single photographs was too variable to develop generic spectral signatures.

Accuracy of Aerial Photograph Interpretation

The confusion matrix shown in Table 4-6 and the summarised errors of omission and commission shown in Table 4-7 demonstrate this technique has the potential to map 4 or 5 benthic assemblages in PPB. Care must be taken in interpreting these results however as only a small study area was chosen and the benthic assemblages were intimately known by the interpreters. Under these conditions it is difficult to assess this technique objectively.

Daedalus 1268

Image Classification

The Daedalus imagery exhibited poor depth penetration and proved ineffective at mapping benthic assemblages even at < 2 m. This is contrary to the work of Allen (1991) who held promise for such scanners in the Werribee region. However, Greenway and Fry (1988) reported that the Daedalus scanner was unsuitable for seagrass mapping. The Daedalus scanner was developed for terrestrial applications where high signal to noise ratios are not as critical (Harris and Jupp pers. comm.).

1993). It is likely that the scanner has reached the limits of its resolving capability in this environment because of the problems with signal to noise ratios in the images.

CASI - Indented Head - St Leonards

Image Classification

The results of the classification indicate that all non-mixed plant assemblages can be differentiated using both CASI and/or digitally enhanced aerial photography. This is possible because of the fine colour resolving capabilities of CASI (even at 10 nm bandwidths) and high radiometric resolution (16 bit). Given these characteristics, CASI has greater potential than aerial photography for objectively classifying not only dominant plant assemblage but also cover variations therein. Aerial photography allows finer spatial detail to be interpreted. The results suggest that aerial photography is better at defining mixed classes. This is most likely due to inadequate training of the CASI imagery rather than its lack of ability to discriminate these features. Field verification will resolve this.

CASI can delineate benthic features down to 12 m but field verification is required to test its resolving accuracy at these depths. It is possible that CASI will provide more information on benthic assemblages than is required for the modelling of PPB. Subsequent discussions with Dr. David Jupp suggest that CASI performs equally as well in more turbid environments, Jupp (pers. comm. 1996).

Classification Accuracy

An on screen visual inspection of the CASI imagery reveals that it exhibits excellent water penetration and discrimination of the benthic assemblages. Severe depth of penetration effects are not evident until after band 8 (620-628 nm). This is consistent with radiometer profiles taken in the centre of PPB that suggest the peak spectral irradiance, at 5 m, occurs at 580 nm (Rollings et al. 1994) and reveal that most assemblages identified during the first round of Bay truthing exercises can be mapped. Of those classes that were tested with sufficient locations, and average accuracy of

80% can be inferred (Table 4-12). These values should be treated as a guide as only 43 pixels were verified during the classification assessment.

The poor performance in the seagrass class is attributed to scant training data within the CASI image. Class 8 (seagrass) was trained based on an area extrapolated from one transect. It is apparent that this class should really be labelled *Caulerpa* 3 (Table 4-8). Training area 7 was also very small and appears to be a mixed class as ascertained from the confusion matrix. Evidence of studies based on satellite imagery, which could map seagrass, would suggest that imagery of such quality as CASI could also map its distribution (Allen 1990). The confusion matrices also indicate that cover density variations within assemblages should be mappable. The evidence is contradictory however. In Table 4-9 and Figure 4-8, Bare class 1 and *Caulerpa* 2 class 6 are not significantly separable. The confusion matrix supports this however as most classified into class 6 are in fact bare substrate. This points to inconsistencies in the training, possibly deriving from ground data. This is further demonstrated with merged classes 3 (*Caulerpa* 2) and 4 (*Caulerpa* 4) where class 4 should really have been labelled *Caulerpa* 2/3. Class 1 (bare) and class 11 (*Caulerpa* 2) are significantly separable and have good correlation with the Bay truth programme. This suggests that bare and *Caulerpa* 2 are potentially separable. In many instances, bare substrate and *Caulerpa* 2 (also seagrass 2 and caul/fired/sarg 2) are commonly inter-classified. Density cover type 2 represents 5 - 30%. The apparent mixing of bare substrate and the various density-cover 2 assemblages reflects the variation within this class. Those being confused with bare substrate are closer to 5% while those that classify out well are closer to 30%. Experience tells that a cut off of around 20-30% is a usual discrimination limit for cover variations such as these, at least in terrestrial ecosystems (Rollings 1990a, Race and Rollings 1992). Further evidence of density cover gradients in the imagery can be seen in Figure 4-8. Cover variations in *Caulerpa* show a distinct linear relationship parallel to canonical variate axis 1. The evidence suggests that cover variation estimates are possible but further work is needed to fine tune both the mappable range and its precision. Allen (1990) demonstrated that seagrass could be mapped to several densities at Corner Inlet in Victoria using a Daedalus 1260 ATM. This would suggest that mapping variation in assemblage structure is possible in PPB, particularly if CASI imagery is used. Quantitative field data on assemblage biomass would be required.

One problem experienced during classification verification was the time delay between each exercise. The imagery was flown in March while the verification was undertaken in October. During this time filamentous red epiphytes had colonised many of the *Caulerpa* areas. In light of this, any filamentous red areas identified in October have been treated carefully in the assessment and have been included in a *Caulerpa* class unless field evidence suggests otherwise.

Table 4-13 clearly demonstrates that mixed assemblages are consistently classified into one of the constituent assemblages both in CASI and SPOT imagery. This is not unexpected as the canonical variate cross plots frequently suggested a continuous mixture series for the Mornington image where these mixed assemblages were trained as separate information classes. Subsequent training of the Indented Head - St Leonards image for mixed assemblages produced training classes that were statistically significant in half of the cases although all would classify well. Additional quantitative field data on assemblage composition is needed to determine to what level and precision mixed assemblages may be mapped.

CASI - Mornington

Image Classification

An on screen, visual inspection of the CASI imagery over Mornington reveals that it exhibits good water penetration and offers discrimination of benthic features. However, imaging was undertaken under less than optimal conditions with a very low solar elevation angle of 28 degrees. The increased atmospheric path length has manifest in increased limb brightening and sun glint. Additionally, less irradiance is penetrating the water column making this imagery less interpretable when compared to the Indented Head - St Leonards imagery. Figure 4-9 shows that the distribution of the mapped benthos follows a somewhat symmetric pattern along the axis of flight. This might be due to the severe effects of the atmosphere and makes the imagery difficult to classify. As such, the results obtained at Mornington give an indication of the performance of CASI in deeper waters but must be interpreted with care.

Classification Accuracy

Evidence presented in Table 4-15 suggests that only five of the 18 trained information classes are significantly separable in this imagery. Again these figures must be treated carefully. The Mahalanobis distance is only a guide to class separability. The canonical variates plot shown in Figure 4-12 would suggest that many more of these classes can be mapped although this cannot be proved without additional ground data. Based on experience and the information presented, all those classes which should be separable but have been suggested for class merging have been marked with a * in Table 4-15.

The confusion matrix for the Mornington CASI classification was compiled with sixteen pixels due to unfavourable conditions in PPB and restrictions placed on divers due to the deeper water when compared to Indented Head - St Leonards (Table 4-18). Filamentous red algae were consistently classified although cover variations did not map well (Figure 4-14). Few other conclusions can be drawn from this test site.

It would appear unlikely that differences between reef substrate and boulder can be distinguished using spectral classification techniques. The results presented in Table 4-14 do not support this however. *Sargassum* 4 on boulder, and *Sargassum* 4 on reef, are quite significantly separable. This is more likely to reflect the marked differences in depth that are characteristic of the Mornington site. This is expected when considering the cover estimates for its assemblage. *Sargassum* is generally only present at cover level 4 and occasionally level 3. Under these circumstances the almost complete cover of the *Sargassum* will mask any spectral contribution from the substrate. The effects of depth are more significant than the spectral difference between these two substrates. Unlike Indented Head - St Leonards, the depth effects at Mornington are more severe. This may be an aberration due to the lower solar elevation angle.

Differences between hard and soft substrate were consistently demonstrated. *Caulerpa* on sand and *Caulerpa* on reef can be delineated although the effect of the substrate on the cover estimate is not known. In terrestrial ecosystems, the substrate can have a marked effect on any estimates of biomass (Huete 1988).

The canonical variates plot in Figure 4-10 also suggests that various assemblages and assemblage mixes are mappable. These are summarised in Table 4-22. Despite the image being acquired under less than optimal conditions, the Mornington imagery demonstrates that benthic features can be mapped to a depth of 12 m.

SPOT - Indented Head - St Leonards

Image Classification

Allen (1990) pointed to the utility of SPOT imagery for mapping benthic features in shallow water. This is supported by the work of Greenway and Fry (1990) and Catt and Hopley (1990). Recent work by Rollings and Coops (1993) also supports the use of SPOT data for mapping benthic habitats albeit in the clearer waters of Pacific atolls. The SPOT imagery was capable of resolving most classes to a depth of 5 m although the noise levels were high, which inhibited clear interpretation for training. Techniques such as image stacking may be employed to overcome heavily noise affected SPOT imagery and improve interpretability (Hick pers. comm. 1993).

The results of this study show that SPOT has classified a significantly smaller area as *Caulerpa* than either the photography or CASI. This highlights the problem of defining a multispectral decision boundary between 2 classes, which are members of a continuous range. The disparity in the area calculation of *Caulerpa* between SPOT and the other sensors reflects either the inability of SPOT to resolve the lower densities of *Caulerpa* or differences in the discrete training of a continuous information class. The latter point highlights the problems involved in dividing a continuous environmental gradient into a discrete number of classes that are to be incorporated into a vector based GIS.

Classification Accuracy

The results of the Indented Head - St Leonards classification suggest that bare substrate, *Caulerpa* and *Sargassum* can be mapped to varying degrees of accuracy. Cover estimates however do not seem to be mappable. The lack of ability to map *Ecklonia* reflects the difficulty in acquiring adequate training data due to the small

patches occurring in the study area. Similarly, seagrass, while present in the study area was difficult to train as no pure areas were detected during the video transects. The significant differences experienced between the various bare classes can be attributed to the presence of micro-phyto benthos which vary markedly both spatially and temporally in areas of bare substrate and in assemblages of low cover.

Spot - Mornington

The SPOT imagery at Mornington showed little discrimination of benthic features. This was expected as its maximum depth of penetration under these conditions was previously determined to be 5 m. The study site at Mornington becomes deep very rapidly. Consequently, no classification of the SPOT image was undertaken.

4.3.10 Conclusions

1. CASI imagery, supplemented by concurrent field data, can provide information on the aerial extent and cover of dominant plant assemblages in PPB down to a depth of 12 m (based on Indented Head - St Leonards and Mornington classifications). This includes the ability to discriminate variations in percentage cover provided attention is directed towards appropriate training areas.
2. Digitally enhanced aerial photography can provide information on the aerial extent and dominant plant assemblages in PPB down to a depth of at least 6 m (based on Indented Head - St Leonards interpretation). It is possible that variations in dominant plant assemblage cover can also be delineated.
3. SPOT multispectral imagery can map a subset of the benthic assemblages to a depth of <5 m. Further investigation is needed to assess the use of image stacking to improve image signal to noise ratios (i.e. multiple dates are used to average out noise effects in the image).
4. Daedalus 1268 Airborne Thematic Mapper Imagery will not provide reliable information on the aerial extent of dominant plant assemblages in PPB.

Operational Considerations

Data Resolution

For the purposes of this case study the CASI was flown to produce a 5 m pixel. Over the whole of PPB this would represent a data volume of approximately 4 Gbytes. This data volume is manageable provided adequate processing facilities are available. During processing of the imagery acquired for this task, one flight line required an average of 3 hours for tape reading, up to nine hours for format conversion and one hour for preprocessing. Economy in data volume may be achieved by increasing the pixel size to 10 m and reducing the dimensionality of the data set. Thought should be given to flying with 10 or 8 channels instead of 14. A transform divergence measure (see Richards 1986) would give an indication which parts of the spectrum were more important for discriminating between the relevant benthic features.

Rectification

Due to the difficulties experienced with reading and loading CASI data, the following discussion on rectification of large, airborne scanner runs is restricted to Daedalus only. Many parts of PPB have poor ground control and pose operational problems when rectifying imagery to the Australian Map Grid. Rollings et al. (1993) (included in Appendix 2) gives a full treatment of the various rectification techniques used in order to gauge suitable sources of ground control and determine suitable ground control point distributions. For pixels of the order of 10 m, the use of differential GPS provides the most accurate and flexible georeferencing source for ground control points. Given adequate control, it is also possible to "path process" (use control from only the ends of the run that cover land features) an entire run of imagery provided a stable mounting and platform are used. CASI has the facility to tag nadir point pixels with a GPS derived position providing an invaluable source of ground control. Even with this facility, it is always desirable to have control points in PPB itself. The use of two fast boats each with a moorable buoy and dye marker may solve this problem. Each boat could lay one buoy with dye marker and take station a few kilometres away, also streaming a dye marker. By coordination with the aeroplane, the boats could move down the Bay as the aircraft positioned for the next flight line thus providing a quick and efficient means of providing control anywhere in the Bay.

Given the pre-determined size of the model cells, consideration should be given as to whether the specified 10 m positional accuracy as specified, is appropriate.

Any rectification should be undertaken in microBRIAN or any similar system with a complete suite of rectification tools. The additional statistics available in microBRIAN for accepting or rejecting rectification models was paramount to the success of the rectification's undertaken in this case study.

The stability and accuracy of rectification models is dependent on a number of factors:

- the pixel size of the image
- the precision and accuracy of ground control points
- the interpretability of ground control points on the image
- the order of model used
- the stability of the platform (including gyroscopic stabilising and post processing)

The pixel size required for a particular mapping project is determined by the task at hand. Forster (1985) suggested appropriate pixel sizes necessary to satisfy national mapping standards at various scales (Table 4-23). If we adhere to the guidelines in Table 4-23 the 5 m pixel used for the CASI imagery will barely satisfy the National Mapping Standards for 1:50 000 scale mapping. Forster's arguments were developed for space-borne systems and are based on line-pair equivalents as used in photogrammetry. The estimates he uses may therefore be inappropriate for air-borne systems and are likely to underestimate the achievable mapping accuracy possible for a given pixel size. The PPB Design (CSIRO 1992a) states a required horizontal accuracy of 10 m in the x and y directions. Under national mapping standards, this represents a mapping scale of around 1:20 000. The work undertaken so far indicates that of the data sets evaluated, only aerial photography can meet this standard all of the time. It is likely that CASI (which has a post processing roll correction routine) will also meet this criterion. CASI has a facility for geocoding selected pixels along the nadir point while acquiring imagery. The use of this facility in any subsequent imaging flights would greatly enhance the rectification of the imagery. The scaling of

test points which indicate a less than ten metre position residual for SPOT XS data should be treated with caution at this stage. All redundant test points were derived in the vicinity of ground control points. Before this result can be accepted, other points around the image should be included.

Table 4-23 Estimates of required pixel sizes for various mapping scales.

Map Scale		Maximum pixel size needed in metres	
		Standard Mapping	Revision Mapping
1:250 000	Best	75	150
	Worst	14	28
1:100 000	Best	30	60
	Worst	6	12
1:50 000	Best	15	30
	Worst	3	6

(from Forster 1985)

Ground control points used for the rectification of satellite imagery should ideally be scaled to a precision of 20% of the image pixel size (Forster, pers. comm. 1988). For a 10 m pixel this represents a 2 m accuracy. This is not achievable from standard 1:25 000 topographic maps but can be achieved using 1:2 500 maps. The results of the rectifications used in this case study suggest that there is a small but significant gain to be achieved from using the higher resolution ground control. This is supported by Rollings (1990a) who demonstrated the benefits of using high precision ground control when constructing rectification models.

Classification Accuracy

It appears that the major benthic assemblages can be mapped according to presence or absence to an accuracy of 80-90%. Given the cancelling effect between errors of commission and omission, the overall accuracy of some classes approaches 100% if a small error in the distribution of these classes is acceptable. These classification accuracies will also vary favourably if certain assemblages are merged for the purposes of modelling.

Depth Effects

Given that the peak spectral emittance from the water column occurs at around 580 nm, variations in depth of penetration effects on the imagery are not apparent until the visible red wavelengths. Given the clarity of the imagery, it should be possible using standard depth of penetration models to derive depth images. The effects of depth can be accounted for in the classification process through prudent training. It is also possible however to deconvolve the bottom reflectance from the water depth. However, this is possible at the expense of processing time and complexity of the algorithm. An alternative for operational purposes would be to correct the imagery for depth effects by utilising existing bathymetric information and estimates of the apparent optical properties of the water column.

Imaging Geometry and Windows

All airborne scanner imagery requires careful planning in order to minimise undesirable atmospheric and sunglint effects. This must be balanced against the need to maximise solar penetration of the water column. Operational constraints regarding sunglint restrict imaging with solar elevation angles greater than 60 degrees. From the imagery acquired for the case study we can conclude that scenes acquired with a solar elevation greater than 40 degrees afforded good results while imagery where the elevation angle dropped below returned less than ideal imagery. If, for operational considerations, we do not image when the solar elevation angle is less than 40 degrees, this implies a restriction on our window of imaging opportunity.

Additionally, the aircraft should be flying either directly into or away from the sun. The geography of the Bay is such that the flight lines that will be planned parallel to the coast will be on a bearing of either 055 degrees or 145 degrees. Fortuitously, this coincides with the optimum solar elevation angles either side of midday when the sun is too high in the sky for imaging. For example, Table 4-24 gives the solar elevation and azimuth for the 7th February, 1994 from which it can be seen that approximately 3 hours of imaging with optimum geometry would be possible on that day provided suitable cloud conditions existed.

Table 4-24 Calculated solar elevation angles and azimuth for February 7th, 1994.

Time	0900	1000	1100	1200	1300	1400	1500	1600
Elevation	38	50	60	65	67	61	51	40
Azimuth	080	067	049	021	344	313	294	282

General flight direction - 055 M imaging possible between 0930 - 1100 → - 145 M imaging possible between 1430 - 1600 → Total = 3 hrs.

Physical Conditions on PPB

Very little is known about the behaviour of the light field throughout PPB. Evidence suggests that overall there is little difference in the range of turbidities encountered at selected sites around PPB. This implies that at least some time, most of PPB experiences good water clarity and hence light penetration. Vertical mixing by wind action is common and can quickly change clear waters, that are ideal for imaging, very turbid.

Cloud Cover

A perennial problem with passive remote sensing systems is the presence of cloud. Based on the work of Coops (pers. com. 1993), Table 4-25 gives the probability of a cloud free day over PPB for four different months.

Table 4-25 Probability of a cloud free day for PPB 11.00 am to 4.00pm.

Month	Probability of a Cloud Free Day
January	35%
April	30%
July	40%
October	28%

This does not take into consideration those parts of the day that will be cloud free and provide imaging windows of an opportunistic nature. This needs to be considered when arranging the lease of suitable imaging instruments.

Map Production

The very large nature of the data sets involved in mapping large areas provides unique data handling problems. Thought may be given to processing the raster image files in their un-rectified state and finally sewing the strips together when they have been transferred into an appropriate vector format (consistent with the PPB Environmental Study Database). This would require the development of a "strip processing" strategy. Alternatively a "once off" processing strategy could be employed. The various strips of imagery could be sewn together and reduced to a "reflectance value" using the spreadsheet models of Jupp and Kirk with in-water parameters being estimated via strategically placed sampling points at the time of image acquisition. The latter technique while providing processing economies of scale would require much more coordination and pre/post-flight processing. The benefits of a PPB-wide spectral library for all major benthic assemblages would be of benefit for future modelling and monitoring programs.

4.3.11 Recommendations

- Imagery supplied in an un-rectified form is a major technical barrier to the use of airborne data. Precise rectification is essential, yet out of the capability of lay-users. A TO-ASIST might easily be developed for mapping an area once but to monitor over time (a real benefit of SIT) would require data supplied in rectified form.
- Uncalibrated imagery is difficult to use for lay-users and is another major technical barrier to the use of airborne data. Advanced processing of the imagery to true reflectance, or at least calibrated radiance, should be demanded from data suppliers. The use of calibrated imagery would allow a spectral library of benthic communities to be established. This would be a desirable situation for monitoring and would allow benthic mapping to be developed as a TO-ASIST.
- The complexities of imaging geometry and timing need to be considered if optimal imaging conditions are to be achieved. This is critical for aquatic and marine applications but less so for terrestrial ones.

4.3.12 TO-ASIST or not TO-ASIST

This research case study has established that SIT can be used to map benthic assemblages to a depth of 12 m in PPB. Of course, in clearer waters the depth of penetration will increase. Two methods were suggested for benthic mapping, one using traditional image training and classification. The other suggestion was to establish a spectral library of benthic assemblages and correct the imagery back to true reflectance whereby the spectral library could be applied.

There is a demonstrated need for monitoring benthic assemblages in PPB and other environments. That need is recurrent, as environmental monitoring is a crucial step in the resource management process (Table 1-1 and Figure 1-2). The research conducted in chapter 4.3 demonstrated that the technique works reliably and there is certainly a series of repetitive tasks that can be simplified. It appears that benthic monitoring is suitable for customisation as a TO-ASIST, at least if the first method is adopted. Both

methods suffer a common problem however, rectification of airborne scanner imagery. The instability of the platform makes geometric correction difficult and beyond the capability of lay-users. This task involves complex processing procedures and high user-input based on experience, for this reason, the application is at odds with the TO-ASIST concept. The ideal solution would be for data suppliers to take responsibility for their product and supply corrected imagery (something that suppliers of space-borne imagery are willing to do). If the second method is to be adopted there is another technical problem with the imagery. Airborne imagery is difficult to process and use, particularly when multiple flight lines are used. Processing calibration to true reflectance, particularly across adjacent flight lines, requires a high level of technical knowledge and skill, something that is out of the hands of lay-users. Under these circumstances, either the imagery needs to be processed by the data supplier (something that should happen) or a suite of tools could be written to assist technically competent operational users to undertake the task. The tools could assist the user to account for atmospheric effects, sunglint off the water surface and across-track effects that are common in airborne imagery. This raises the issue of a second type of TO-ASIST, one which is designed to assist the operational community adopt new advances in SIT. Benthic mapping is therefore suitable for development as a TO-ASIST provided certain data pre-processing issues are addressed.

4.4 Remote Models for Monitoring in-water Chlorophyll Concentration - Research Case Study 2

This case study was initiated to research whether accurate models based on water-leaving-radiance could be developed to map the spatial and temporal distribution of chlorophyll-a in the moderately turbid waters of PPB and whether these models might be developed for use with remote sensing instruments. This project was officially part of this Ph.D. although my contribution to each aspect of this project was mostly in the area of project design, processing and analysis of the spatial data sets (Table 4-26). Other sections of the final report detailing field operations (other than those directly relating to in-water optics and remote sensing instrumentation) have been summarised in this thesis. The entire PPB report is included in Appendix 3.

Table 4-26 Percentage contribution claimed for research case study 2.

Component of Research Case Study	Approximate Contribution
Project design for field component	20
Project design for remote sensing component	80
Writing literature review for chlorophyll methods	10
Writing literature review for spatial techniques	90
Field work for ground data gathering	10
Field work for remote sensing	80
Analysis of field data	50
Analysis of remotely sensed data	90
Empirical and process modelling of optical data	80
GIS processing and analysis	100
Final analysis	70
Report writing	60

4.4.1 Introduction

Chlorophyll-a is a photosynthetic pigment contained in all phytoplankton. It is commonly used as a parameter for estimating phytoplankton biomass (Wood and Beardall 1992). It has been measured routinely in PPB by the EPA since the Victorian government declared its State Environment Protection Policy (SEPP) for the waters of PPB in 1975 (Longmore et al. 1990). Monitoring of fixed site has shown that chlorophyll levels in the Bay are generally low ($< 1.5 \mu\text{g l}^{-1}$) compared to similar water bodies subject to nutrient enrichment, although elevated concentrations ($> 3.5 \mu\text{g l}^{-1}$) may be found off Werribee, in Hobsons Bay and Corio Bay, and off the Patterson River (Longmore et al. 1990, Figure 4-13).

The potential of remote sensing techniques to assist in monitoring chlorophyll in PPB was assessed by Howard and MacDonald (1990). Although the analysis was restricted mainly to the Coastal Zone Colour Scanner (CZCS), they considered that both satellite and airborne scanners had the potential to yield accurate estimates of chlorophyll, providing that rigorous optical studies were undertaken, and that new algorithms to retrieve quantitative chlorophyll estimates were developed. Turbidity is considered a major limiting factor in the application of remote sensing in coastal environments. Existing algorithms for the CZCS are not suitable for waters such as PPB that have relatively high levels of suspended sediments (when compared to oceanic waters) and variable and unknown levels of gelbstoff (Parslow 1990). Recent advances in remote sensing of chlorophyll in turbid water bodies provide encouragement for potential application of remote sensing in PPB (Jupp et al. 1993). Remote sensing surveys characteristically exhibit broad spatial coverage and the ability to collect information over a short space of time and may therefore provide a favourable alternative for long term monitoring of chlorophyll in PPB. Airborne surveys offer an advantage over satellite sensors because they have better spatial and spectral resolution and can more readily be deployed over features of interest.

4.4.2 Research Questions

Research Question 1: Can the scattering and absorption properties of seston, gelbstoff and chlorophyll in PPB be modelled using spectral information acquired from radiometers?

Research Question 2: Can existing knowledge of chlorophyll prediction models derived for oceanic environments be adapted for use in turbid embayments such as PPB?

Research Question 3: What are the implications to make these techniques operational?

4.4.3 Study Site

A study site was chosen in Hobsons Bay as it exhibits the most extreme environment with respect to chlorophyll-a concentration, water depth, turbidity and substrate.

Information regarding these criteria was obtained from preliminary field investigations and previous studies / literature reviews (see MMBW and FWD 1973, Brown 1990, Longmore et al. 1990, Black and Mourtikas 1992, CSIRO 1992c).

Depth, turbidity and substrate were considered particularly important because these parameters play a critical role in determining the utility of remote sensing for estimating chlorophyll concentrations (MeRVaL 1993a). These factors complicate the spectral reflectance signal received by the sensor and can be major sources of error in chlorophyll estimates.

The study site is approximately 20 km² in area (4 km x 5 km) (Figure 4-13). The boundary coordinates are listed in Table 4-27.

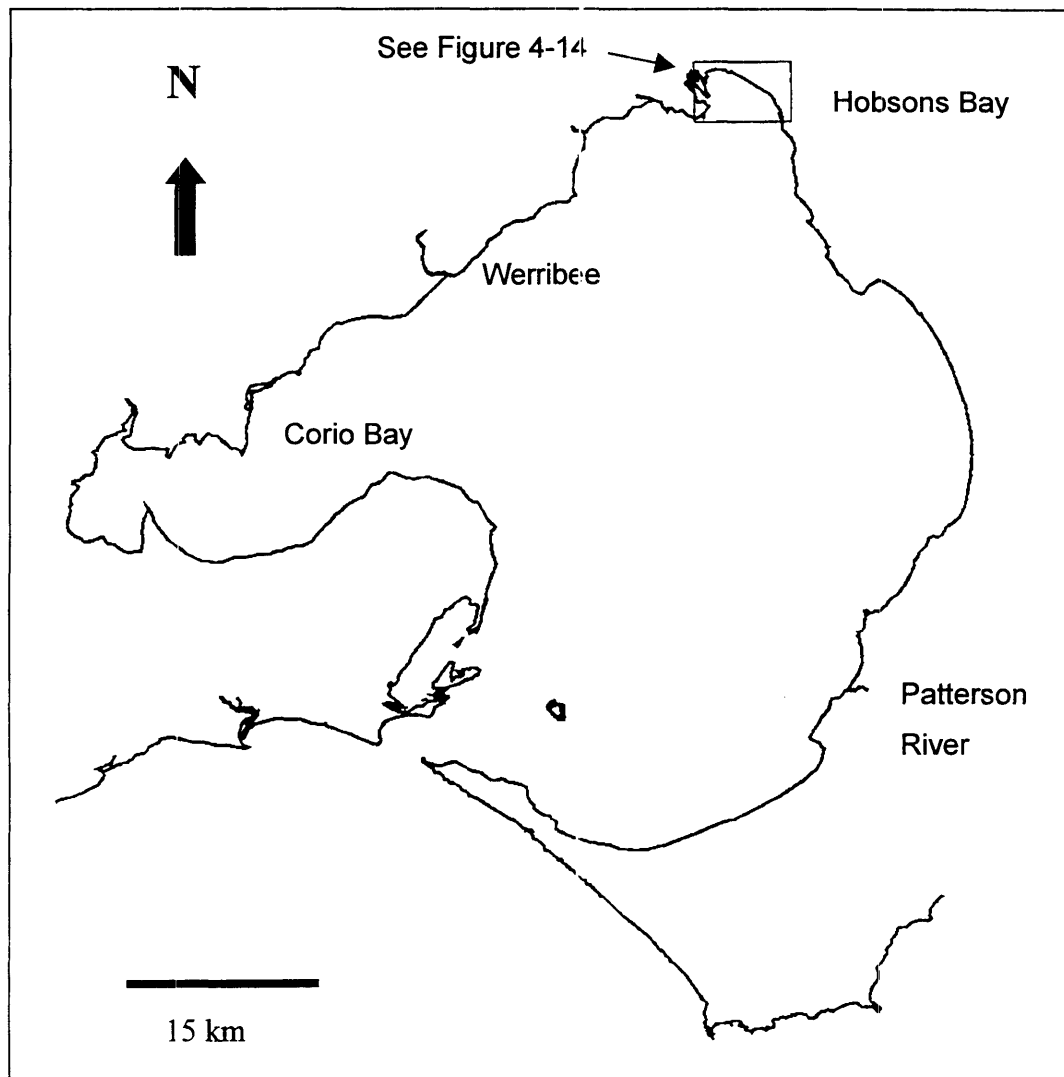


Figure 4-13 Hobsons Bay chlorophyll study site for PPB case study (after Rollings et al. 1994).

Table 4-27 Boundary coordinates of study sites (AMG Zone 55).

Hobsons Bay	Pixel size (m)	Boundary coordinates
	10	(316090, 5808780) to (321590, 5806080)

Hobsons Bay

The Hobsons Bay site, encompasses the area from Gellibrand Pier to St Kilda yacht club, and extends approximately 2.5 km offshore. It is contained within the northeastern zone of PPB and receives significant freshwater input from the Yarra

River. Depth ranges from 3.0 to 13.1 m (shipping channel) and the substrate is comprised of silty clays (Watson 1972). Levels of suspended solids are high and chlorophyll concentrations often exceed $2.5 \mu\text{g} \cdot \text{l}^{-1}$ (EPA 1990).

4.4.4 Data Collection

A number of field-based data collection programmes were conducted in support of the chlorophyll concentration modelling task.

Sampling design

The entire ground truth was completed 2 hours either side of image acquisition. A high-speed catamaran was used to make continuous measurements of chlorophyll fluorescence while underway. Another craft was used to take optical profiles and vertical profiles of temperature, salinity, dissolved oxygen, pH and chlorophyll.

Fluorometry

Fluorometry was used as a technique to collect a large number of samples of chlorophyll concentration, rapidly. A series of parallel transects was established at the study site (Figure 4-14). The boat was navigated along these transects using real-time differentially corrected GPS. Complete details of fluorometry can be found in Rollings et al. (1994), included in Appendix 3.

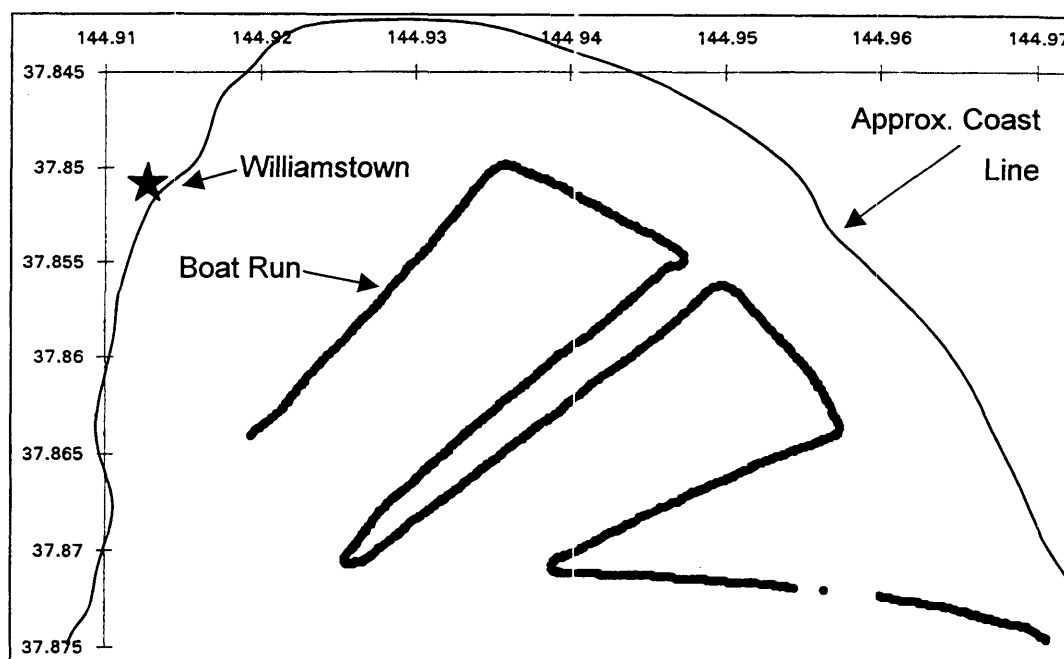


Figure 4-14 Hobsons Bay fluorometer boat run (coordinates in Lat. Long.).

Vertical Profiles

The vertical structure of the water column was investigated at each study site with the use of a fine scale profiler (Centre for Water Research, University of W.A.). A transect dissecting the study area was set up, using weighted buoys as end markers. At approximately 650 m intervals along the transect, the instrument was deployed from the side of the vessel and allowed to free fall (at $0.8 \text{ m} \cdot \text{s}^{-1}$) until it reached the bottom. Depth, temperature, conductivity (salinity), dissolved oxygen, pH and chlorophyll were measured at 0.05 sec intervals (20 Hz) and logged to a 486 PC (Toshiba, Japan). GPS-derived position was logged continuously so that the sample location could be obtained by matching time.

Water Column Optical Measurements

Optical measurements were made in conjunction with vertical profiles at each site using a radiometer (Model QSM-2500, Techintum Instruments, Sweden) fitted in an underwater housing. The downwelling light field was measured from 400 - 750 nm immediately above and below the water surface, and at depths of 1, 5, 10, and 15 m (where possible) and bottom. The upwelling light field was measured at the bottom of the water column, a depth of 1 m and at the surface. Data were output to a Sharp 386

notebook computer and recorded at one second intervals. (With a nominal scan speed of 350 nm/min, this is equivalent to 1 reading every six nm).

Atmospheric Profiles

Simultaneous measurements of downwelling light (256 channels) was made at Williamstown (Figure 4-14) using a Spectron 590SE spectroradiometer. Data were logged every 15 minutes to an on board tape unit for the duration of image acquisition.

Remote Sensing Data Acquisition and Processing

The imagery acquired for the Research Case Study 1, was also used for this case study with one exception. For the Hobsons Bay study site, CASI was also flown in spectral mode utilising a rake of twelve lines of pixels each acquiring 288 channels (see Appendix 2 and Appendix 3 for details of the CASI instrument, flight logs, including solar elevation and azimuth angles, wind speed and cloud conditions on the day of the overpass).

4.4.5 Image Processing and Analysis

Data Import and Rectification

Data import and rectification was identical to that undertaken in Chapter 4.3.5

Chlorophyll Modelling

The data modelling procedures used follow those of Morel and Gordon (1980) and involve three approaches:

1. **empirical** modelling based on statistical relationships between water-leaving radiance and in-water measurements;

2. **semi-empirical** modelling based on statistical relationships between certain spectral bands (and combinations thereof) and in-water measurements;
3. **process** modelling, whereby the inherent and apparent optical properties of the water column are used to predict water leaving radiance.

Empirical models

Image brightness values were extracted from images in microBRIAN using LOCATOR and subsequently imported into a spreadsheet (QUATTRO PRO) where they were linked to chl-a data. Empirical models were produced using step-wise, multiple linear regression analysis techniques (SPSS version 5.0.2).

A spatial data set comprising 14 channels of image data and a spectral data set comprising 288 channels of data were extracted using this method. The spectral data set was later split into two because of processing restrictions of SPSS and the computer used.

Ratio-based models

The following ratio models used by Harding et al. (1992) in a previous study were applied to CASI data:

$$\log_{10}[\text{Chl or pigment}] = a + b \log_{10}(R1/R3);$$

$$\log_{10}[\text{Chl or pigment}] = a - b \log_{10} G ,$$

where $G = [(R2)^2/(R1 \cdot R3)]$ and $R1 = 460 \text{ nm}$, $R2 = 490 \text{ nm}$ and $R3 = 520 \text{ nm}$ (Harding et al. 1992). CASI bands closest in wavelength to R1-3 were used, i.e. 447.9 (1), 399.1 (3) and 420.4 (4) respectively.

Equation 4-1 Ratio models for determining chlorophyll concentration.

Process model

Light entering the water column can be absorbed (a), backscattered (b_b) or transmitted (Kirk 1986). The sum of all backscatter and absorption just below the surface is characterised by $R(0)$, the reflectance below the surface or the ratio of the upwelling light field over the downwelling light field. Process models based on b_b/a ratios can be used to predict $R(0)$. Spectra built from $R(0)$ models were compared to airborne scanner spectra collected during this study following the work of Kirk (1986) and Jupp et al. (1994). Atmospheric correction algorithms developed by Jupp et al. (1994) were used to correct airborne spectra to surface reflectance.

A Model for $R(0)$

$R(0)$ in its simplest form can be expressed as:

$$R(0) = 0.33(b_b/a)$$

Equation 4-2 $R(0)$ Model 1 (from Kirk 1986).

for waters where backscattering does not dominate the water column. When the b_b/a ratio increases, i.e. when backscatter starts to dominate, a modification of the $R(0)$ equation provides a better model of the form:

$$R(0) = 0.33(b_b/(a+b_b))$$

Equation 4-3 $R(0)$ Model 2 (from Morel and Prieur 1977).

Kirk has further modified this relationship for turbid inland Australian waters as;

$$R(0) = 1.016 - (0.6 - \mu_0)((b_b/(b_b + a))).$$

where μ_0 = cosine of the refracted solar beam.

Equation 4-4 $R(0)$ Model 3.

This form of the model was used in this study. All models are of a similar form and are dependent on accurate measurements or estimates of both the absorption and scattering properties of the water column.

Using published and measured values for the various absorption and scattering properties of the water column constituents, a model for $R(0)$ was constructed. The model predicts $R(0)$ between 400 and 750 nm at a wavelength interval of five nm. This interval was selected as it best follows the measurements taken in the field with the Techum radiometer.

Absorption Coefficients

The total scattering coefficient for the water column can be expressed as a simple sum of the individual scattering components according to:

$$a(\text{total}) = a(\text{water}) + a(\text{chlorophyll}) + a(\text{particulates}) + a(\text{gelbstoff})$$

Equation 4-5 Total absorption is equal to the sum of its components.

Ideally, for modelling purposes it is advantageous to express this equation as a series of unit absorption curves with a corresponding *concentration factor* representing the concentration of each constituent component. In this way the total absorption coefficient may be expressed as:

$$a(\text{total}) = a(w) + C a c^* + D a p^* + Y a y^*$$

where $a c^*$ =chlorophyll concentration in $\mu\text{g/l}$
 $a p^*$ =particulate scattering measured in m²u
 $a y^*$ =absorption due to gelbstoff referenced to 440nm

Equation 4-6 Total absorption using unit absorption equation

(from Jupp et al. 1994).

The absorption curve for pure water is well established and published data from Smith and Baker (1981) were used.

The absorption curve for gelbstoff was taken as:

$$a_y(\lambda) = a_y(440)e^{-0.01287(\lambda-440)}$$

Equation 4-7 Modelled absorption curve for gelbstoff.

Absorption curves derived from the optical program confirm that this form is suitable for use in the model. Figure 4-15 shows an absorption curve derived from laboratory measurements for $a_y(440) = 0.018$ and the modelled equivalent.

The exponent index of 0.01287 was used from Jupp et al. (1994) as it produced a theoretical curve with a better overall fit rather than an exponent of 0.014 as quoted by Kirk (1986) (Figure 4-15). The unit absorption curve for chlorophyll was taken from published data after Jupp et al. (1994).

The unit absorption curve for particulates or tripton ($a(p)$) is difficult to derive as it is highly dependent on the composition and particle size distribution of the water body in question. Consequently, a standard relationship between $a(p)$ and turbidity cannot be established. This highlights the need to undertake an extended sampling program in PPB in order to establish the behaviour of the suspended particulates over time.