Remote sensing study of marine and coastal features and interpretation of changes in relation to natural and anthropogenic processes
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Final Technical Report

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**Limitations statement**

This report is the final technical report for Task RS 1 of the Adelaide Coastal Waters Study delivered to the Client through the CSIRO Project Managers.

The data and interpretations of such as presented in this report have been subjected to stringent quality control and scientific analysis, within the time and budgetary constraints of the RS 1 Task. However ultimately, acceptance and distribution of this report will be the responsibility of CSIRO as Project Managers and the Client and any management decisions based upon this report will be the responsibility of these parties.

Regardless it should be stated that this report forms part of a collaborative research program for the Adelaide Coastal Waters Study and should any new findings from other research tasks impact upon the contents or conclusions of this report, addenda will be produced and provided as appropriate.

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Executive Summary

This report presents the final data and interpretations of data sets for ACWS Task RS 1 including maps of benthic features, land-based discharges of stormwater and treated wastewater, maps and quantification of historical changes in benthic features and critical comparisons between various remote sensing instruments, field observations and laboratory measurement of representative spectra of benthic features and water quality data.

This report presents new information on historical changes in benthic feature distributions, how they relate to land-based discharges and coastal processes and addresses mechanism for changes in benthic features. The focus has been on seagrass, macroalgae and sediment distribution, but also includes consideration of changes in mangrove communities.

The study area extends from Port Gawler to Marino Rocks and approximately 4 km offshore of high tide level. Different remotely sensed and field acquired data sets do not consistently overlap entirely or have the same spatial resolution, so this report provides information mostly based upon areas of overlap of the data sets.

The maps and tabulations in this report provide information on spatial and temporal distributions of seagrass, macroalgal and reef communities, sediment and transient plume features. They are not intended to be used as definitive descriptions of habitats or ecosystems – their verification will require input from other research tasks (EP 1, PPM 1 and PPM 2).

The maps of benthic substrates and features and plume features have been produced from georeferenced, rectified and mosaicked aerial photos using archival data supplied by DEH, more recent data from a new aerial coverage in November 2003, data from the CASI airborne hyperspectral sensor array and multispectral data from the Quickbird II satellite imaging sensor array. Verification of the feature maps has been based upon extensive field studies for this and related projects, including 50 sites from 1999 to 2003, 35 sites for the ACWS field studies conducted in November 2003 and numerous studies conducted by Kinhill and KME for SA Water and by DEH. The accuracy and application of remotely sensed data for mapping of marine and aquatic substrates has been tested and verified by many Australian and international studies and many relevant references are cited in the text of this document.

The most useful aerial photography imagery, with extensive coverage and reasonable contrast and spectral quality is from 1949, 1965, 1970, 1983, 1995, 1999 and 2003. Hyperspectral data derived from the CASI instrument for coverages flown in 1999, 2001 and 2003 (and supported by in-field and laboratory radiometric measurements) are presented and interpreted to provide maps of benthic features and feature covers. New methods for analysis of such digital data sets are also provided and represent a new development in the level of sophistication of hyperspectral data analysis.

Maps of land-based discharge plume dispersion have been derived from quantitative and qualitative studies utilizing remotely sensed data (aerial imagery and satellite imagery), field observations, bathymetry and laboratory analyses of water samples (specifically for chlorophyll, coloured dissolved organic matter and suspended matter).

The results from aerial photography and satellite image analyses are compared critically with those from airborne hyperspectral (CASI) data.

The quantification of temporal and spatial variability of changes in benthic features is of major significance in that it demonstrates that multiple approaches to management and conservation of these features and communities will be required to ensure that Adelaide does not lose its seagrasses and associated ecosystems.

The general conclusions from this study are that:

- Bolivar WWTP discharges have had a significant effect on seagrass loss since marine discharges of its wastewater commenced in 1965;
- Outer Harbor/Port Adelaide River outflows have had a significant impact on seagrasses south of the Outer Harbor breakwaters due possibly to high suspended sediment loads;
• Stormwater discharges from the River Torrens, Patawalonga and wastewater discharges from Glenelg Wastewater Treatment Plant have possibly had minimal impact upon seagrass decline since in the former cases they are advected mostly within the near shore region. In the latter case the plant discharges at least 300 m inshore of the landward fringe of seagrasses at the time of plant start-up and the buoyancy of the wastewater is such that dilutions at the seabed even in the near field are probably several thousand times;

• Port Adelaide and Glenelg Wastewater Treatment Plant sludge discharges (now discontinued) appear to be have been causal factors in substantial seagrass losses;

• Overall the decline of seagrasses off the Adelaide metropolitan coastline continues, but there are areas where recolonisation is exceeding loss. These areas should be the subject of further study so that an understanding can be gained as to why these patches are recovering;

• New and existing remote sensing technologies e.g. new satellites and airborne digital cameras should be investigated and compared with the well established analogue, plate camera and hyperspectral CASI imagery so that the most cost effective (and high reliability information delivery) methodologies for long-term monitoring of the marine environment can be established.
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1. **Introduction**

1.1 **Project scope and approach**

The brief for Adelaide Coastal Water Study Task RS 1 was to provide baseline maps of ecologically significant benthic features (biotic and abiotic), maps of changes over time for benthic features, bathymetry for the study area (which for this task extends from Port Gawler to Marino Rocks) and also provide observational evidence for the likely impacts of natural and anthropogenic processes on benthic features. The RS 1 task has provided baseline data, detailed bathymetry, interpretations of remotely sensed, field and laboratory data, quantification of changes in benthic features and hypotheses relating to mechanisms for historical changes in benthic features.

The report focuses on seagrass ecosystems, dominated by *Posidonia* spp., but also considers intertidal Zosteraceae, macroalgae, sediment substrates and briefly mangroves and *Spirographis* (an introduced Mediterranean polychaete).

Remotely sensed, field, laboratory and published data have been acquired and combined to provide a basis for interpretation of present and past distributions of benthic features and a basis for suggesting mechanisms for changes in these features.

The approach in this study has been to conduct largely independent investigations of the applications of different remote sensing technologies. David Blackburn Environmental Pty Ltd has employed principally aerial photography and field observations and measurements of benthic feature types to produce maps of marine and coastal features. CSIRO Land and Water has employed principally airborne hyperspectral imagery using the CASI instrument to produce maps of marine and coastal features which have atmospheric and water column effects mostly removed and thus producing maps which are the result of less subjective methods than those required to interpret aerial photographs. Both teams collaborated on the design and implementation of new aerial coverages and field surveys and shared the field observational data sets. This report compares the results of the two approaches.

1.2 **Project deliverables**

The following deliverables have been provided to the Project Managers and other individual research teams:

- Baseline habitat map
- Bathymetry for Port Gawler to Sellicks Beach and some 30 km offshore
- A vector of the coastline defined by the tidal high water mark
- Feature mapped aerial photographs from 1949 to 2003
- Land based discharge plume maps
- Rectified orthocadastral base map
- Preliminary (2004) CASI image interpretations
- CASI spectral libraries for seagrasses, macroalgae, sediments and water column features
- CASI methodology for image interpretation
- Water column light attenuation characteristics for optically deep waters.

This report is a compilation of these data sets with an extended analysis of imagery to provide feature and change mapping of benthic cover and land based discharge plume features at much higher temporal, spatial and spectral resolutions than available from any previous studies of the Adelaide metropolitan coastline region. This new information has led to new insights on possible mechanisms for benthic feature changes.
1.3 Principal data sets

This report provides new information about the extensive spectral libraries that have been developed for particular substrate types (seagrass species, macroalgal species and sediments). These spectral libraries acquired from the CASI airborne hyperspectral instrument and from field measurements using the RAMSES submersible spectroradiometer suite have been used in the hyperspectral inversion optimization method SAMBUCA. (Semi-Analytical Model for Benthic Unmixing, Bathymetry and Concentration Assessment): a proprietary tool of CSIRO Land & Water enabling simultaneous assessment of water column depth, concentration of optically active water constituents (chlorophyll, colored dissolved organic matter and total suspended matter) as well as the relative distribution of two dominant benthic cover or composition types per pixel.

The principal remote sensing imaging systems used for this study were aerial photography and airborne hyperspectral imaging spectrometry (the Compact Airborne Spectrographic Imager – CASI). Field studies conducted at the time of image acquisition have been used to parameterize the SAMBUCA Model, but were not used to validate or “ground truth” the images as there were not enough sites available.

Data from other studies of benthic features in the Adelaide metropolitan region have been investigated and incorporated as appropriate to provide validation of the data sets produced from this Task. These include data from remote sensing instruments, underwater surveys (diving, photography) and surface observations and are referenced in the text.

Some high spatial accuracy, multispectral band satellite remote sensing data (from the Quickbird II satellite) have also been used in a qualitative manner.

Monochromatic aerial photography provides only grey scale data and this allows interpretation of imagery only on the basis of spatial patterns and “greyness”. Interpretation of such imagery requires a highly subjective approach based upon the local experience of the spatial data analyst, with an understanding of patterns and associations of features.

Conventional colour aerial photography uses only three color bands to discriminate spectral features in visible wavelengths and nearby infrared, but provides at least a visible color spectrum to aid in the discrimination of seagrass, macroalgal and sediment features. Near visible infrared photography provides an extra dimension for discrimination of shallow water and coastal feature types.

Current airborne imaging spectrometers have up to 72 bands in the visible and near infrared region enabling a significant enhancement in spectral discrimination. CASI missions were flown in 1999 with an older CASI version enabling only 13 spectral bands to be imaged. In 2001 and 2003 a dedicated 30 band spectral band set was used that was developed specifically for shallow coastal and coral reef benthic cover mapping. Therefore there are fundamental differences in technologies and spectral resolutions between aerial photography and airborne digital imagery and this report addresses the methods and results of each separately. Quantitative comparisons of aerial photography and CASI interpretations are given in Chapter 5. These and qualitative comparisons are summarized in the conclusions in Chapter 7 along with recommendations for future applications of remote sensing appropriate to long term environmental monitoring in the ACWS area.
2 Remotely sensed data


Remotely sensed data for this study focused on airborne photographic and hyperspectral digital imaging systems. In addition, field measurement and observations using a submersible spectroradiometer suite, in situ light beam absorption, and attenuation as well as in-situ light backscatterometer measurements supported these remote sensing data. Laboratory analyses of the spectral light absorption by algal pigments, total suspended matter and coloured dissolved organic matter completed the spectral information gathering.

Information maps derived from remote sensing data must firstly be referenced to established real world coordinate grids to allow their mapping on to existing maps e.g. ortho-cadastral maps, and their mapping against other spatially referenced data sets. All of the maps in this report are referred to consistent spatial datums and the data sets comply with ANZLIC standards for spatial data transfer (i.e. metadata regarding place and time of collection, data formats, data quality. Where necessary the maps and figures in this report have coordinate grids and location and feature labels attached.

Mapping remotely sensed data and field observational data requires definition of the real world coordinate projection system that applies to the study area. Consistency in real world coordinate systems is crucial to allow the combination of spatial data sets from other Tasks – ecological data, land based discharge data, hydrodynamic models etc. The projections and data sources are described below.

Computer software used for remotely sensed data rectification and image analyses included TntMips © Microimages, ArcView, ArcInfo, ERMapper © ESRI and ENVI © Research Systems Inc. SAMBUCA software © CSIRO L&W was used for spectrally based classifications of CASI and in-field spectrometer data sets.

2.1 Spatial coordinate projection systems

The remotely sensed data sources and interpreted maps are referenced to the WGS84, AGD84 and GDA94 datums (minor corrections for conversion between these datums have been applied where required), and the Universal Transverse Mercator (UTM) Projection for Australian Map Grid (AMG) Zone 54 South is the projection basis for all maps. Maps referred to this projection can easily be converted to latitude and longitude coordinates – this has not been done in this report because, firstly the whole study area lies within one AMG Zone (so there are no anomalies at grid zone boundaries) and secondly it is more intuitive to work with coordinates in metres rather than degrees, minutes and seconds when interpreting the scale of mapped features.

2.2 Data sources

Aerial photography was derived from a number of different cameras and aircraft, film types and flight altitudes. Historical imagery was provided by DEH and new imagery taken on November 25th, 2003 was provided on commission by Aerometrex Pty Ltd. Aerial photographic data prior to 2003 (back to 1949) was digitized from 10 inch contact prints, the Aerometrex images were scanned from negatives obviating issues of loss of contrast and variable “wet photographic chemistry” processing anomalies. Additional aerial photography was acquired by Aerometrex in October 2004 and is of
exceptional quality. As this was not within the scope of the budget for Task RS 1 it has not been included (except summarily) in the data sets for this report. The imagery remains copyright of David Blackburn and represents an important resource for any future remotely sensed monitoring programs. As a result of the differences in the types of aerial photographs, resolutions of the digitized images range from 0.35m to 2.5m pixel sizes. Some imagery from the Quickbird II satellite (2.5 m resolution) and the airborne digital camera system, Vecxel Ultracam (0.5 m resolution) is presented.

CASI data from 1999, 2001 and 2003 (2m to 2.5 resolutions) forms the core of objective image interpretations for this report.

Airborne hyperspectral imaging spectrometry data used a 13 band CASI sensor in 1999 and a 30 spectral band CASI instrument in 2001 and 2003 for the Bolivar WWTP outfall region and in 2003 for the Bolivar to Seacliff region. The image resolution was between 2 m and 2.5 m. Spectral characteristics of the water column and benthic substrates were obtained in November 2003 using the in-field spectroradiometer system RAMSES, with additional optical properties of the water column measured by AC-9 (9 spectral bands beam attenuation and absorption) and a HydroScat-6 (for light backscattering measurements at 6 wavelengths).

Water samples were taken and analysed at CSIRO Centre for Marine Research (CMR) laboratories for spectral light absorption of the algal pigments, the non-algal particulate matter (tripton) and coloured dissolved organic matter (CDOM).

Field studies to provide validation data for the photography were conducted between 1999 and 2003 and these produced GPS located information about the distributions of benthic features. 50 field sites were investigated during 1999 surveys. In-field studies included diving surveys, surface and land based observations, with underwater and surface photography and collection of seagrass and algal specimens for taxonomic identification and spectral reflectance characterization from 35 sites in November 2003.

### 2.3 Data preparation

#### 2.3.1 Aerial photography

All available aerial photography needed to be georeferenced, (referred to real world coordinates) or rectified (warped to allow for aircraft heading, pitch or bank and topography), contrast matched or mosaicked. This is a non-trivial and exacting process. Given the 85 individual photo frames this process took about 5 months to complete.

Georeferencing was carried out by digitizing base cadastral maps at 1,200 dpi. The published base maps at 1:50,000 scale (produced by the SA Department of Lands) were:
- Vincent 6528-1
- Gawler 6628-4
- Adelaide 6628-3 & PT 6528-2
- Noarlunga 6627-4 & PT 6527-1.

The scanned resolution was approximately +/-1m. Quoted horizontal positional accuracy for the published maps is +/- 12.5 m.

To improve rectification of the airborne aerial photography imagery, 30 accurate GPS fixes (RMS of +/- 5m with 12 GPS satellites acquirable) were obtained for structures which could be clearly identified in aerial photography. These fixed features included:
- ends of jetties
- wharf structures
- breakwaters
- marinas
- navigational beacons and markers
- ends and anchor blocks of underwater pipelines
- land based discharge outfalls
• Penrice salt pan bunds
• individual mangrove trees.

Cadastral features from published maps were first used to provide approximate positional data and the images were then warped to match the more accurate GPS data – this warping is the rectification process. Next the individual photo files were digitally trimmed to reduce as much as possible sea surface reflection and wave influences. Contrast trend removal algorithms were applied to reduce issues of up-sun and down-sun contrast variations. This provided image files which were then “stitched” together using the georeferencing information.

The 2003 imagery had the best control due to the positional data obtained during the November field survey and so the 2003 mosaic has been used as the reference for georeferencing and rectification of all other aerial photography sets.

Through this process we have been able to determine that absolute horizontal positional errors for individual pixels in the suite of mosaics are of the order of +/-10m, while relative positional errors in comparing successive mosaics are approximately (or better than) +/-2m.

2.3.2 CASI data

The CASI data is registered line by line during the flight and 5 dimensional data (x,y,z location and attitude of the aircraft and time) are registered for each line. This makes automated geo-correction possible using standardized software (that is proprietary to the owner of the CASI instrument). CASI accuracies are equivalent to those for aerial photography. The positional accuracy of the CASI and photographic data sets has been confirmed in maps which demonstrate that distinctive fixed features discernible in the two data set types are within about 2 m of their true positions.

To process the 48 flight tracks for geo-correction of the CASI took several weeks. There were some anomalies in flight lines that had to be reflown on a second day and these required special corrections to make them compatible with other adjacent flightlines.

The pixel size for scanned aerial photography was from 35 cm to 2.5m. The CASI data was recorded between 2.0 and 2.5 m resolution. Nominally 2m was chosen as the pixel size for image analyses, but once these were complete the analysed images were resampled to 10 m pixels, a more practical resolution when comparisons with GPS located field observations were required. Moreover it reduced the size of images by a factor 16. In future applications, an a priori decision on spatial scale for final products needs to be made, as flying the CASI at 2 m resolution or at 10 m resolution, and indeed preprocessing and final processing efforts are 25 times less when 10 m pixels are sufficient for the purposes of the application. An additional bonus is that the signal to noise ratio of CASI data (at 2 m already about 20 times larger than aerial photography) would increase significantly with an increased pixel size of 10 m.

2.4 Image analysis considerations

For all but the 2003 coverage, aerial photography was taken with little regard for solar elevation, sea state and water column conditions – this is a result of earlier aerial photography being targeted to provide mostly terrestrial coverage where the water column is not an issue.

Solar elevation is crucial for obtaining good coverage of coastal and marine areas. Low sun angles are essential for minimizing the degree to which the images are obscured by sea surface reflections. Likewise sea states are important as waves increase the spread of reflections and impose a pattern of small scale variations in brightness and contrasts (wave crests to wave troughs) which confound the interpretation of water depths in aerial photography imagery.

Sea surface reflections can result in extreme mismatches in contrast between successive photographs. The result is that in interpreted maps there are likely to be artificial linear boundaries between mapped features. The processes of image interpretation can remove most of these and how successful this can be is shown by a comparison of un-interpreted and interpreted images shown in Figures 2.1 and 2.2. Figure 2.1 is a small extract (off Semaphore) of two aerial
photographs from 1975 with markedly different contrast and brightness. Figure 2.2 is an extract of an interpreted image of the same area where image mismatches are almost totally eliminated.

Other confounding problems with aerial photography include:
- Dust and marks such as fingerprints on negatives and contact prints
- Scratches on negatives
- Watermarks from the developing process
- Creases in contact prints
- Boat tracks (a problem with any remotely sensed imagery over water) and Newton rings.

It is not possible to state simply that in any aerial photograph the red/green/blue (RGB) reflectance of benthic features will have a range of values between (on a scale of 0-255 – black to white) for example R:30-70, G:110-180, B:70-150. Only after correcting the colour, brightness and contrast ranges of each image, to a standard reference image would it be possible to define characteristic spectral ranges of individual feature classes for all aerial photographs. In practice this is a pointless exercise and it is more practical to conduct independent mapping on each photo mosaic, using common regions of interest and algorithms for testing feature associations. The various influences on the spectral characteristics of light reaching the aerial photography film are summarised below. These influences also affect airborne digital imagery e.g. CASI imagery, but with the hyperspectral data sets, corrections can be made for atmospheric, water surface and water column properties. The CASI sensor has a narrower field of view than airborne photographic cameras. This narrower field of view coupled with known radiometric units of the data make it possible to correct for most of the above effects using physics based approaches.

**Solar elevation**
High sun angles (sun at zenith= high in the sky) may result in the direct reflection of the sun in the image (the hotspot effect) or in high reflections of direct sun light caused by waves. CASI imagery is ideally acquired around sun angles of 30 to 60 degrees zenith angle. Thus depending on the season and latitude the optimal time for imaging will change throughout the year. Images of features with a three dimensional structure taken at this time will, however, have substantial
shadows on the ‘down-sun’ side of features such as mangrove trees, tall samphire shrubs, buildings etc.

**Solar azimuth**

Aerial photographs will have colour, brightness and contrast trends which relate to the solar azimuth in relation to flight direction. Atmospheric haze tends to brighten the ‘up-sun’ regions of water features photographs due to back scattering effects. Vegetation such as mangroves and samphires reflect more strongly in the ‘down-sun’ direction. ‘Down-sun’ vegetation appears brighter in all spectral bands, especially red, than does ‘up-sun’ vegetation. Because aerial photographs generally cover areas about 4km on side they are subject to substantial contrast differences in frames. CASI with a flight line into and away from the sun and a narrower field of view will have less initial contrast mismatching between flight lines. In addition, automated procedures are available in prototype form, which automatically reduce any residual contrast differences. Compared to aerial photography the reduction of contrast mismatching between runs (frames) in CASI imagery is a factor 10 to 20 better. Satellites such as Quickbird acquiring imagery from 300 km altitude have an imperceptible problem with influences of solar azimuth if the image is acquired according to stringent guidelines as the sensors are typically pointable and over water surfaces should always be pointed away from the sun. A new airborne digital camera system being trialled by Aerometrex (Vexcel Ultracam) acquires frames every one second and this results in imagery that has imperceptible frame to frame contrast mismatching.

**Sea surface conditions**

Smooth water will have solar reflection limited to a small ‘hot spot’ at reciprocal angles to the incoming light beam. Wind ripples cause scattering of solar reflections which may obscure up to half of an image. Wind streaks and tidal current interaction effects on the sea surface may appear as semi-linear features in photos, especially when there are also solar reflections from them. These features can greatly confound image interpretations. Large waves can not only cause problems with surface reflections, but also refract light paths so that sea floor features may appear to be shifted. Large waves may also be associated with high turbidity in the water column.

This influence is specifically a problem with all airborne systems that use a camera with a 2 dimensional field of view. With airborne and satellite digital imagery these effects are much less as they typically build an image by successive line scans; thus most sun glint can be avoided. Airborne and satellite digital imagery can be corrected for the skylight reflectance at the surface (the blue light under clear sky conditions and the grey light under clouds) using the CSIRO developed C-WOMBAT_C atmospheric and air-water-interface radiative transfer based correction code). Colour aerial photography is not corrected for this skylight reflection at the water surface. As the water surface typically reflects between 5 and 6% of diffuse skylight this can be a major part of the supposed water-leaving signal of aerial photography. This removal of atmospheric, and air water interface contamination of the water-leaving signal significantly enhances the signal to noise of multi and hyperspectral remote sensing data.

**Atmospheric haze**

Haze due to aerosols, mist or fog in the atmosphere between the airborne or satellite sensor and the ground will brighten images due to increased atmospheric back-scattering of light. The effect is more pronounced at low azimuth angles (looking into the sun, henceforth referred to as the ‘up-sun’ direction). As most aerosols are smaller than the visible wavelengths of light the blue light is scattered more than the green and red light resulting in a bluish cast to photographs. Cloud above the aircraft will scatter all wavelengths of light equally as the water droplets are larger than the wavelength of visible light. Under full and even cloud cover conditions there is no sun glint but there is more diffuse skylight reflectance at the surface. High altitude, even, cloud cover is ideal for obtaining airborne imagery but an anathema for satellite imagery. Both airborne and satellite acquired digital imagery can be corrected for atmospheric effects such as aerosol light scattering and absorption, ozone, oxygen and water vapour absorption which influence the transmission and spectral characteristics of light passing through the atmosphere. In this study these correction were performed to the CASI data with the C-WOMBAT-C algorithms of CSIRO Land & Water (Brando & Dekker, 2003).
**Light in the water column**

Turbidity is an often used term to describe the opaqueness of water. It is a poorly defined term as it encompasses both the effects of light absorption and light scattering, but does not discriminate between them. If we more properly separate the optically active constituents into some major groups with specific scattering and or absorption properties it becomes easier to understand the effects of the water column on substrate visibility. Initially three main categories can be discriminated: pure water, the suspended particulate matter and the coloured dissolved organic matter. The suspended particulate matter (often referred to as suspended solids or total suspended matter - TSS) can be separated into the algal (or phytoplankton ) component and the non-living organic and the mineral components. Inorganic suspended sediments often appear bright due their low absorption and high scattering of light (unless the minerals are strongly coloured), while non-living organic suspended material e.g. detritus will often have a dark yellow to brown colour, the algae absorb light strongly in the blue and red due to the photosynthetic absorption of light by light harvesting pigments dominated by chlorophyll (and they thus will colour water green).


Suspended solids at concentrations of greater than about 100 mg/L will totally obscure sea floor features in water depths of more than about 1 m. Chlorophyll concentrations, due to algal cells, of about 1 mg/L will have a similar effect. Finally we need to discuss the coloured dissolved organic matter that by definition only absorbs light. It is the material made up of tannins (or humic and fulvic acids) that give some natural waters in peat or pine forest areas a yellow or orange colour (sometimes, as for example drainage from “button-grass” plains in Tasmania the water is black). All of these substances occur in the ACWS region but at low concentrations as is apparent from the transparency of the ACWS waters ranging from 3 to 10 m, with the exception of the Outer Harbour River plume with very high suspended matter (principally inorganic) loads.

The combined effect of the light absorption and scattering leads to light being increasingly attenuated with depth in the blue wavelengths – due to algal pigments, the organic particulate matter and the coloured dissolved organic matter. In the red wavelengths it is due to increasing light absorption by pure water and by the red chlorophyll pigment absorption. Thus the spectral information from the substrate cover will increasingly be limited to green wavelengths as the water column depth increases.

**Water depth**

Clear seawater that is free of suspended matter and dissolved material rapidly absorbs red light, green light less and blue least of all. Coupled with a strong increase of light scattering from red via green to blue wavelengths, the blue reflectance increases with water depth. At most, about only five percent of incident red light returns to the surface after passing through a five metre seawater column. Sea floor features such as seagrasses will absorb a large part of the incident light and so the intensity of red light reflected back from seagrasses in five metres of water may be less than one percent of the incident illumination. Light absorption increases from the blue through the green to the red wavelengths and significantly increases into the nearby infrared wavelengths. For pure seawater light scattering decreases from the blue through the green to the red and nearby infrared in an exponential fashion. Thus for pure seawater light attenuation is low in the blue (mainly caused by scattering), low in the green but increases rapidly towards the red and nearby infrared. Algae, tripton (the non algal part of total suspended matter) and dissolved organic matter all increase attenuation of light through absorption, scattering or both. The effects of water depth can be determined, at least for shallow, relatively clear waters by applying image analysis algorithms which are able to determine the spectral range of sea floor features simultaneously with the water column composition (the SAMBUCA model).

**Benthic material and vegetation cover**

The colour and brightness of the benthic material (sand, silt, mud, clay, rock) and the benthic vegetation (seagrasses and macro-algae) will influence their visibility as measured from CAP or airborne or satellite imaging systems. A bright sand feature versus a dark Posidonia cover will be measurable to greater depths than more subtle differences between Zostera and Posidonia beds. However if high spectral resolution data such as from a CASI are available, subtle spectral
differences will be enough for discrimination till the water column attenuates that specific spectral signal difference too much.

**Aerial photography film type**

Black and white negative film was used exclusively for aerial photography in the study area until 1979. Colour aerial photography (CAP) was used exclusively only from 1985. False colour (infrared) photography was obtained only during December 1993. B&W images contain only grey scale information which is divided by image processing software into 256 brightness levels (0=no reflection, 255=100% reflection). Colour and infrared photographs can be processed as three separate pseudo red, green and blue colour bands each with 256 reflectance levels, resulting in $256^3$ or 16.8 million possible band reflectance combinations. Infrared images give very good discrimination of terrestrial vegetation, because of their strong red reflectances, but poor discrimination of marine features, because of the red absorption by the water column.

Airborne imaging spectrometry such as used here has 30 spectral bands in a 12-bit recording mode (later mapped to 16-bit data). Thus there are virtually unlimited possible spectral band combinations theoretically possible. However, if noise is taken into consideration as well as the natural range of possible concentrations variations in the water column, the amount of feasible water leaving spectra is reduced to hundreds or thousands at the most.

**Aerial photography film processing**

Variations in processing conditions for individual photographic prints can result in changes in colour balances, even between successive photos in an aerial photo run. Colour and contrast matching during image processing generally corrects for such differences. Inevitably photographic negatives have some dust, scratches and other marks due to less than pristine handling and darkroom conditions. Artefacts produced within the photographic printing equipment include Newton rings which are interference patterns caused by moisture or air gaps between the film and the enlarger glass and result in curved, coloured patterns on prints. These are extremely difficult to remove and may require considerable manual editing during image processing, or be excluded from image classifications entirely. Figure 2.3 illustrates some of the artefacts that can occur during handling and processing of films.

Airborne imaging spectrometry data avoids all these issues as the data are recorded in directly acquired digital radiance units.

![Confounding artifacts in contact prints of aerial photography – dust, Newton rings and boat tracks.](image)

**FIGURE 2.3** Confounding artifacts in contact prints of aerial photography – dust, Newton rings and boat tracks.

Image processing methods using models for removal of atmospheric and air-water interface effects and for dealing with water column influences on the spectral reflectances of benthic features are considered in detail in Chapter 5 in the analysis of CASI data.
Maps of benthic features – Aerial photographs

Maps of benthic features based upon aerial photography interpretation and substantiated qualitatively by field surveys (surface and underwater observation at 50 sites) are presented here. Previous studies of seagrass distributions using aerial photography interpretation have been conducted for the EPA (EPA 1998, Hart 1996, 1997a, 1997b) and these prior maps have been considered here. With the inclusion of new hyperspectral CASI data sets (see Chapter 5) and new field observations, the resolution of these maps, both in spatial and feature class terms has been improved considerably over those previously presented to the ACWS Scientific Committee.

The feature maps shown below are based upon subjective/semi-objective interpretations of aerial photography. Initially the imagery was classified into 17 different feature classes. This was subsequently reduced to 8 feature classes on the basis that these were considered to be more ecologically relevant. Reducing the number of features also had the advantages of greatly decreasing the time required for image analysis and increasing the reliability and replicability of classifications. As the process of feature mapping is inherently subjective it was difficult to estimate the reliability of classifications. By replicate mapping of features (a process involving not entirely independent classifications) it is estimated that error rates for classifications for dominant features such as bare sediments and dense seagrasses are generally less than 5%.

The 2003 maps have been verified using field observations of benthic features and substrates conducted at the time of acquisition of CASI data and aerial photography in November 2003. Field observation data for this survey are given in Appendix 2. For CASI data analysis water column measurements of light attenuation and substrate reflectance were also made in the field.

It would be an expensive and very time consuming exercise, employing independent image analysts with an appropriate level of local knowledge and analytical skills (and patience) to provide accurate estimates of error rates in aerial photograph image classifications. This must be seen as a pointless exercise, given that conventional ground-based ecological surveys provide habitat maps based upon the assumptions of linear interpolations between observation points or transects – the reliability of such maps cannot be tested practically. However remote sensing image analyses are based upon spatially continuous data sets.

Although the 8 feature classes are shown in this Chapter, an agreement was reached with the Project Managers, leaders of other Tasks and the Scientific Committee to use a more workable and ecologically relevant set of classes. The present set five of classes upon which final mapping products are based is:

- Posidoniaceae (*Posidonia sinuosa* and *P. australis* grouped together)
- Zosteraceae (*Heterozostera tasmanica*, *Zostera muelleri* and *Z. mucronata* grouped together)
- *Amphibolis antarctica*
- Macroalgae (*Ulva*, *Halimiphon*, *Dictyota*, *Gracilaria*, *Gelidium*, *Scaberia* etc. grouped together—includes *Spirographis* by default as it generally has epizoic macroalgae on the worm tubes)
- Sediments bare of seagrass or macroalgae (although consistently covered by a surface layer of microphytobenthos including microalgae and diatoms).

Figure 3.1 shows the highest quality benthic feature map yet produced from aerial photography interpretation. It is based upon November 2004 coverage, which was flown without ACWS support and so is provided only as an example of what can achieved with ideal aerial photography. The imagery was scanned from 25 cm by 25 cm negatives to provide data at 35 cm resolution and resampled to 1 m pixels for the image classifications. Validation of the feature maps relied upon field observations made in November 2003 during the CASI and accompanying aerial photography flight and independent field studies (Blackburn 2004).
Interpretations of imagery prior to 2003 have been based upon hind-casting of the 2003 classifications and have involved detailed assessment of feature patterns and spatial distributions.

Historical image interpretations incorporated observations and data from a number of previous studies (Kinhill Stearns 1985a, 1985b; Gobbie and Blackburn 1993; Hart 1997a, 1997b; EPA 1998, Kinhill 1998b; Blackburn 2001a, 2001b, 2004).

The accuracy of feature maps was established through:
- detailed examination of photos in relation to mapped

FIGURE 3.1  8 class feature map derived from 2004 aerial photography
• replicate remapping of mosaics and statistical comparisons of the resultant maps
• reference to pre-existing community maps
• ground truthing from field surveys and
• the application of decision rules for determining whether features occur or do not occur together (see Figure 3.2).

Replicate remapping at different resolutions and comparisons of statistics of feature areas showed that maps could be reproduced with a greater than 90% correspondence where photographic quality was good (less than 10% sun glint and interference by wave features) e.g. 1974 and 1993 photos, but this degraded to only about 75% correspondence, in complex areas such as mixed seagrass/macroalgae and mangrove/samphire communities, where photographic quality was poor (notably 1983 photos).

One aspect of image classification was to ensure that errors of commission or omission did not occur, or at least were very limited. An error of commission is one where pixels are classified as a particular feature, when in fact they belong to another. Such errors result from the fact that by chance, or due to colour and contrast trends, pixels from different real features, have spectral reflectances which are contained within or overlap those of other feature classes. An error of omission is the converse and occurs when a pixel which should have been included in a particular feature has been classified to another. These errors can be reduced by using spatial pattern analysis and defining restricted regions of interest to allow only localised classifications which are then tiled to produce a full study area classified map.

A logic matrix (Figure 3.2) for determining whether different features occur together frequently, occasionally or never was developed in a study for SA Water of the Bolivar WWTP discharge (Kinhill 1998). Although this includes feature types not studied for the ACWS it is useful to include it to demonstrate that aerial photography interpretation is not entirely subjective.

As the inversion optimization method SAMBUCA has to calculate millions of possible permutations per pixel these expert knowledge rules were used to reduce permutations that are physically unlikely or impossible. Moreover such expert rules help guide the solution away from local solutions in the optimization process that could give false results due to e.g. spectral ambiguity (or alikeness) in the CASI interpretations.

These rules can be summarised as “what occurs with what”, “what occurs next to what”, “what does not occur with or next to what”.

FIGURE 3.2 Logic matrix for testing if features are likely to occur together
Image classifications took into account, as far as possible, each of the influences on spectral characteristics (of the 3 bands used in CAP) but in the final classifications, spatial relationships were of major importance. Examples of decision rules (qualified by their locations in the study area) for testing association between features are summarised below:

- 'If dark and next to dark and depth is subtidal then Posidonia'.
- 'If dark and next to bright and depth is subtidal then Posidonia'.
- 'If bright and next to dark and depth is subtidal then subtidal sediments'.
- 'If dark and next to dark and depth is intertidal then Zosteraceae'.
- 'If dark and next to bright and depth is intertidal then Zosteraceae'.
- 'If depth is intertidal and if dark and next to bright (seawards) and next to reddish communities landwards, then mangroves'.

In these examples 'dark' and 'bright' are used to represent overall low and high reflectances respectively, whereas in the actual classifications quantitative spectral reflectance data were employed. In conclusion it is not an easy task to produce a simple list of feature classes versus spectral ranges for all photography since images have had to be individually processed to account for film types, water depths, reflections etc. with spatial relationships being important in classifications.

For aerial photography the matrix of reflectance data for all features in all photographs would be of dimensions (n [5-17]) features x 6 time periods x 5 spectral bands (3 Red-Green-Blue or RGB bands, 1 B&W band, 1 Infrared band) or between 150 and 510 possible classifications.

In addition to the rules described above there are other considerations applied to interpreting remotely sensed data for feature classifications.

The typical water depth distributions of various benthic feature classes have been determined from numerous field observations and these typical depths are summarised in Table 3.1 (this table is repeated in Chapter 5 in discussions of CASI data interpretations).

**TABLE 3.1** Indicative depth distributions for benthic features, Adelaide metropolitan waters.

<table>
<thead>
<tr>
<th>Feature category</th>
<th>Species/feature</th>
<th>Depth range m AHD</th>
<th>Depth range m ISLW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seagrasses</td>
<td>Posidonia australis</td>
<td>0.0 -7.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Seagrasses</td>
<td>Posidonia sinuosa</td>
<td>-2.4 -12.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>Seagrasses</td>
<td>Amphibolis antarctica</td>
<td>0.0 -6.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Seagrasses</td>
<td>Zostera spp.</td>
<td>1.5 0.0</td>
<td>3.1</td>
</tr>
<tr>
<td>Seagrasses</td>
<td>Heterozostera tasmanica</td>
<td>1.5 -2.0</td>
<td>3.1</td>
</tr>
<tr>
<td>Brown algae</td>
<td>Scaberia, Cystophora, Sargassum</td>
<td>-2.0 -6.0</td>
<td>-0.4</td>
</tr>
<tr>
<td>Red algae</td>
<td>Dictyota, Gracillaria, Haliphiton</td>
<td>-0.5 -5.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Red algae</td>
<td>Gelidium</td>
<td>-2.0 -3.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>Green algae</td>
<td>Ulva</td>
<td>1.5 -4.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Intertidal and beach sand</td>
<td></td>
<td>4.0 1.3</td>
<td>5.6</td>
</tr>
<tr>
<td>Shallow subtidal sand</td>
<td>Sand</td>
<td>1.3 -2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>Deep subtidal sand</td>
<td>Sand</td>
<td>-2.7 -15.0</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

Notes:
1) These data were used as a guide to aid seeding of image classifications
2) Indian Spring Low Water (ISLW) is approximately 1.6 m below Mean Sea Level (MSL)
3) MSL is equivalent to the Australian Height Datum (AHD)
4) Spirographis is grouped with macroalgae esp. Ulva and reds as these generally grow on the worm tubes.

Using these typical depth distributions, “regions of interest” or exclusion masks were applied to aerial photo mosaics to prevent misclassification of shallow water features with deep water features, even if the RGB values overlapped.

Texture and patterning was also used to aid the identification of features – for example crescentic blowouts occur only in subtidal *Posidonia* beds, small sub-circular features are typically shallow.
water *Posidonia australis*, *Zostera* or *Spirographis*. The short term variability of features was also used as a key to classification;

- *Zostera* and macroalgae, in particular *Ulva* and red algae are highly variable in distribution and cover on seasonal timescales
- *Posidonia* varies significantly only on time scales of years
- *Spirographis* has colonised typically as sub-circular patches which become more extensive and less regular over time scales of several years (and do not occur with seagrasses).

Examples of the short timescale variability of *Zostera* and macroalgae distributions are given in figures 3.3 and 3.4.

The changes in distributions of *Zostera* (mixed with *Ulva*), offshore of the Bolivar WWTP over a 10 month period from November 2003 to September 2004 are very marked with the seaward margin of this feature almost 1 km further landward in 2004. The density of *Zostera* in 2004 was also markedly less than in 2003. In comparison there are no noticeable changes in the distributions of offshore *Posidonia* beds over the same time period.

**FIGURE 3.3** Seagrasses, Bolivar region, November 2003

**FIGURE 3.4** Seagrasses, Bolivar region, September 2004
3.1 Characteristic spectral signatures for features in aerial photographs

The question of whether it is possible to define characteristic spectral signatures which can be used to identify features such as seagrasses, mangroves, samphires and sediments in digitized aerial photography has often been raised. The following discussion addresses the problems of matching spectral characteristics of features common to different aerial photographs and why both expert system rules and experienced user input can be used to produce reliable classifications of photographic image features.

Aerial photography provides analogue images of features on the earth's surface and its representation of the spectral reflectances of individual features is limited by a number of confounding influences. For example where images are acquired over water, the water depth, sea surface conditions, sun glint and skylight reflection at the water surface can alter the spectra of light reflected from benthic features. Emergent features such as mangroves and samphire have different reflectances in the 'up-sun' and 'down-sun' directions and may cast shadows. Atmospheric conditions can also affect the reflectance spectra of surface features. The types of photographic film, the storage of film and photographic paper, processing methods and specific chemistry for processing also profoundly affect the spectral data retrievable from photographs.

Aerial photography is limited by its low spectral discrimination (3 indeterminate bands for color photography and only 1 grey scale band for black & white photography) and confounding influences due to variable sun angles, sea states and turbidity.

A major advantage of aerial photography as a remotely sensed data source is that there is a long historical record of images, representing spatially and temporally extensive data sets that cannot be derived from any other remote sensing or field based ecological or sedimentological surveys.

Airborne or satellite borne multispectral and hyperspectral imaging systems have the potential to provide data sets which overcome the inherent limitations of aerial photography. Options for future cost effective remote sensing data acquisition are considered in a later section of this report.

An algorithmic model for interpreting CASI data is presented in Chapter 5.

For all but the issue of boat wakes, digital imagery such as CASI data does not suffer from these problems or they can be dealt with through radiative transfer based computations.

Aerial photography cannot easily be classified using objective statistical image analysis procedures because of the limited spectral data available from analogue photography. A conventional image classification methodology; using field observational and local knowledge information is called feature mapping. Feature mapping has been widely used for the mapping of terrestrial vegetation and landform features throughout the world and details of its implementation can be found in documents such as the reference and tutorial manuals for GIS software products such as TNTmips and ArcInfo and publications such as Vincent (1997).

Feature maps are subjective classifications of the remotely sensed imagery, substantiated by field observational data sets and for the November 2003 survey we investigated 50 underwater and surface observation sites with handheld, still camera photography and collections of benthic biota from the sites for in-field and laboratory spectroradiometric measurements and visual interpretations of photographs. In addition bathymetric data were used to develop a water depth removal model to reduce the effects of the water column on image contrast.

Feature mapping involves selecting samples of pixels which have similar ranges of reflectance values and which are likely to belong to the same feature class – this requires some substantial local knowledge of what occurs where and what elements of features are likely to occur together – sand and seagrass are commonly intermixed, intertidal and subtidal seagrasses are rarely or never so.

The boat tracks and field observation sites, plus sites for water quality sampling are shown in figures 3.5 and 3.6 (as heavy blue lines and points). The red lines on these plots are the nominally planned areas of aerial photographic coverage. The background image is the coverage actually
achieved. Bathymetric contours at 5 m intervals (referred to Mean Sea Level are shown as lines in yellow through green and blues).

**FIGURE 3.5** Boat tracks and field locations, November 25 & 26, 2003 field surveys

Additional data from eleven field survey locations from a study conducted for DEH Office of Coast and Marine (Blackburn 2004) have been used to validate benthic feature types and locations for this report.
3.2 Benthic Feature Maps – feature classes

Initially, 17 feature classes were used in image interpretations and these were;

- Littoral i.e. the beach zone defined as extending to Mean High Water Spring which is approximately 1 m above the Australian Height Datum – basically bare sand with some seagrass detritus particularly north of Largs Bay
- Bare intertidal which extends from AHD to Indian Spring Low Water (-1.56 m AHD) – basically bare sand along the metropolitan coastline, with locally gravel beaches particularly around Glenelg
- Bare subtidal which extends from Indian Spring Low Water to depths of about 8m below AHD – mostly bare sand, but locally with some *Sabella* or *Spirographis* (there is some taxonomic debate on the nomenclature) polychaete worm communities and dead seagrass root mat. The sabellid communities have been classified separately wherever they could be identified.
- Intertidal reefs – solid rocky reefs, mostly occurring south of Seacliff
- *Posidonia sinuosa* with 100% cover – these are the dense seagrass beds occurring offshore of most of the bare subtidal sands along the metropolitan coastline
- Cobbles with *Posidonia* – unconsolidated rocky reefs with *Posidonia* of generally less than 20% cover and mixtures of red and brown macroalgae occurring from Glenelg Jetty to Seacliff
• *Posidonia sinuosa* 50% cover – generally on the margins of denser beds, but around Outer Harbor in places the dominant community
• *Posidonia sinuosa* 20% cover - commonly associated wit the trailing edges of crescentic sand blowouts as a coloniser but also on the fringes of denser seagrass beds
• *Posidonia australis* 50% cover, *Posidonia sinuosa* 50% cover- dense seagrass beds mostly north of Outer Harbor
• *Posidonia sinuosa* 20% cover, *Heterozostera tasmanica* 20% cover – restricted to areas from Barker Inlet to Port Gawler in shallow subtidal locations e.g. offshore of the Bolivar discharge
• *Posidonia australis* 100% – dense beds north of Outer Harbor in water to about 6m below ISLW
• Zosteraeae and macroalgae – *Zostera muelleri* and *Zostera mucronata* with *Ulva* and at greater depths a number of red macroalgae – abundant on intertidal and subtidal flats north of Barker Inlet to about Chapman Creek (i.e. in the vicinity of the Bolivar discharge) – locally 100% cover.
• Brown macroalgae – includes *Cystophora* and *Scaberia* – locally in stable blowouts particularly south of Brighton
• Gelidium (a branching red alga) – found only on cobbles south of Glenelg but locally at high densities (>25% cover)
• Dead rhizomes – dead seagrass root matte occurs in patches inshore of the offshore seagrass along the metropolitan coastline from Semaphore to Glenelg
• *Sabella (Spirographis) spallanzanii* – introduced Mediterranean fan worm occurs on firm substrates (calcrete, shelly estuarine clays, razor clam shells, jetty piles, underwater pipelines etc), but is most abundant between Glenelg and Henley Beach. Generally has macroalgae including *Ulva* and red algae growing on the worm tubes.
• Sediment plume – this is a persistent feature in the ebb tide flow from the Outer Harbor shipping channel.

Due to the substantial computing loads required to identify and confirm these classes it was decided to reduce the number of classes to 8, by grouping feature types that could not be reliably distinguished in the full set of aerial photographs.

The 8 benthic substrate feature classes used for the earlier (up until November 2004) aerial photography and CASI interpretations are listed in Table 3.2.

**TABLE 3.2** Feature classes defined for interpretation of aerial photography and CASI data sets.

<table>
<thead>
<tr>
<th>Aerial photo feature classes</th>
<th>CASI feature classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Littoral (beach) sands</td>
<td>Sand class 8 (beach sands)</td>
</tr>
<tr>
<td>Intertidal sands</td>
<td>Sand class 9 (intertidal and shallow subtidal sands)</td>
</tr>
<tr>
<td>Subtidal sands</td>
<td>Sand class 10 (deep subtidal sands)</td>
</tr>
<tr>
<td>Sparse Posidoniaceae</td>
<td><em>Posidonia sinuosa</em> and <em>P. australis</em></td>
</tr>
<tr>
<td>Medium Posidoniaceae</td>
<td><em>Posidonia sinuosa</em> and <em>P. australis</em></td>
</tr>
<tr>
<td>Dense Posidoniaceae</td>
<td><em>Heterozostera tasmanica</em></td>
</tr>
<tr>
<td>Zosteraceae</td>
<td><em>Zostera muelleri</em> plus macroalgae</td>
</tr>
<tr>
<td><em>Amphibolis</em></td>
<td><em>Amphibolis antarctica</em></td>
</tr>
<tr>
<td>Macroalgae/Spirographis (with <em>Ulva</em> and <em>Haliptilon</em> on the worm tubes)</td>
<td><em>Ulva</em> and red branching macroalgae (<em>Dictyota</em> and <em>Haliptilon</em>)</td>
</tr>
<tr>
<td>Reefs with predominantly brown macroalgae cover, cobbles with <em>Ulva</em>, <em>Gelidium</em> etc.</td>
<td>Reefs</td>
</tr>
</tbody>
</table>

**Notes:**
1) The definitions of littoral, intertidal and subtidal sands used here are based upon the discrimination of the landward limit of the surf zone discriminated in the remotely sensed imagery used for this project. Intertidal sands are at low tide levels within the littoral zone.
2) Subtidal sands are intertidal at low tide levels.
Subsequent to the classifications based upon these classes an agreement was reached with the Project Managers, leaders of other Tasks and the Scientific Committee to use a more workable and ecologically relevant set of classes. The present set of classes upon which final mapping products are based is:

- **Posidoniaceae** (*Posidonia sinuosa* and *P. australis* grouped together)
- **Zosteraceae** (*Heterozostera tasmanica*, *Zostera muelleri* and *Z. mucronata* grouped together)
- **Amphibolis antarctica**
- **Macroalgae** (*Ulva*, *Halipliton*, *Dictyota*, *Gracilaria*, *Gelidium*, *Scaberia* etc. grouped together—includes *Spirographis* by default as it generally has epizoic macroalgae on the worm tubes)
- **Sediments without seagrass or macroalgae** (although consistently covered by a surface layer of microphytobenthos including microalgae and diatoms).

Photographs of some of the dominant species are given below. When the water depths at which these photographs were taken are cited they are related to Indian Spring Low Water (ISLW), which is approximately 1.6 m below mean sea level (MSL) or 1.6 m below the Australian height datum (AHD).

**FIGURE 3.7** Zostera muelleri with Giffordia (a filamentous brown alga) in the vicinity of the Bolivar WWTP discharge (tidal depth approximately 1.3 m ISLW)

*Zostera muelleri* is the dominant species of intertidal areas between Outer Harbor and Port Gawler. *Zostera mucronata* is also commonly associated with this species in slightly deeper waters, but has proven to be indistinguishable from the dominant species using remote sensing spectral discrimination algorithms. It is often mixed with or dominated by the macroalga *Ulva lactuca* (sea lettuce), particularly within the sheltered waters south of Section Bank, and into the St Kilda and Barker Inlet water bodies.

The photo shown in Figure 3.7 was taken approximately 1 km offshore of the Bolivar WWTP tidal creek at AMG coordinates 6152200 S, 2661000 E.
Heavily epiphytised seagrasses are a confounding influence for spectral mapping of seagrass species. This problem has been largely overcome by using field observations throughout the study area and relating these observations to remotely sensed data sets. The photo shown in Figure 3.8 was taken approximately 4 km offshore of the Bolivar WWTP tidal creek at AMG coordinates 6157100 S, 265600 E.

The photo shown in Figure 3.9 was taken approximately 2.5 km offshore of the Bolivar WWTP tidal creek at AMG coordinates 6157100 S, 266150 E.
FIGURE 3.10 Mostly dead *Posidonia australis* in the lowest part of the intertidal zone (approximately 50 cm above ISLW)

The dieback of seagrass in an area of approximately 50 ha is a result of exposure of the *Posidonia* beds at low tide during high temperature summer conditions i.e. a result of natural causes. Spectrally the dead seagrass beds have been classified as *Posidonia* overlapping with macroalgae. The small spatial extent of this feature means that any misclassification has an insignificant effect on the overall classifications and feature area estimates.

The photo shown in Figure 3.10 was taken approximately 1.5 km offshore of the Bolivar WWTP discharge tidal creek at AMG coordinates 6157100 S, 266940 E..

FIGURE 3.11 Healthy *Posidonia australis* with minimal epiphyte loads at approximately 3m below ISLW

The photo shown in Figure 3.11 was taken approximately 4 km offshore of the Bolivar WWTP discharge tidal creek at AMG coordinates 6152885 S, 266155 E.
FIGURE 3.12  *Posidonia sinuosa* with epiphytes at approximately 5m below ISLW.

The photo shown in Figure 3.12 was taken approximately 5 km offshore of the Bolivar WWTP discharge tidal creek at AMG coordinates 6152450 S, 265200 E.

![Posidonia sinuosa with epiphytes](image)

FIGURE 3.13  *Gelidium* (a red alga) from cobble reefs in the Glenelg to Brighton region

![Gelidium](image)

3.3 Feature Map Layouts

Figures 3.14 and 3.17 to 3.22 have an overlay of a polygon (in red) which shows the planned nominal coverage of the November 2003 flight. Coordinates shown on the margins of the maps are in latitude and longitude with metres as the scale unit referred to the Map Grid of Australia 1994 (MGA 94) projection.

The imagery was initially interpreted at the best available resolution (pixels 35cm to 2m on side for aerial photography, 2m to 2.5 m for the CASI data) but has been resampled to 10m by 10m pixels, because of practical considerations relating to the sizes of the data sets, and at the request of the Scientific Committee. A full map at 10m resolution is about 37Mb in size, at 2m resolution it is about 925Mb in size and at 35cm resolution it is about 30Gb in size.
Note that not all of the coverages are as extensive as that obtained in late November 2003. All available and useable aerial photography was studied and mapped, but unfortunately not all of the study area (Marino Rocks to Port Gawler) was covered in past aerial photographic imagery. Two versions of the 2003 feature map are supplied – one with 17 classes and one with 8 classes. The reduced number of classes is considered to provide a more accurate map of ecologically important classes than the 17 originally investigated. Eight classes are also more easily applicable to historical image interpretation, where there are limited or no field verified data.

The aerial photography classes for sparse, medium and dense seagrass cover include all seagrass species and genera (i.e. *Posidonia sinuosa*, *P. australis*, *Heterozostera tasmanica*, *Zostera muelleri/mucronata* and *Amphibolis Antarctica*). The macroalgae class includes principally green and red algae (e.g. *Ulva*, *Dictyota*, and *Haliptilon*). The reef class includes red algae (*Gelidium*), and brown algae including the macrophytes *Cystophora*, *Scaberia*, *Sargassum* and unidentified turf algae on cobbles and reefs.

Figure 3.14 is a 17 class feature map based upon November 2003 aerial photography and field observational data. The greyscale underlay is from 1999 aerial photography, chosen because of its almost complete coverage of the study, but also because it includes distinctive land features, useful for setting for the reader, the context of the imagery and maps.

*Amphibolis antarctica* has not been included as a class for aerial photography interpretation. Apart for some dense patches between Seacliff and Marino Rocks it is otherwise sparse. Locations of four sites where it was observed by SARDI scientists were provided by SARDI and these locations are plotted in figure 3.15 over a benthic feature map from 2003 aerial photography. Cover of less than 2% was observed at several dive sites during the November, 2003 field work, but it is generally patchy and occurs either as narrow fringes on the margins of *Posidonia* beds or stands of less than 100 m$^2$ elsewhere. It has been successfully mapped using the CASI data (for the first time ever - a unique scientific development) and will be considered in later discussions of those data sets (Chapter 5).
FIGURE 3.14  Feature map of 2003 aerial photography with 17 feature classes
Summary statistics for areas of major features are given in Table 3.3. In the table the following combinations of classes have been used to generate estimates of the contributions of Posidoniaceae, Zosteraceae, Amphibolis, macroalgae and essentially bare sediments

- Dense (50%-100% cover) Posidonia spp.
- Dense (>50% cover) Zosteraceae with some macroalgae
- Sparse (mostly 20% cover or so) subtidal seagrasses
- Amphibolis >50 cover
- Macroalgae (Ulva, Gelidium, Haliptilon, Dictyota, Gracilaria etc. generally on clay or reef substrates)
- Essentially bare subtidal and intertidal sediments (though often with benthic microalgae).

**TABLE 3.3** Contributions of major, combined feature classes based upon feature mapping of November 2003 aerial photography

<table>
<thead>
<tr>
<th>Feature and cover %</th>
<th>Area (ha)</th>
<th>% of total mapped area</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. sinuosa 100%</td>
<td>10146</td>
<td></td>
</tr>
<tr>
<td>P. sinuosa 50%</td>
<td>1534</td>
<td></td>
</tr>
<tr>
<td>P. australis 50%, P. sinuosa 50%</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>P. australis 100%</td>
<td>1441</td>
<td></td>
</tr>
<tr>
<td><strong>Dense Posidonia-Total</strong></td>
<td><strong>13174</strong></td>
<td><strong>58.9</strong></td>
</tr>
<tr>
<td>P. sinuosa 20% and Heterozostera 50%</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Zostera plus Heterozostera plus macroalgae &gt;50%</td>
<td>526</td>
<td></td>
</tr>
<tr>
<td><strong>Dense Zosteraceae-Total</strong></td>
<td><strong>555</strong></td>
<td><strong>2.5</strong></td>
</tr>
<tr>
<td>P. sinuosa 20%</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>P. sinuosa plus Halophila 20%</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Halophila 40%, P. sinuosa 15%</td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td><strong>Sparse subtidal seagrass-Total</strong></td>
<td><strong>83</strong></td>
<td><strong>0.4</strong></td>
</tr>
<tr>
<td>Amphibolis &gt;50%</td>
<td>17</td>
<td>0.1</td>
</tr>
<tr>
<td>Macroalgae (Ulva and reds) &gt;50%</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Spirographis &gt;50%</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>Gelidium and cobble reefs &gt;75%</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td><strong>Macroalgae (intertidal and subtidal)-Total</strong></td>
<td><strong>198</strong></td>
<td><strong>0.9</strong></td>
</tr>
<tr>
<td>Bare subtidal</td>
<td>7132</td>
<td>31.9</td>
</tr>
<tr>
<td>Bare intertidal</td>
<td>1202</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>TOTAL MAPPED AREA (ha)</strong></td>
<td><strong>22361</strong></td>
<td></td>
</tr>
</tbody>
</table>
**FIGURE 3.15** *Amphibolis* locations provided by SARDI

Figure 3.16 shows a photo mosaic of November 2003 aerial photography. Contrast mismatches between adjoining aerial photography frames are evident. In the feature classification presented in Figure 3.17 these artifacts have been largely removed.
FIGURE 3.16 2003 aerial photograph mosaic

Figure 3.17 has the same coverage as illustrated in Figure 3.14 but reinterpreted for 8 feature classes. Subsequent figures use the 8 classes for their classifications.

Note that the classifications which refer to particular water depths have used bathymetric data derived from a number of sources and published navigation charts, DEH Office of Coast and Marine.
stakeline surveys, Flinders Ports Corporation (side scan sonar surveys) and were supplied as vector bathymetry and raster surface model of bathymetry to the Environmental Projects Office. In addition some 8400 depth soundings were taken during surveys conducted by Kinhill (1998) for SAWater in relation to a project studying changes in benthic cover in the region of the Bolivar WWTP.

With only 8 feature classes it is not practical to separate the different subtidal seagrass species (mostly Posidonia) or to separate shallow water seagrasses (Heterozostera from Zostera) or macroalgae (reds and greens) from Spirographis although my local knowledge of where different macroalgae and fan worms communities occur has allowed these to be separated into broad regions of occurrence.

To reiterate and also explain further the eight classes they are:

- Littoral – i.e. beaches to mean sea level
- Shallow subtidal – bare sediments from mean sea level (0m AHD) to 4m below MSL
- Deep subtidal – bare sediments from 4m below MSL to the limits at which they could be mapped (typically -8m to -10m MSL)
- Sparse seagrass – less than 10% cover - mostly Zosteraceae on intertidal flats north of Barker Inlet
- Medium seagrass – 10% to 50% cover – Posidonia along most of the study area coastline, but also intertidal Zosteraceae north of Barker Inlet generally inshore of dense seagrass beds
- Dense seagrass – greater than 50% cover – similar distribution to the above
- Macroalgae/Spirographis – a combination of macroalgae dominating north of Barker Inlet and fan worms with macroalgae between Semaphore and Gleneig often on clay or reef substrates
- Reefs (cobbles and rocky reefs) with substrates bare of macroalgae.

There are notable differences between Figures 3.14 and 3.17. Inevitably, trying to interpret a large number of classes (17) leads to a greater risk of erroneous classifications than with a smaller number of classes (8). The limited spectral information in aerial photography means that classification becomes more subjective and less reliable as the number of classes increases. If CASI hyperspectral data had been available at the time of production of the 17 class map it may have been possible to improve its accuracy.
FIGURE 3.17 Feature map of 2003 aerial photography with 8 feature classes

This map is considered to be the most reliable so far produced from aerial photography. It has few artifacts due to frame to frame contrast mismatches and is consistent in general with maps produced from CASI hyperspectral data (Refer to Chapter 5 and Appendix 1 – the latter for statistics on comparative estimates of cover for Posidonia based upon CASI and aerial photo interpretations and field observations).
FIGURE 3.18  Eight class feature map from 1995 and 1996 aerial photography

This map is generally reliable, but has line striping artifacts, in the Outer Harbor to Semaphore and Glenelg to Seacliff regions, due to unknown causes, but probably related to film processing and printing.
This map is clearly incomplete. This is a result of extreme contrast mismatches between photo frames and some very poor contrast in areas of each frame. It is unlikely that these images could be reliably mapped for most of the limited coverage.
FIGURE 3.20  Eight class feature map from 1983 aerial photography

This map has excellent coverage and is considered to be reliable for most of the study area.
FIGURE 3.21  Eight class feature map from 1970 aerial photography

There is very limited useful offshore coverage in this set of photographs although within about 1 km of low water mark the map is considered to be reliable.
FIGURE 3.22 Eight class feature map from 1965 aerial photography

This map is clearly incomplete. This is a result of extreme contrast mismatches between photo frames and some very poor contrast in areas of each frame. It is unlikely that these images could be reliably mapped except for areas between the Bolivar outfall region and Largs Bay.
3.4 Feature Map Reliability

It is not appropriate to conduct statistical analyses to investigate the reliability of the maps given above, or to investigate statistical correlations between them. At the scale of the full study area subjective comments on reliability are most appropriate.

The 2003 map (Figure 3.17) however is compared critically to interpretations of 2003 CASI data and statistics for CASI and aerial photography interpretations and field observations from 2003 and 2004 are given in Appendix 2. These statistics demonstrate that although the different data sets were derived using different technologies, analytical procedures and observational methods there is a high degree of correspondence between the results.

A much greater degree of reliability of feature maps based upon aerial photography is achievable if small sections of the total study are used for critical change detection.

Comparisons between selected areas of feature maps from 1977 to 2003 aerial photography are given in Chapter 4. Although these extracts represent only some 10% of the total study area, they are considered to be representative of features and changes in a number of areas where distinctly different processes operate in determining the gain or loss of seagrasses.

In terms of understanding causes of changes in seagrass communities, the maps given in Chapter 4 are probably more relevant than those presented above. However the maps in this chapter give a pictorial overview of the obvious changes in distributions of Posidonia dominated communities. The studies conducted by the EPA (1998) and Hart (1996, 1997a, 1997b) are important in that they show changes in the landward edge of subtidal seagrass communities, but do not demonstrate in detail, fine scale changes in distributions or cover percentages within these communities. They also do not allow the determination of rates of change of boundaries of features such as crescentic blowouts. Estimates of such rates are given in Chapter 4.
4 Change mapping from aerial photography

Change mapping is used to demonstrate how features have changed over time e.g. increases in seagrass cover, no change or decrease in seagrass cover or what ever other feature is of interest such as bare sediments, macroalgae or reefs.

The prerequisites for producing meaningful change maps from remotely sensed imagery are:
- Overlapping coverages for images from different time periods
- Reliable mapping of features so that artefacts due to misclassifications are minimised.

Historical aerial photography and new aerial photography flown November 25, 2003 has been used to derive change maps.

Studies conducted by the Environment Protection Authority (Hart 1997a, 1997b, EPA 1998) used aerial photography to map changes in seagrass distributions in the Adelaide Metropolitan region. These studies concentrated upon mapping landward edges of seagrass beds interpreted from aerial photography taken between 1949 and 1996. They differ from the present study in that they mapped only seagrass bed margins rather than also investigating seagrass community structure and fine scale patterning with seagrass patches. They also discriminated only seagrass from sand, with no attempt to derive estimates of cover percentages. This does not represent a criticism of those studies. With the availability of airborne and satellite hyperspectral and multispectral data it has been possible to extend the interpretations and maps to differentiate cover percentages and a greater number of benthic features. CASI data have been particularly valuable in allowing better discrimination of features and the improvement of aerial photographic interpretations.

4.1 Changes in the Bolivar region

A previous study conducted for SAWater (Kinhill, 1998) focussed upon changes in seagrass and coastal vegetation communities (mangroves and samphires) in a 16km$^2$ area in the region of the Bolivar WWTP outfall.

The study was pivotal in demonstrating that remote sensing over Adelaide Coastal environments had application to documenting historical changes in seagrass features and relating the changes to natural and anthropogenic influences. The report published in 1998 resulted from 5 years of research, field studies and data analyses, predating the studies published by Hart and the EPA. That study concluded that there had been a decline in seagrass coverage since the Bolivar discharge commenced in 1965. Some of the results of that study are described below. More recent work using both aerial photography and CASI data support this conclusion and that the decline in seagrass coverage is ongoing. Figure 4.1 shows the study area for the Kinhill (1998) report.

The Bolivar region is emphasised in this report because:
- Bolivar WWTP is the largest land based discharge in the Adelaide region and discharges continuously
- It has been the subject of numerous environmental and engineering studies
- It has an extensive historical record of field and remotely sensed data
- It has been studied using data from three CASI coverages
- It has a high biodiversity of macrophytes
- Studies of the WWTP discharge and its impacts are of interest to SAWater, a major stakeholder in the ACWS.
Areas and cover percentages for significant features in the study area, between 1949 and 1993 are given in Table 4.1.

**TABLE 4.1** Statistics for significant features in the region of the Bolivar WWTP outfall

<table>
<thead>
<tr>
<th>Date of photos</th>
<th>Feature class</th>
<th>Feature area (km²)</th>
<th>Cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/01/1949</td>
<td>Posidonia</td>
<td>4.3</td>
<td>26.3</td>
</tr>
<tr>
<td></td>
<td>Subtidal sands</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Zosteraceae</td>
<td>1.7</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>Intertidal sands</td>
<td>4.8</td>
<td>30.1</td>
</tr>
<tr>
<td></td>
<td>Mangroves</td>
<td>0.8</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>Samphire</td>
<td>1.7</td>
<td>10.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>13.2</strong></td>
<td><strong>82.8</strong></td>
</tr>
<tr>
<td>22/12/1956</td>
<td>Posidonia</td>
<td>4.6</td>
<td>28.8</td>
</tr>
<tr>
<td></td>
<td>Subtidal sands</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Zosteraceae</td>
<td>3.2</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>Intertidal sands</td>
<td>3.2</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>Mangroves</td>
<td>1.3</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>Samphire</td>
<td>0.5</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>12.8</strong></td>
<td><strong>80.0</strong></td>
</tr>
<tr>
<td>28/06/1967</td>
<td>Posidonia</td>
<td>4.2</td>
<td>26.3</td>
</tr>
<tr>
<td></td>
<td>Subtidal sands</td>
<td>0.4</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Zosteraceae</td>
<td>3.0</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>Intertidal sands</td>
<td>2.7</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td>Mangroves</td>
<td>1.6</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>Samphire</td>
<td>0.5</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>12.4</strong></td>
<td><strong>77.6</strong></td>
</tr>
<tr>
<td>05/12/1974</td>
<td>Posidonia</td>
<td>3.4</td>
<td>21.3</td>
</tr>
</tbody>
</table>
The changes over time in cover of *Posidonia* and mangroves for this study area are illustrated in figures 4.2 and 4.3. These figures display plots of percentage cover for *Posidonia* relative to the total subtidal areas and percentage cover for mangroves relative to upper intertidal and lower supratidal areas. Cover percentages given in Figure 4.3 for mangroves for 1999 and 2003 are based upon CASI and are estimates only – they are considered reasonable since there have been apparently no chenier developments since about 1995.

### Table 4.1: Cover (%) of Feature Class

<table>
<thead>
<tr>
<th>Date of photos</th>
<th>Feature class</th>
<th>Feature area (km²)</th>
<th>Cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subtidal sands</td>
<td>2.5</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>Zosteraceae</td>
<td>0.6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Intertidal sands</td>
<td>5.8</td>
<td>36.2</td>
</tr>
<tr>
<td></td>
<td>Mangroves</td>
<td>1.4</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>Samphire</td>
<td>0.6</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>14.3</strong></td>
<td><strong>89.4</strong></td>
</tr>
<tr>
<td>06/01/1979</td>
<td><em>Posidonia</em></td>
<td>2.2</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td>Subtidal sands</td>
<td>2.8</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>Zosteraceae</td>
<td>3.3</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>Intertidal sands</td>
<td>3.6</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>Mangroves</td>
<td>1.3</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>Samphire</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>13.5</strong></td>
<td><strong>89.7</strong></td>
</tr>
<tr>
<td>08/12/1993</td>
<td><em>Posidonia</em></td>
<td>1.0</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Subtidal sands</td>
<td>4.1</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>Zosteraceae</td>
<td>1.1</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>Intertidal sands</td>
<td>5.7</td>
<td>35.4</td>
</tr>
<tr>
<td></td>
<td>Mangroves</td>
<td>1.7</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>Samphire</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>13.9</strong></td>
<td><strong>86.5</strong></td>
</tr>
</tbody>
</table>

The changes over time in percentage cover of *Posidonia* in the Bolivar region are illustrated in Figure 4.2. Between 1956 and 1966 imperceptible losses of *Posidonia* occurred. The Bolivar WWTP came online in 1965 and soon after this the first losses of *Posidonia* beds occurred in the shallow subtidal, directly offshore of the Bolivar discharge and immediately around where the wastewater plume enters the subtidal zone. It is possible that losses of this community were related to a combination of the low salinity, high nutrient and chlorophyll discharges. Which of these water parameters is...
dominant in causing losses of *Posidonia* has not been quantified, but plume dilution models presented later in Figures 6.1 and 6.2 and images of wastewater plumes in Figures 6.3 to 6.6 suggest that it is more than coincidental that seagrass loss started post 1965. In 2001 a new nutrient reduction plant was brought on line at the Bolivar WWTP, using dissolved air flotation and filtration (DAFF) technologies, since then there has also been increased land-based reuse of wastewater and aquifer injection. These initiatives have resulted in reductions of both flows and nutrient loads in the marine discharges from the WWTP. The trend in seagrass loss offshore of Bolivar however appears to have continued since that time with the greatest losses in the shallower subtidal areas (i.e. closest to the Bolivar discharge) and some gains in deeper subtidal areas. See Chapter 5, figures 5.24 to 5.26 and associated discussion for further details on these changes.

This ongoing loss in the circumstances of substantial discharge amelioration may represent a hysteresis effect where much greater reductions in discharge flows and loads presently being achieved will result in net seagrass regrowth. The ongoing changes in *Posidonia* beds should be closely monitored in the future to determine whether the engineering and reuse strategies are effective in the long term.

**FIGURE 4.3** Changes over time in percentage cover of mangroves in the Bolivar region

Despite local dieback of mangroves (as illustrated in Chapter 6) there has been an overall increase in mangrove areas attributed to basin subsidence and sea level rises with mangroves colonising on their landward fringe. Mangrove communities along much of the coastline between North Arm Creek and Chapman Creek are now growing up to the seaward edges of the Penrice Soda Products salt field bunds. Because of this barrier to their landward colonisation, the increases in total cover that have occurred over at least 5 decades cannot continue indefinitely. As mangrove areas are increasing, samphire areas are decreasing, being replaced by mangroves. Local losses of mangroves are most likely to be related to changes in subtidal and intertidal sediment dynamics and possible effects on sediment structure due to low salinity water in the vicinity of the Bolivar WWTP discharge.

### 4.2 Change Maps for the central metropolitan coastline

Given the uncertainties in producing aerial photography based feature maps of demonstrable reliability for the whole study area and also the variable extents of aerial coverages it was decided to focus upon a number of sites where image quality was of good or high standard, had significant
overlap between time series aerial photography and also covered areas that had distinctive seabed features.

A general overview of changes in the northern and southern parts of the Adelaide metropolitan coastline is given in figures 4.4 to 4.7.

FIGURE 4.4  Seagrass distributions offshore of Semaphore, 1949

This image from aerial photography taken in 1949 is of benthic and coastal features, south of Semaphore. The inshore edge of seagrasses is approximately 560 m seaward of the high tide mark. Seagrass cover in the offshore areas is dense and homogeneous, while inshore it is irregularly patchy, showing no evidence of the crescentic blowouts which characterise seagrass beds further south. Much of the coastline at that time was undeveloped dunes and dune swales.
The inshore edge of seagrasses in this image from 2003 aerial photography is approximately 1050 m seaward of the high tide mark, with the greatest losses between 1949 and 2003 occurring in the areas in the south of the image. These were the most fragmented areas in 1949. Seagrass beds from about 2km offshore remained dense and un-fragmented. By 2003 more than 95% of the coastline in this region was under urban development, with the exception of narrow dune rehabilitation areas and part of the Fort Glanville site.

Changes in seagrass beds near Grange are shown in figures 4.6 to 4.10.
Old seagrass root matte was exposed by seabed erosion near the end of the jetty (linear dark feature). Observations made by David Blackburn in the mid to late 1960s found scarps, up to 50 cm high, composed of firm, grey clays with root material, on the landward edges of these patches. Regularly spaced, bare circular patches near the centre of the image are scars of seismic shot-holes as a result of petroleum exploration works by Santos in the mid 1960s.

Marked offshore loss of seagrass occurred between 1970 and 1983, most of this between 1970 and 1977. The seismic survey scars are no longer visible as a result of complete loss of seagrass where they occurred. The inshore exposed root matte had been eroded by this time.
The main changes between 1983 and 1995 were a decrease in seagrass cover and density, apparent in the south western corner of this image.

There was little change in seagrass cover, density or distribution between 1995 and 2003. There was no change measurable in the location of the landward edge of seagrass beds (Table 4.2). In the more offshore areas near Grange there was an increase in cover (gains exceeding losses by 1.3 times) during the period 1995 to 2003 (see Table 4.3 – area 6).

Differences in seagrass distributions offshore of West Beach are shown in Figures 4.11 and 4.12.
FIGURE 4.11  Seagrass distributions offshore of West Beach, 1949

This image is from 1949 aerial photography and shows the crescentic blowouts in offshore seagrass beds. This features are thought to be indicative of moderate wave energise and they gradually migrate seawards as their inshore edges are eroded and the seaward edges are colonised by seagrasses (Clark 1987). The dense homogeneous beds in the centre of the image lie over a very stable seagrass feature which is apparent in later photography and is probably related to the very deep sands in this location. The coastline was almost completely undeveloped with dunes and dune swales representing part of a sand plain and dune system which extended more than 5 km to the east of the coast. The landward edge of the seagrass beds was about 1km offshore in 1949.

FIGURE 4.12  Seagrass distributions offshore of West Beach, 2003
This image is from 2003 aerial photography. The crescentic blowouts are much more clearly defined as they widened over time due to erosion of the seagrass beds. The distinctive bifurcated feature near the right centre of the image is just visible in 1949 imagery. It has remained remarkably stable since the late 1940s, while around it seagrasses have progressively disappeared. The dark feature in the lower right of the image is a deep trench where the seabed has been eroded by up to 4 metres since the late 1940s. Coastal urbanisation covers more than 60% of this coastal stretch, with the narrow shoreline dunes presently being rehabilitated. The landward edge of seagrass beds was about 1.5 km offshore of the high tide mark.

Changes in seagrasses offshore of West Beach are shown in the following montage (figure 4.13) spanning 1977 to 2003, with most substantial changes occurring between 1977 and 1988, following extensive urbanisation of the coastline in the late 1960s.

![Figure 4.13: Seagrass distributions offshore of West Beach, 1977 to 2003](image)

Changes in the distance offshore of the landward edge of *Posidonia* dominated seagrass beds, based upon aerial photography from 1949 to 2003 are given in Table 4.2. Measurements were made along the long axes of jetties or perpendicular to the local coastline and were made starting at the high water mark. The “edge” was defined as the average of obvious and dense seagrass beds within +/- 500m north to south of the measurement transect.
TABLE 4.2  Changes in distance offshore of landward seagrass edges.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Largs jetty</td>
<td>470</td>
<td>480</td>
<td>520</td>
<td>530</td>
<td>550</td>
<td>570</td>
<td>590</td>
<td>600</td>
</tr>
<tr>
<td>Semaphore jetty</td>
<td>560</td>
<td>580</td>
<td>580</td>
<td>590</td>
<td>630</td>
<td>660</td>
<td>1030</td>
<td>1050</td>
</tr>
<tr>
<td>Grange jetty</td>
<td>560</td>
<td>700</td>
<td>790</td>
<td>1300</td>
<td>1600</td>
<td>1700</td>
<td>1700</td>
<td>1700</td>
</tr>
<tr>
<td>Henley jetty</td>
<td>570</td>
<td>760</td>
<td>780</td>
<td>1050</td>
<td>1100</td>
<td>1600</td>
<td>1800</td>
<td>2000</td>
</tr>
<tr>
<td>River Torrens</td>
<td>570</td>
<td>930</td>
<td>960</td>
<td>980</td>
<td>1000</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>Patawalonga</td>
<td>620</td>
<td>850</td>
<td>920</td>
<td>1200</td>
<td>1300</td>
<td>1350</td>
<td>1400</td>
<td>1500</td>
</tr>
<tr>
<td>Glenelg jetty</td>
<td>600</td>
<td>780</td>
<td>840</td>
<td>1150</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Brighton jetty</td>
<td>200</td>
<td>260</td>
<td>350</td>
<td>560</td>
<td>1100</td>
<td>1100</td>
<td>1300</td>
<td>1300</td>
</tr>
</tbody>
</table>

Note: Distances offshore are in metres.

Figure 4.14 illustrates these changes graphically.

![Distance to seagrass edge](image)

FIGURE 4.14  Changes in the distance offshore of landward seagrass margins

The largest changes occurred between the mid 1970s and the mid 1980s. This observation is in general agreement with the findings of the Environment Protection Agency (1998) which put 1977 as a pivotal year in the increased rate of seagrass loss.

4.3  Small scale change map areas

Ten areas each 1.5 km by 1.5 km were selected for detailed feature and change mapping.

These areas were selected to;
- Cover a representative range of benthic features
- Show clear differences in the spatial distributions and relationships between features types e.g. seagrasses and blowouts
- Have in some cases proximity to land based discharges and different types of coastal morphology.

The selected areas are shown in Figure 4.15 with blue representing seagrass and macroalgae of all species with cover percentages greater than 10% and yellow representing bare or sparsely covered sediments.
FIGURE 4.15 Areas selected for detailed change mapping

Statistics of change for the selected areas are listed in Table 4.3.

TABLE 4.3 Statistics of change for 10 selected areas

<table>
<thead>
<tr>
<th>Change areas</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
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<tbody>
<tr>
<td>Time interval</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1977-1983</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>3.9</td>
<td>9.3</td>
<td>11.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>88.0</td>
<td>74.5</td>
<td>76.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss</td>
<td>11.1</td>
<td>18.8</td>
<td>14.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio</td>
<td>0.35</td>
<td>0.50</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Changes in features for 10 selected areas for the period 1977 to 2003

<table>
<thead>
<tr>
<th>Year</th>
<th>Gain</th>
<th>4.1</th>
<th>7.5</th>
<th>7.0</th>
<th>9.8</th>
<th>7.8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
<td>77.5</td>
<td>84.4</td>
<td>55.7</td>
<td>78.6</td>
<td>57.0</td>
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<tr>
<td></td>
<td>Loss</td>
<td>20.8</td>
<td>9.1</td>
<td>40.0</td>
<td>14.0</td>
<td>37.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Gain/Loss</th>
<th>0.09</th>
<th>0.20</th>
<th>0.82</th>
<th>0.18</th>
<th>0.70</th>
<th>0.21</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983-1995</td>
<td>Gain</td>
<td>11.6</td>
<td>11.7</td>
<td>8.1</td>
<td>24.7</td>
<td>7.0</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>83.4</td>
<td>77.5</td>
<td>79.8</td>
<td>61.5</td>
<td>74.0</td>
<td>68.2</td>
</tr>
<tr>
<td></td>
<td>Loss</td>
<td>7.3</td>
<td>13.6</td>
<td>13.6</td>
<td>16.5</td>
<td>19.0</td>
<td>18.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Gain/Loss</th>
<th>1.59</th>
<th>0.86</th>
<th>0.60</th>
<th>1.49</th>
<th>0.37</th>
<th>0.71</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995-1999</td>
<td>Gain</td>
<td>15.3</td>
<td>12.2</td>
<td>8.7</td>
<td>15.2</td>
<td>19.2</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>75.6</td>
<td>80.4</td>
<td>85.7</td>
<td>68.2</td>
<td>75.0</td>
<td>67.3</td>
</tr>
<tr>
<td></td>
<td>Loss</td>
<td>9.9</td>
<td>9.8</td>
<td>6.7</td>
<td>19.2</td>
<td>8.2</td>
<td>26.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Gain/Loss</th>
<th>1.55</th>
<th>1.24</th>
<th>1.30</th>
<th>0.79</th>
<th>2.33</th>
<th>0.33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>Gain/loss for areas</td>
<td>0.09</td>
<td>1.59</td>
<td>1.55</td>
<td>0.66</td>
<td>0.81</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Average gain/loss ratio for all areas 0.79

Note
1. The total area of each 1.5 km by 1.5 km location is 225 ha. The change percentages are the percent of this area covered by each change class.
2. Blank cells indicate that no useful overlap between successive aerial photographs was available for the given time periods. Area 4 and 7 were fully covered only by 1999 aerial photography and so no change statistics were calculated.
3. The loss reported for the period 1995 to 1999 for area 5 is an overestimate as a result of sea surface reflections and turbidity.

The average gain to loss ratio of 0.79 is important in that it indicates that there has been a decline in seagrass cover of about 21% in the selected study areas (totalling 1600 ha) over the period 1977 to 2003. An estimate of seagrass loss (EPA 1998) is that 4000 ha of seagrass was lost along the Adelaide metropolitan coastline between 1949 and 1995 (or based upon the losses in the selected areas, assumed to cover an area of some 16,000 ha in total). Although the data sets from the EPA and the present study have different spatial and temporal coverages, the correspondence of the percentage of seagrass lost is remarkably close.

The ratio of gain to loss over the period 1995 to 2003 is 1.1, suggesting that seagrasses in that period have recovered to some extent. This may be a reflection of cessation of WWTP sludge discharges and reductions in nutrient and suspended solids loads from land based discharges.

The following figures show
- Firstly the locations and contexts of selected areas in relation to aerial photography images of benthic features (surrounding areas approximately 2.4 km EW and 2.2 km NS). The selected area features are mapped as BLUE for seagrass/macroalgae gain and RED for seagrass/macroalgae loss. Areas of no change have been made transparent to allow the underlying aerial photo rasters to be visible
- Secondly high resolution maps of changes for each time period and each selected area with ORANGE indicating loss of seagrass/macroalgae cover, GREEN indicating gains in cover and YELLOW indicating no change.

The use of different palettes for the figures was required to allow discrimination of gain/loss data over aerial photo underlays and easy discrimination of gain/no change/loss data in the stand-alone change maps.
4.3.1 Changes between 1977 and 1983

**AREA 5 – Offshore of Point Malcolm and along the Port Adelaide WWTP sludge pipeline**

Significant losses occurred on the inshore edge of the seagrass beds, along the route of the Port Adelaide WWTP sludge pipeline and around the sludge discharge region (Figure 4.16). Losses along the pipeline route may be related to mechanical disturbance caused by pipeline construction e.g. trenching. Losses in the region of the discharge have been well documented (Neverauskas 1984, 1987a, 1987b) and almost certainly relate to the high levels of nutrients and suspended solids in the sludge.

**FIGURE 4.16 1977 and 1983 aerial photo bases with changes between these times, Area 5**

Legend: **BLUE** = areas of seagrass/macro-algae gain

**RED** = areas of seagrass/macro-algae loss

Figure 4.17 illustrates the changes in benthic features for area 5. Losses of macrophytes are shown in orange, no change is shown in yellow and gains in cover of macrophytes are shown in green.
FIGURE 4.17 Changes in benthic features between 1977 and 1983, Area 5
Legend: **ORANGE** = loss of seagrass/macro-algae cover
**GREEN** = gains in seagrass/macro-algae cover
**YELLOW** indicates no change

The major losses of seagrass are within the landward parts seagrass fringe, but substantial losses have occurred along the pipeline route and seaward close to the WWTP sludge discharge.
**AREA 6 – offshore of Grange and West Lakes**

Figure 4.18 shows the base aerial photography images for area 6 for 1977 and 1983 and Figure 4.19 shows the change map for this location. Major losses of benthic macrophyte cover occurred within the near shore fringe of seagrasses.

**FIGURE 4.18** 1977 and 1983 aerial photo bases with changes between these times, Area 6
Legend: **BLUE** = areas of seagrass/macro-algae gain

**RED** = areas of seagrass/macro-algae loss
FIGURE 4.19 Changes in benthic features between 1977 and 1983, Area 6

Legend: ORANGE = loss of seagrass/macro-algae cover
GREEN = gains in seagrass/macro-algae cover
YELLOW indicates no change

As for Area 5, the major losses of seagrass were within the near shore regions of seagrass beds. Some increase in seagrasses occurred offshore, but further offshore there were losses of cover.
**AREA 9 – offshore of West Beach**

Figure 4.20 shows the base aerial photography images for area 6 for 1977 and 1983 and Figure 4.21 shows the change map for this location. Most of the losses and gains in seagrass cover were associated with seagrass blowout features, with on the offshore margins of seaward prograding blowouts and gains on the landward margins of these features.

**FIGURE 4.20** 1977 and 1983 aerial photo bases with changes between these times, Area 9
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
The influence of blowouts on seagrass losses and gains can be seen in the numerous crescentic features. Losses exceeded gains however. Based upon 20 measurements each of the widths of gain and loss areas for crescentic blowouts (measured perpendicular to the longitudinal axes of the blowouts) the ratio of gain to loss is 0.78, which is very close to the gain to loss ratio of 0.79 for this whole area (Table 4.3). This correspondence and the clear crescentic nature of the dominant changes support the idea that the mechanisms of change in the area are related mostly to crescentic blowout development.

The mean seaward movement of the inshore or eroding edge of blowouts during this period was 16.5 m, while the mean seaward rate of recolonisation by seagrasses was 12.8 m, equating to an average of 2.8 m (standard deviation 0.42) per year of seaward erosional loss and an average of 2.1 m (standard deviation 0.32) per year of seaward colonisation.
4.3.2 Changes between 1983 and 1995

**AREA 1 – Offshore of Outer Harbor, near the spoil dumping ground**

Figure 4.22 shows the base aerial photography images for area 1 for 1983 and 1995 and Figure 4.23 shows the change map for this location.

**FIGURE 4.22** 1983 and 1995 aerial photo bases with changes between these times, Area 1
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
FIGURE 4.23 Changes in benthic features between 1983 and 1995, Area 1

Losses of seagrasses between 1983 and 1995 greatly exceeded gains. Only 0.09% experienced gains. This area is offshore of Bolivar and in the region used for Port Adelaide River dredge spoil dumping, an operation which smothers seagrass beds with very fine silts which do not disperse readily under wave and tidal current influences. The main losses occurred in the north western to central parts of the site, with a general vector towards the southwest.

An example of direct impacts upon seagrasses is shown in figure 4.24, where dumping of dredge spoil (technically outside of the approved dump area) was captured in November 2003 CASI imagery.

FIGURE 4.24 Circular patches of dumped Port Adelaide River dredge spoil
**AREA 5 – Offshore of Point Malcolm and along the Port Adelaide WWTP sludge pipeline**

Figure 4.25 shows the base aerial photography images for area 5 for 1983 and 1995 and figure 4.26 shows the change map for this location.

![Aerial Photography Figures](image)

**FIGURE 4.25** 1977 and 1983 aerial photo bases with changes between these times, Area 5
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
FIGURE 4.26 Changes in benthic features between 1983 and 1995, Area 5

Legend:
- **ORANGE** = loss of seagrass/macro-algae cover
- **GREEN** = gains in seagrass/macro-algae cover
- **YELLOW** indicates no change

Onshore loss of seagrass continued, but after cessation of the Port Adelaide WWTP sludge discharges in 1992 there appears to have been some recovery of seagrasses along and near the sludge pipeline.
**AREA 6 – offshore of Grange and West Lakes**

Figure 4.27 shows the base aerial photography images for area 6 for 1983 and 1995 and figure 4.28 shows the change map for this location.

**FIGURE 4.27** 1983 and 1995 aerial photo bases with changes between these times, Area 6
Legend: **BLUE** = areas of seagrass/macro-algae gain
          **RED** = areas of seagrass/macro-algae loss
FIGURE 4.28 Changes in benthic features between 1983 and 1995, Area 6

Legend: **ORANGE** = loss of seagrass/macro-algae cover  
**GREEN** = gains in seagrass/macro-algae cover  
**YELLOW** indicates no change

The patterns of changes for this area and time period are mixed and localised to relatively small patches and do not suggest any specific land based discharge effects. This area seems to have stabilised since the 1983 imagery was taken.
**AREA 8 - approximately 4 km offshore of Henley Beach and the River Torrens**

Figure 4.29 shows the base aerial photography images for area 8 for 1983 and 1995 and figure 4.30 shows the change map for this location.

**FIGURE 4.29** 1983 and 1995 aerial photo bases with changes between these times, Area 8
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
Major losses of seagrasses occurred in this region. It is approximately 5 km offshore of the mouth of the River Torrens and given the imagery of plume dispersion from the river (figures 6.23 to 6.30); it is hard to see how the Torrens discharge could be directly implicated in the substantial losses of seagrasses in this area. There may be a link to losses further offshore at area 7, where there exist linear seagrass and sediment features perpendicular to the shoreline and predominant swell waves.
AREA 9 – offshore of West Beach

Figure 4.31 shows the base aerial photography images for area 9 for 1983 and 1995 and Figure 4.32 shows the change map for this location.

FIGURE 4.31 1983 and 1995 aerial photo bases with changes between these times, Area 9
Legend: BLUE = areas of seagrass/macro-algae gain
RED = areas of seagrass/macro-algae loss
FIGURE 4.32 Changes in benthic features between 1983 and 1995, Area 9
Legend:  ORANGE = loss of seagrass/macro-algae cover  
GREEN = gains in seagrass/macro-algae cover  
YELLOW indicates no change

The changes for this area and time period are predominantly related to the dynamics of seagrass blowouts, though there has been a local impact (an apparent gain in cover) as a result of the SARDI seawater intake pipeline. This gain was not of seagrasses but rather colonisation by the introduced Mediterranean fan worm *Spirographis (Sabella) spallanzanii* of the pipeline and calcrite rubble exposed during pipeline construction. It stands out in the 1995 imagery because of the macroalgae growing on the worm tubes.

The overall ratio of gain to loss for this was 0.7, most of the losses occurring in inshore seagrass areas, possibly due to ongoing erosion of the seabed in this area. The average rate of movement of the trailing and leading edges of blowouts was 3.3 m (SD 1.2) and 3.2 m (SD 0.9) respectively, giving a gain/loss ratio of 0.98. The ratio derived from crescentic features does not reflect the more diffuse losses that occurred inshore.
AREA 10 – offshore of Glenelg and the Patawalonga

Figure 4.33 shows the base aerial photography images for area 10 for 1983 and 1995 and Figure 4.34 shows the change map for this location.

**FIGURE 4.33** 1983 and 1995 aerial photo bases with changes between these times, Area 10
Legend: **BLUE** = areas of seagrass/macro-algae gain  
**RED** = areas of seagrass/macro-algae loss
FIGURE 4.34 Changes in benthic features between 1983 and 1995, Area 10
Legend: **ORANGE** = loss of seagrass/macro-algae cover
**GREEN** = gains in seagrass/macro-algae cover
**YELLOW** indicates no change

Most of the seagrass loss occurred in offshore areas, approximately 3 km offshore of the high tide mark. There appears to be no significant link between these losses and discharges from the Patawalonga.
4.3.3 Changes between 1995 and 1999

**AREA 2 – Largs Bay**

Figure 4.35 shows the base aerial photography images for area 2 for 1995 and 1999 and figure 4.36 shows the change map for this location.

**FIGURE 4.35** 1995 and 1999 aerial photo bases with changes between these times, Area 2
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
Colonisation of seagrasses exceeded seagrass loss in the inshore parts of this area. Some offshore loss occurred. The reasons for this loss are unknown.
AREA 5 – Offshore of Point Malcolm and along the Port Adelaide WWTP sludge pipeline

Figure 4.37 shows the base aerial photography images for area 5 for 1995 and 1999 and figure 4.28 shows the change map for this location.

FIGURE 4.37 1995 and 1999 aerial photo bases with changes between these times, Area 5
Legend: BLUE = areas of seagrass/macro-algae gain
       RED = areas of seagrass/macro-algae loss
FIGURE 4.38 Changes in benthic features between 1995 and 1999, Area 5
Legend: ORANGE = loss of seagrass/macro-algae cover
       GREEN = gains in seagrass/macro-algae cover
       YELLOW indicates no change

This change map is ambiguous. Some onshore colonisations occurred and this is probably a correct interpretation of the imagery. The apparent losses offshore in the north western part of the map are almost certainly due to the fact that there was very low contrast for benthic features in the deeper waters, resulting from a combination of sun glint and substantial turbidity in the water column at the time of the 1999 coverage. However the route of the sludge pipeline so apparent in the 1983 and 1995 imagery is not apparent here because there been essentially no change in benthic features along that route. Offshore losses as a legacy of the WWTP sludge discharge have apparently stabilised.
**AREA 6 – offshore of Grange and West Lakes**

Figure 4.39 shows the base aerial photography images for area 6 for 1995 and 1999 and figure 4.40 shows the change map for this location.

**FIGURE 4.39** 1995 and 1999 aerial photo bases with changes between these times, Area 6
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
FIGURE 4.40 Changes in benthic features between 1995 and 1999, Area 6

Legend:  
- **ORANGE** = loss of seagrass/macro-algae cover  
- **GREEN** = gains in seagrass/macro-algae cover  
- **YELLOW** indicates no change

The patterns of loss and colonisation are strongly related to crescentic blowouts, but there have been increases in offshore losses, which may be related to ongoing impacts of the Glenelg sludge outfall (which ceased operation in 1992) or more complex issues such as general increases in offshore turbidity.
**AREA 8- approximately 4 km offshore of Henley Beach and the River Torrens**

Figure 4.41 shows the base aerial photography images for area 8 for 1995 and 1999 and figure 4.42 shows the change map for this location.

**FIGURE 4.41** 1995 and 1999 aerial photo bases with changes between these times, Area 8  
Legend: **BLUE** = areas of seagrass/macro-algae gain  
**RED** = areas of seagrass/macro-algae loss
Colonisation of seagrasses exceed losses by a factor of about 1.5 times, with the biggest gains occurring inshore. This location is well offshore of the River Torrens outfall and so unlikely to be impacted by that discharge. It is an interesting site and requires further study to determine what ecological and physical processes have allowed this degree of recolonisation to occur.
**AREA 9— offshore of West Beach**

Figure 4.43 shows the base aerial photography images for Area 9 for 1995 and 1999 and figure 4.44 shows the change map for this location.

**FIGURE 4.43** 1995 and 1999 aerial photo bases with changes between these times, Area 9

Legend: **BLUE** = areas of seagrass/macro-algae gain

**RED** = areas of seagrass/macro-algae loss
Losses of seagrasses exceeded gains, mostly on the margins of crescentic blowouts i.e. the leading edges of blowouts were losing seagrass faster than seagrass could recolonise on the trailing edges. The ratio of gain to loss was about 0.37 i.e. about a 2.7 greater rate of loss than gain of cover.
AREA 10 – offshore of Glenelg and the Patawalonga

Figure 4.45 shows the base aerial photo images for area 10 for 1995 and 1999 and figure 4.46 shows the change map for this location.

FIGURE 4.45 1995 and 1999 aerial photo bases with changes between these times, Area 10
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
 Colonisation of seagrasses occurred mostly in the offshore regions but inshore losses in the south eastern part of the area resulted in losses exceeding gains by 1.4 times.
4.3.4 Changes between 1999 and 2003

AREA 3 – 4km offshore of Semaphore

Figure 4.47 shows the base aerial photography images for area 3 for 1999 and 2003 and Figure 4.48 shows the change map for this location.

FIGURE 4.47 1999 and 2003 aerial photo bases with changes between these times, Area 3
Legend: BLUE = areas of seagrass/macro-algae gain
RED = areas of seagrass/macro-algae loss
FIGURE 4.48  Changes in benthic features between 1999 and 2003, Area 3
Legend:  **ORANGE** = loss of seagrass/macro-algae cover
         **GREEN** = gains in seagrass/macro-algae cover
         **YELLOW** indicates no change

Gains in offshore seagrass cover exceeded inshore gains by a factor of about 1.5.
**AREA 5 – Offshore of Point Malcolm and along the Port Adelaide WWTP sludge pipeline**

Figure 4.49 shows the base aerial photography images for area 5 for 1999 and 2003 and Figure 4.50 shows the change map for this location.

**FIGURE 4.49** 1999 and 2003 aerial photo bases with changes between these times, Area 5
Legend: **BLUE** = areas of seagrass/macro-algae gain

**RED** = areas of seagrass/macro-algae loss
FIGURE 4.50 Changes in benthic features between 1999 and 2003, Area 5
Legend:  **ORANGE** = loss of seagrass/macro-algae cover
         **GREEN** = gains in seagrass/macro-algae cover
         **YELLOW** indicates no change

Offshore losses slightly exceed onshore gains in seagrass cover. The previously obvious sludge pipeline and sludge discharges are not apparent in the imagery from 2003, suggesting that cessation of the sludge discharge from the Port Adelaide WWTP has allowed some degree of seagrass recolonisation.
AREA 6 – offshore of Grange and West Lakes

Figure 4.51 shows the base aerial photography images for area 6 for 1999 and 2003 and Figure 4.52 shows the change map for this location.

**FIGURE 4.51** 1999 and 2003 aerial photo bases with changes between these times, Area 6.
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
FIGURE 4.52 Changes in benthic features between 1999 and 2003, Area 6
Legend: ORANGE = loss of seagrass/macro-algae cover
GREEN = gains in seagrass/macro-algae cover
YELLOW indicates no change

The gain in seagrasses exceeded losses by a factor of about 1.3 times and the changes were associated with the dynamics of crescentic blowouts.
**AREA 8- approximately 4 km offshore of Henley Beach and the River Torrens**

Figure 4.53 shows the base aerial photography images for Area 8 for 1999 and 2003 and Figure 4.54 shows the change map for this location.

**FIGURE 4.53** 1999 and 2003 aerial photo bases with changes between these times, Area 8

Legend: **BLUE** = areas of seagrass/macro-algae gain

**RED** = areas of seagrass/macro-algae loss
FIGURE 4.54 Changes in benthic features between 1999 and 2003, Area 8
Legend: **ORANGE** = loss of seagrass/macra-algae cover
**GREEN** = gains in seagrass/macra-algae cover
**YELLOW** indicates no change

Losses of seagrasses exceed gains by a factor of about 1.3 times in this offshore location.
AREA 9—offshore of West Beach

Figure 4.55 shows the base aerial photography images for area 9 for 1999 and 2003 and Figure 4.56 shows the change map for this location.

**FIGURE 4.55** 1999 and 2003 aerial photo bases with changes between these times, Area 9
Legend: BLUE = areas of seagrass/macro-algae gain
RED = areas of seagrass/macro-algae loss
FIGURE 4.56 Changes in benthic features between 1999 and 2003, Area 9
Legend: ORANGE = loss of seagrass/macro-algae cover
GREEN = gains in seagrass/macro-algae cover
YELLOW indicates no change

Significant recolonisation of seagrass occurred in this area (2.3 times as much as losses) and the gains are clearly associated with the system of crescentic blowouts.

The average annual rate of movement of crescentic blowout features was 2.6 m (SD 0.98) for the trailing erosional edges and 4.7 m (SD 1.51) for the colonising leading edges giving a gain to loss ratio of 1.8, which is in fairly close agreement with the estimated gain/loss ratio for the whole of area 9 for this time period.
**Area 10 offshore of Glenelg**

Figure 4.57 shows the base aerial photography images for Area 10 for 1999 and 2003 and Figure 4.58 shows the change map for this location.

**FIGURE 4.57** 1999 and 2003 aerial photo bases with changes between these times, Area 10
Legend: **BLUE** = areas of seagrass/macro-algae gain
**RED** = areas of seagrass/macro-algae loss
Losses greatly exceeded gains by a factor of about 2.4 times in this area near Glenelg and the Patawalonga, the former being one of the most eroded beaches and the latter being one of the major land-based discharges of high nutrients and high suspended solids.

4.3 Consideration of the Benthic Feature Maps and Change Maps
The maps presented in this chapter clearly portray a wide range of differences in the distributions and dynamics of *Posidonia* dominated seagrass beds. At different times and in different locations changes in the cover and distribution of seagrasses are likely to be influenced by:

- WWTP discharges;
- Discharges from the Port Adelaide River (observed in plume imagery);
- Wave climates and sediment dynamics (observed in plume and coastal morphology imagery);
- Underwater construction activities (observed in images of Port Adelaide and Glenelg WWTP discharge pipelines and SARDI intake and discharge pipe images);
- Almost inconsequentially stormwater discharges (observed from plume trajectories constrained within or close to the littoral and surf zones – see Chapter 6).

Inshore areas near Largs Bay and West Beach have substantial increases of cover (approximately one and a half time greater than losses) since about 1995. These areas also suffered the least dramatic changes in offshore movement of the landward edge of seagrass beds during the mid 70s to 80s.

It is beyond the scope of this study to further investigate the mechanisms involved in the dynamics of seagrass loss, colonisation, changes in cover and changes in community structures. The maps are provided to demonstrate that ecological dynamics (seagrass loss, seagrass recolonisation) are variable from site to site and from time to time and no single “fix” for restoring seagrass beds will necessarily be effective at all places in the Adelaide metropolitan coastal waters.
5 Airborne Hyperspectral imagery results and future monitoring recommendations

The purpose of the airborne hyperspectral mapping of the Adelaide Coastal Waters was to demonstrate and apply an innovative and objective substratum mapping method with the following advantages:

- Use of 30 spectral bands specifically designed for aquatic ecosystem mapping (instead of three for CAP) allowing better identification of water column optical properties, bathymetry and substratum type and cover.
- Correction for atmosphere and air-water interface effects using all spectral information; the atmospheric correction is objective and based on radiative transfer physics correcting for absorption and scattering in the atmosphere.
- A spatial resolution of 2 to 2.5 meters
- An image created through across track line scanning as the aircraft moves along thereby avoiding the forward looking and aft looking effects of atmosphere and sun glint on the water surface common in aerial photography.
- Application of an objective repeatable method for classifying the image, thus enabling transfer of method and knowledge once operational
- Transfer of the same method to any other type of remote sensing imagery allowing future comparison between archived information and new information

This classification using SAMBUCA (Semi-Analytical Model for Benthic Unmixing and water column Concentration Assessment) optimisation and inversion of spectral imagery requires adequate parameterization of the model. This parameterization consists (in broad terms) of creating a representative spectral library of water column optical properties and of substratum type and cover optical properties. Fig 5.1 shows the processes that occur with light from the sun and sky traveling downwards and interacting with the water column and substratum.

The essential data needed and acquired in this study included:

- Airborne hyperspectral imaging spectrometry (CASI – 1999 to 2003 for Bolivar and 2003 for the ACWS Coastal strip)
- Acquisition of bathymetric data in relation to indicative depth ranges for benthic features
- In-field measurements of water column characteristics (upwelling and downwelling irradiance) using the RAMSES spectroradiometric system that measures light in hundreds of spectral intervals from which any remote sensing spectrum may be recreated.
- Reflectance measurements of substratum type and vegetation cover using the same RAMSES spectroradiometer in three configurations:
  - Lowering the RAMSES onto the substratum and measuring the reflectance
  - Taking a substratum sample (diver or grab-based) onto the boat and measuring the reflectance above water
  - Taking a substratum sample into the lab and measuring the reflectance under fully controlled circumstances
- Measuring the light absorption, scattering, backscattering and attenuation in the water column using:
  - For bulk optical properties the in situ light absorption and beam attenuation sensor with 9 wavelength bands AC-9.
  - For bulk optical properties the in situ light backscattering sensor HYDROSCAT-6 instrument
  - For the specific analysis of the light absorption by water column components (algal pigments, non algal particulate matter and coloured dissolved organic matter) samples were taken and sent to the CSIRO Marine and Atmospheric Research (CMAR) Laboratories in Hobart for the spectrophotometric analysis
- Chlorophyll and suspended sediment concentrations were determined on the same water samples allowing the calculation of the per unit concentration, specific light absorption, light scattering and light backscattering.
FIGURE 5.1 The source, travel and fate of photons (light) as it interacts with the atmosphere, the air-water interface, the water column and the substratum

The image classification relied on the SAMBUCA model inversion for the final assessment of water column concentration assessment, bathymetry and per pixel distribution of the two most likely substratum type/cover combinations. As the SAMBUCA inversion takes approximately 0.1 second in the optimal case to invert an (image based) spectrum it could not be applied on a pixel-by-pixel basis as the 40 by 4 km coverage at 2 to 2.5 m resolution pixels would be about 26 million pixels and would take about 700 hours to invert. To reduce the number of pixels to be optimized for a SAMBUCA computationally intensive solution, the spectral dimensionality of the full dataset was first determined in order to assess the actual amount of significantly different spectra in an image.

The amount of statistically different spectra within the image was assessed by the Spectral Angle Mapping (SAM) technique in the ENVI image processing software package. SAM is a technique well established in geological surveying and prospecting and is now proving to be a useful method for both terrestrial and marine substrate features mapping. It is not well referenced in published literature, but is considered in detail in workshop notes from the ERIM Conference, 1996 (Analytical Imaging and Geophysics, 1996) as well as the ENVI manual.

As the SAM technique measures the similarity in spectral shape, but not in albedo (the absolute level of reflectance) it was necessary to also apply a measure of albedo. For this assessment we used a least squares minimum assessment method we call the f factor. Once it was established that on average about 400 spectra correctly represented all spectral dimensionality within each of the defined regions we could iteratively run SAMBUCA on these 400 spectra and remap the results to these defined region hyperspectral images.

As SAMBUCA will solve for any permutation of depth, concentration of optical water quality parameters and substratum type and/or cover (the relative distribution of the two substratum spectra that simulate the closest fit to a measured spectrum from CASI) it improves the result if constraints are put on the solution space by only allowing SAMBUCA to solve within environmentally relevant ranges. This also speeds up the inversion per pixel.
Thus the objective classification of benthic features required as much relevant information from a number of different studies and data sets including:

- Historical and recent aerial photography (1949 to 2003)
- Field surveys with surface and underwater observations (diving, sample collections, underwater photography – 1999 to 2003)
- Acquisition of bathymetric data in relation to indicative depth ranges for benthic features
- The optical parameterization of bulk in situ and laboratory based light absorption, (back) scattering, attenuation, concentration ranges of chlorophyll, tripton and CDOM.
- The spectral characterisation of seagrass and algal samples (2003)
- Plume dispersion using aerial photo interpretations, dye tracing studies, CASI data and Quickbird II satellite imagery.

Indicative depth ranges for benthic features, plus local knowledge of the spatial distributions and community structures, provided by DBE have been used to parameterize the CASI classifications method SAMBUCA to limit the range of solutions. These data are provided in Table 5.1.

### TABLE 5.1 Indicative depth distributions for benthic features, Adelaide metropolitan waters.

<table>
<thead>
<tr>
<th>Feature category</th>
<th>Species/feature</th>
<th>Depth range m AHD</th>
<th>Depth range m ISLW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>Seagrasses</td>
<td>Posidonia australis</td>
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<td>-7.0</td>
</tr>
<tr>
<td></td>
<td>Posidonia sinuosa</td>
<td>-2.4</td>
<td>-12.0</td>
</tr>
<tr>
<td></td>
<td>Amphibolis antarctica</td>
<td>0.0</td>
<td>-6.0</td>
</tr>
<tr>
<td></td>
<td>Zostera spp.</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Heterozostera tasmanica</td>
<td>1.5</td>
<td>-2.0</td>
</tr>
<tr>
<td>Brown algae</td>
<td>Scaberia, Cystophora, Sargassum</td>
<td>-2.0</td>
<td>-6.0</td>
</tr>
<tr>
<td>Red algae</td>
<td>Dictyota, Gracilaria, Halitpion</td>
<td>-0.5</td>
<td>-5.0</td>
</tr>
<tr>
<td></td>
<td>Gelidium</td>
<td>-2.0</td>
<td>-3.5</td>
</tr>
<tr>
<td>Green algae</td>
<td>Ulva</td>
<td>1.5</td>
<td>-4.5</td>
</tr>
<tr>
<td>Intertidal and beach</td>
<td>Sand/silt/mud</td>
<td>4.0</td>
<td>1.3</td>
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<tr>
<td>Shallow subtidal sand</td>
<td>Sand</td>
<td>1.3</td>
<td>-2.7</td>
</tr>
<tr>
<td>Deep subtidal sand</td>
<td>Sand</td>
<td>-2.7</td>
<td>-15.0</td>
</tr>
</tbody>
</table>

Notes:
1) These data were used as a guide to constrain the solution space of SAMBUCA based inversion of CASI image spectra.
2) Indian Spring Low Water (ISLW) is approximately 1.6 m below Mean Sea Level (MSL)
3) MSL is equivalent to the Australian Height Datum (AHD)

Field observations used to calibrate and verify the CASI data interpretations are given in Appendix 1.

### 5.1 CASI data – Introduction and coverage

CASI (Compact Airborne Spectrographic Imager) instruments have been built since 1988. Several generations of CASI data were produced and this study used two versions: more limited version in 1999 and a sophisticated version in 2001 and 2003.

The CASI instrument is an airborne hyperspectral digital imaging spectrometer which acquires image data in up to 72 narrow spectral bands of the visible to near visible infrared wavelengths (within a nominal range of 380 to 908 nm but an operational range of 440 to 800 nm). The CASI can also be flown in spectral mode in which case 288 spectral bands are recorded but in a spatially incomplete manner. As there is an optimum between signal to noise and spectral resolution CSIRO Land & Water developed a specific band set for shallow coastal water mapping containing 30 spectral bands that coincide with existing multi spectral satellites and that cover all anticipated
optically active water column and substrate features in addition to having bands for fine tuning atmospheric and air-water interface corrections (including sun and sky glint). The CASI data is 10 times more detailed in spectral resolution than CAP, covers the entire desired spectral range, is quantifiable in what it measures (radiance units), has less image distortions due to its line scanning mode, is provided with automatic geocorrection software, has programmable spectral bands and is a commercial standard in airborne imaging spectrometry (together with its competitor HyMap).

In November 2003 an ACWS dedicated mission was flown between Port Gawler and Seacliff. Planned coverage over Marino Rocks did not occur due to an error in map coordinates supplied to the flight crew. Later inspection of aerial photography and field surveys demonstrated that water depths (in some cases as close to shore as 1 km from the high tide mark) are consistently greater than 6 m, a depth at which CASI interpretation of benthic substrates becomes really no more reliable than aerial photography interpretation for the water column conditions during the CASI flight as the spectral information from the substratum is limited into a narrow spectral range in the green, although if the water is clearer information from can be derived from greater depths. Aerial photographs were the only data available in the Marino Rocks area.

The flight blocks and coverages obtained using the CASI deployment in November 2003 in the Adelaide Coastal Waters Study area are shown in Figure 5.2.

**FIGURE 5.2** CASI coverage plan for November 25 and 26, 2003
5.2 CASI bandset

In 1999 a generic bandset was used as both land and water targets were flown. The CASI used was an older version and is not the same as the CASI used in 2001 and 2003. This older version could not yet accommodate the 30 bands used in the 2001 and 2003 CASI coverages and was comprised of 13 wider spectral bands. In 2001 the Environmental Remote Sensing Group developed a new spectral band set that covered known pigment absorption features of phytoplankton in the water column and on the substrate, took into account the lower S:N in the blue and the NIR (therefore broader bands) and has bands that are similar to MODIS and MERIS satellite sensors (see Table 5.2).

In 2003 this band set was slightly modified by the CSIRO L&W Remote Sensing Group as analyses of the 2001 CASI data revealed that the bands at 866 and 939 were so noisy as to not deliver any information. Therefore these bands were replaced by additional bands at 742 and at 760 nm. At 742 nm pure water absorption has a relative low value and thus light concentrates further in shallow waters thus improving depth estimates. The 760 nm band is in the centre of an atmospheric oxygen and water vapour absorption feature enabling verification of spectral accuracy and allowing improved atmospheric correction.

The CASI band set (based on 2001 band sets slightly modified) has been used by the CSIRO Land & Water Remote Sensing Group for aquatic environmental imaging for 2002 (joint with UQ) Coastal CRC and Coral Reef Projects and 2003 projects (Adelaide – Bolivar & Coastal Water Study).

Table 5.2 CASI band set

<table>
<thead>
<tr>
<th>Band</th>
<th>λ</th>
<th>Band-</th>
<th>Min λ</th>
<th>Max λ</th>
<th>Features</th>
<th>Sensors</th>
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<td>428.7</td>
<td>448.3</td>
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<td>468.8</td>
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<td></td>
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<td>538.5</td>
<td>554.7</td>
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<td>695.9</td>
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<td>7.9</td>
<td>703.6</td>
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<td>757.3</td>
<td>760.4</td>
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<td>MERIS 11</td>
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<td>770.1</td>
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<td></td>
</tr>
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<td>30</td>
<td>778.5</td>
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<td>770.7</td>
<td>785.4</td>
<td>Atm. Ref 761nm O₂, sunglint</td>
<td>MERIS 12</td>
</tr>
</tbody>
</table>

Notes:
1. The greek symbol lambda (λ) is wavelength. The centroid of each band is given in column 2, while the bandwidths and minimum and maximum wavelengths for each band are given in the successive three columns.
2. The set of thirty bands was selected with the aim of covering almost all the visible range and some of the main atmospheric features in the NIR.

3. The variable bandwidth along the spectra compensates the spectral dependence of signal to noise ratio (SNR) for CASI.

4. MP-SS= Maximum Penetration of light to Substrate; also meaning a possible local reflectance maximum due to a local minimum in absorption, this will be valid for all but the most clear ocean waters.

5. CDOM is coloured dissolved organic matter, also known as gelbstoff (yellow stuff)

6. TSM is total suspended particulate matter (organic and inorganic)

7. CPS is cyanophycocyanin and CPE is cyanophycoerythrin, specific cyanobacterial pigments which are indicators of the presence of potentially toxic micro-algae and often indicators of eutrophication.

5.3 Aerial photography versus CASI technologies

The key features of hyperspectral data sets are the discreteness, the narrow spectral bandwidth and the positioning of the adjacent spectral bands. In comparison aerial photographic film is generally sensitive to only broad and overlapping bands in the red, green and blue parts of the visible spectrum. Some films are also sensitive to near visible infrared. The sensitivity to RGB of an example film is shown in Figure 5.3 and the overlap and broad spread of the bands is quite evident. The limited spectral resolution of film means that it is not possible with this medium to objectively and repeatably achieve the high degree of discrimination of atmospheric, air-water interface and marine features obtained using the CASI data.

**FIGURE 5.3** Sensitivity characteristics for an example high resolution colour film (Fuji Provia 400F Professional®).

In the last decade or so the most commonly used film for large format (25 cm negatives) aerial photography in South Australia has been Kodak Aerocolor III Negative Film 2444®. The spectral sensitivity of this film is illustrated in figure 5.4.
5.4 Guide to interpreting the CASI derived mapping results

The SAMBUCA algorithm has been used to classify CASI image spectral data to allow identification of benthic features, water column depth and water column properties. The SAMBUCA algorithm (IP/copyright CSIRO Land and Water) is a more sophisticated version of the semi-analytical (SA) model and minimisation approach developed by Lee et al. (1998, 1999) for retrieving bathymetry and optical properties of the water column simultaneously.

A light signal leaving the water column is considered as a function of the water column’s optical properties, the bottom substrate albedo, the depth of the water column and a combination of viewing and illumination angles. For fixed viewing and illumination angles, the subsurface remote sensing reflectance $r_s$ can therefore be expressed as:

$$
r_s(\lambda) = f(a(\lambda), b_s(\lambda), \rho(\lambda), H)$$

where $a(\lambda)$ is the wavelength-dependent absorption coefficient, $b_s(\lambda)$ is the wavelength-dependent backscattering coefficient, $\rho(\lambda)$ is the albedo of the benthic substrate and $H$ is the depth of the water column.

Specifically, for a fixed viewing azimuth angle from the solar plane of 90°, the Lee et al., (1999) semi-analytical (SA) model is written as:

$$
r_s = r_s^{\text{nr}} \left[ 1 - \exp \left( -\frac{1}{\cos \theta_{\text{sub}} + \cos \theta_{\text{sub}}} \right) \kappa H \right] + \frac{1}{Q} \rho \exp \left( -\frac{1}{\cos \theta_{\text{sub}} + \cos \theta_{\text{sub}}} \right) \kappa H \right)$$

where

$$
r_s^{\text{nr}} = (0.084 + 0.17u)u$$
\[ D_{\text{sc}} = 1.03(1+2.4u)^{1.1} \quad D_{\text{sa}} = 1.04(1+5.4u)^{1.1} \]  
\[ u = \frac{b_u}{(a + b_u)} \quad \kappa = a + b_u \]  

and \( \theta_{\text{subsun}} \), \( \theta_{\text{subview}} \) are the subsurface solar zenith angle and subsurface viewing angle from nadir, respectively. The \( r_{\text{rs}} \) term represents the subsurface reflectance contribution from optically deep water. The \( Q \) factor is a measure of the subsurface radiance distribution, or the ratio of upwelling irradiance to the upwelling radiance. If the upwelling radiance is assumed to be over a lambertian surface then \( Q \) would equal \( \pi \), but the radiance distribution is rarely lambertian (Kirk, 1994) and modelling calculations have yielded a higher value. The value of \( Q \) is therefore set to 4 instead of \( \pi \) as used by Lee et al., (2001).

In order to retrieve the optical properties of the water column, depth and bottom albedo from a single \( r_{\text{rs}} \) value (using optimization), Lee et al., (1998, 1999) parameterise (1) so that it becomes a function of a limited set of one-dimensional variables.

### 5.4.1 Parameterisation of the model

**Absorption**

The total absorption is written as:

\[ a_{\text{tot}} (\lambda) = a_w (\lambda) + a_{\text{phy}} (\lambda) + a_{\text{cdom}} (\lambda) + a_{\text{tr}} (\lambda) \]  

where is \( a_w (\lambda) \), \( a_{\text{phy}} (\lambda) \), \( a_{\text{cdom}} (\lambda) \) and \( a_{\text{tr}} (\lambda) \) is the absorption due to pure water, phytoplankton, dissolved and particulate organic material and inorganic material or tripton. The absorption due to pure water is taken from Pope and Fry (1997). The absorption due to phytoplankton is further broken down into:

\[ a_{\text{phy}} (\lambda) = C_{\text{chl}} \cdot a^*_{\text{phy}} \]  

where \( C_{\text{chl}} \) is the concentration of chlorophyll, \( a^*_{\text{phy}} \) is the specific absorption of phytoplankton (absorption of pigments normalized on the chlorophyll concentration). The absorption due to organic material is expressed as:

\[ a_{\text{cdom}} (\lambda) = C_{\text{cdom}} \cdot a^*_{\text{cdom}} (\lambda_0) \exp (-S_\text{c} (\lambda - \lambda_0)) \]  

where \( \lambda_0 \) was set to 550nm, \( C_{\text{cdom}} \) is concentration of CDOM (i.e. the \( C_{\text{cdom}} (550) \) is set to 1) and \( S_\text{c} \) is the sample dependent.

\[ a_{\text{tr}} (\lambda) = C_{\text{tr}} \cdot a^*_{\text{tr}} (\lambda_0) \exp (-S_\text{c} (\lambda - \lambda_0)) \]  

where \( \lambda_0 \) was set to 550nm, \( C_{\text{tr}} \) is concentration of tripton (i.e. the \( C_{\text{tr}} (550) \) is set to 1) and \( S_\text{c} \) is the sample dependent.

**Backscatter**

The total backscatter \( b_b (\lambda) \) is considered to be a sum of the backscatter due to pure water \( b_w (\lambda) \) and the backscatter due to phytoplankton \( b_{\text{phy}} (\lambda) \) and the tripton in the water column \( b_{\text{tr}} (\lambda) \):

\[ b_b (\lambda) = b_w (\lambda) + b_{\text{phy}} (\lambda) + b_{\text{tr}} (\lambda) \]
The backscatter due to pure water is taken from Morel (1974) and the backscatter due to particles is expressed as:

\[ b_{\text{pure}}(\lambda) = CHL \times X_{\text{pure}} \left( \frac{542}{\lambda} \right)^Y \]  

(11)

Where \( Y \) is the spectral slope and \( X_{\text{phy}} \) is the backscatter due to phytoplankton at 542 nm.

\[ b_{\text{phy}}(\lambda) = TR \times X_{\text{phy}} \left( \frac{542}{\lambda} \right)^Y \]  

(12)

\[ X = CHL \times X_{\text{phy}} + TR \times X_{\text{pure}} \]  

(13)

\( Y \) is estimated from the HydroScat-6 data.

Substrate albedo

Lee et al. (2001) expressed the bottom substrate albedo in terms of reflectance spectrum normalised at 550 nm, \( \rho_{\text{normalised}} \), and a scalar factor \( B \) that defines the albedo at 550 nm:

\[ \rho(\lambda) = B \rho_{\text{normalised}} \]  

(14)

The SAMBUCA algorithm uses two input spectra assuming that a given reflectance reading from an image pixel is composed of a mixture of two substrate spectra (a mixel). This is expressed as:

\[ \rho(\lambda) = q_1 \rho_i + q_2 \rho_j \]  

(15)

where \( \rho_i \) is a given substrate spectrum and \( q_1 \) is the fraction of that substrate’s cover within the mixel. As the total amount of substrate cover must add up to 1, the equation is re-written as:

\[ \rho(\lambda) = q_1 \rho_i + (1 - q_1) \rho_j \]  

(16)

5.4.2 Inversion through minimisation

Given the input spectra, the viewing and illumination angles, and provided that the spectral slopes \( S \) and \( Y \) are set (either to default values or determined from in situ measurements), the function in (1) can be re-written as:

\[ r_{\text{rs}}^{\text{modelled}}(\lambda) = f(C_{\text{CHL}}, C_{\text{CDOM}}, C_{\text{TR}}, X_{\text{CHL}}, X_{\text{TR}}, Y, H, S_{\text{CDOM}}, S_{\text{TR}}, a_{\text{TR}}(\lambda_0), Y) \]  

(17)

The SA model in (2) is therefore reduced to a function of five simple variables. An error function is defined as the difference between the modelled (SAMBUCA) and measured (CASI) \( r_{\text{rs}}(\lambda) \) values:

\[ err = \left[ \frac{1}{400} \sum_{i=1}^{400} (r_{\text{rs}} - r_{\text{obs}})^2 + \frac{1}{700} \sum_{i=1}^{700} (r_{\text{rs}} - r_{\text{obs}})^2 \right]^{0.5} \]  

(18)

SAMBUCA employs a simplex optimisation algorithm (a modified version of the amoeba routine found within IDL version 5.6) to minimise (18) by varying the concentrations, \( q \) and \( H \) within pre-defined limits. If the minimisation routine reaches a function value below an empirically determined (expert knowledge based) error threshold, the values for concentrations, \( q \), and \( H \) variables are returned, hence retrieving the water’s optical quality parameters, substrate composition and water depth. The value of (18) is retained for each pixel, enabling a relative assessment of the reliability of the spectral match achieved. In order to accommodate for more than two end-member substrate
spectra for a given pixel, SAMBUCA can be set to run through pairs of combinations from a spectral library, returning the five variable values as well as the two input spectra used to achieve the lowest error function value in (18).

Because the dimensionality of all the spectral data for the approximate 40 by 4 km ACWS RS 1 project area is large and the SAMBUCA inversion process is computationally heavy and thus slow, we needed to find a way to reduce the spectral image dataset that SAMBUCA needed to invert through optimization. To reduce the number of pixels to be optimized for a SAMBUCA computationally intensive solution, the spectral dimensionality of the full dataset was first determined by Spectral Angle Mapping. Once it was established that on average about 400 spectra correctly represented all spectral dimensionality within each of the defined regions, we could iteratively run SAMBUCA on these 400 spectra and remap the results to the entire images. Spectral angle mapping involves multidimensional analysis of data where each spectral bands (30 in the case of CASI) data are arranged on axes of reflectance values (0 to 100). Each axis is orthogonal in a multidimensional space where the number of axes is equal to the number of bands. Dark pixels will cluster towards the origin of the axes, brighter pixels will lie somewhat away from the origin. Different features such as sand and seagrass will tend to cluster at different locations on the reflectance axes. The Spectral Angle Mapper algorithm determines the similarity between pairs of spectra by calculating the Euclidean angle between them and these are treated as vectors in a space with dimensionality equal to the number of bands. Small spectral angles correspond to high similarity, while large angles correspond to less similarity.

The signal from a substrate (whether covered with vegetation or not) as measured by a remote sensor dominates the measured signal in areas with a very thin water column cover (e.g. 10 cm). When the water column depth increases, the signal from the substrate decreases, and the water column component of the signal increases. Photons reaching the sensor have had to travel downwards through the water, be reflected back from the substrate and travel back up through the water column. Sea surface features (waves and ripples) scatter the incoming light, the water itself scatter the light, dark features absorb light and on the return to the surface again water column and sea surface features scatter the light. This means that only a small percentage of the illuminance actually reaches the remote sensor. Even for very calm and clear waters with seagrass benthos substantially less than 1% of the illuminance may reach the sensor.

This has consequences for the SAMBUCA inversions on CASI data in the ACWS. As SAMBUCA derives chlorophyll, tripton and CDOM concentrations as well as water column depth and substrate relative abundance simultaneously, the physics indicate what will happen.

In shallow areas (typically 10 cm to about 3 meters depth) the substrate maps are most reliable as well as the water depth estimates. The water depth estimates are most reliable in shallow areas because the fast increasing pure water absorption beyond 650 nm (and its pure water specific features caused by water harmonics) gives a shape to the spectrum that is directly related to the magnitude of the water column. In the Adelaide Coastal Waters that overall are very clear, it will be more difficult for SAMBUCA to measure any effect of the water column (concerning chlorophyll, tripton or CDOM concentrations) as the signal comes from the substrate and is hardly modified by the water column (except for the red to nearby infrared absorption of pure water).

As the water column deepens (from 3 to 6 m) the signal from the water column increases in the remotely sensed signal but the signal from the substrate decreases. This decrease takes place over the entire spectrum but it happens faster in the blue (450 nm and shorter) due to absorption by CDOM, tripton and chlorophyll. Then there is a spectral area of highest penetration of light from 450 to 600 nm after which pure water absorption and the red chlorophyll absorption jointly reduce the visibility to the substrate beyond 600 nm. SAMBUCA will produce moderately accurate results in this intermediate area for all inversions of substrate cover, water column depth and concentrations of Chlorophyll, CDOM and tripton.

When the water column depth goes beyond 6 m in Adelaide coastal waters the substrate signal coming through the water column and measured by the CASI only occurs between 450 and 600 nm. As many spectral discriminatory substrate vegetation features occur between 600 and 720 nm this means SAMBUCA or ANY other inversion, will have less and less spectral substrate signal to use for species/genus identification. The water column composition estimation of Chlorophyll,
CDOM and tripton, however, becomes quite reliable as most of the signal is now derived from the water column.

Therefore in our maps wherever the water depth was likely to be deeper than 6m we on purpose did not apply SAMBUCA anymore, rather the mapping presented for depths greater than 6m was interpreted from corresponding aerial photography using the associative rules for features as defined in Figure 3.2. If, in the future, it appears this deeper area needs more accurate species/genus/cover estimation some additional field and lab work on spectral characterization would need to take place and some refinement of our modelling software to tease out more information in the 450 to 600 nm area.

Depth ranges for the CASI data SAMBUCA inversion were taken from bathymetry derived from sonar soundings and published navigation charts. Depth constraints applied to the CASI data were used to produce much finer scale bathymetry from the CASI band sets.

Figure 5.5 shows the base bathymetry for the whole study area used to initially calibrate the SAMBUCA model (height datum for this plot is Indian Spring Low Water, ISLW, which is 1.6m below AHD). Any comparisons between chart bathymetry and CASI modelled bathymetry are referred to AHD.

FIGURE 5.5 Bathymetry for the whole ACWS study area derived from published navigational charts, Office of Coast and Marine soundings, Flinders Port’s Corp soundings and data from Kinhill 1998 (all referred to AHD).
Figure 5.6 is the bathymetry for the Bolivar region modelled from CASI data.

It was possible to calculate the differences between observed and modelled bathymetry. Differences between these are mostly attributable to the different resolutions in the two data sets. Chart and sounding bathymetry uses point data at variable spacings ranging from about 100m to greater than 1 km (greater than 5 km in the more southerly and offshore regions of the study area). Because irregular grid spacings had to be used it was necessary to apply a minimum curvature smoothing algorithm to minimise artefacts in the surfacing routine (kriging) used to produce the bathymetric map. Modelled bathymetry is from an equal spaced grid of pixels with grid spacings of 2m to 10 m and no smoothing was required, or indeed desirable.

The absolute differences between observational bathymetric data and modelled bathymetry range from plus 1m to minus 3m. Most of the areas of differences however lie in the range plus 0.5 m to minus 0.5 m – an acceptable range given the fundamentally different technologies and the uncertainties in accuracy of published charts and sounding data sets.
Figure 5.7 shows some vertical attenuation curves of diffuse downwelling light ($K_d$) and shows the combined effects of absorption, scattering and backscattering and the angle of irradiance measured at several sites in November 2003 and demonstrates why the maximum signal to and from the substrate through the water column is located between 500 nm and 580 nm with a reasonable penetration between 420 and 600 nm. As a rule of thumb 90% of the emergent light from a water body originates within the depth (equal to $1/K_d$) in which downward irradiance falls to 37% ($1/e$) of the subsurface value (Kirk, 1994).

Thus the $K_d$ is 0.6 m$^{-1}$ as occurs for sample site 5 at 410 and 600 nm 90% of the light emerging from this water body comes from the water column part of surface to 1.6 m deep. In this water column 37% of light is attenuated as it transverses down to 1.6 m.; for a minimum measured $K_d$ of 0.1 m$^{-1}$ this same values occur at 10 m depth. In a similar fashion it is now easy to understand that at wavelengths beyond the visible (e.g. the nearby infrared at 700 nm) the pure water $K_d$ is 0.6 m$^{-1}$ leading to a 37% reduction of light at 1.6 m.

Thus the $K_d$ makes a fast calculation possible to which depth meaningful substratum reflectance may be visible. If we assume the vertical downward $K_d$ is similar to the vertical upward attenuation of light from the substratum and the substratum reflects 10% of light upwards it becomes easy to understand that if we assume the downwelling light just under the water surface is 100%, only 10 % arrives at the substratum, of this 10% only 10 % is reflected upwards (i.e. 1 % of original light) and this is attenuated by 90% again through the water column upwards, leaving 0.1 % of the light emanating from the water column at the surface. This would require a signal to noise ratio of at least 1000:1 to measure by a spectroradiometer at the surface.

![Figure 5.7](image)

**FIGURE 5.7** Vertical attenuation spectrum calculated from Bolivar 2003 downwelling irradiance profiles measured using the RAMSES underwater spectroradiometer

The attenuation is caused by the combined effects of spectral absorption and scattering by the optically active water constituents (algal pigments, tripton and CDOM) and the pure water spectrum (dark blue).

In the parameterisation of the model it was necessary to account for local tidal conditions at the time of acquisition of the CASI and underwater field spectral measurements as the water column depth and thus the $K_d$ will vary with the water column depth. The tidal history for November 25, 2003 to November 27, 2003 is shown in Figure 5.8. The tidal excursion in the CASI images may thus be up to 1.6 m between tracks flown at different times of the day.
5.5 The substratum spectral library

In order to be able to correctly map benthic substratum types and vegetation covers it is essential to acquire a representative spectral library for the study area. The CLW Remote Sensing team relied on local expert knowledge to collect this spectral library. The spectral library for this study was created during the fieldwork of November 2003 with augmentation of some spectra from the CSIRO L&W fieldtrips in 1999 and 2001. This library consists of characteristic spectral curves in RAMSES bands resampled to 1 nm intervals over the 400 to 800 nm range for a range of seagrasses, macrophytes and sediments with benthic micro-algae cover. The spectral curves for various substrates are illustrated in Figure 5.9. Unfortunately it became clear during the final processing of the CASI images that we did not have spectra for several types of substratum and vegetation that do occur in this area. These missing spectra were:

- *Halophila*
- *Amphibolis*
- Wrack or detrital seagrass and macro-algal material
- The spectrum of the actual intertidal material present at the Bolivar site.

Fortunately it was possible to obtain a sample of *Amphibolis* through collaboration with PIRSA-SARDI at a later stage. This sample was sent to the CLW labs in Canberra wrapped in plastic with some seawater in a cool box at a later stage and we were able to measure the spectrum adequately. As the circumstances for measuring seagrass and macro-algae are much more controlled in our lab set-up we recommend in future to have samples sent to the lab for final spectral reflectance measurements.
Some of the spectral curves are quite similar e.g. *Posidonia sinuosa*, *Heterozostera tasmanica* (bright), red branching algae and *Amphibolis* are quite similar so it was necessary to investigate the likely spatial associations of these feature types. This is outlined Figure 3.2 as a logic matrix for whether feature types were likely to occur together. Dark and light classifications were used to distinguish features with different degrees of epiphytism or microalgae. These features were defined using in-field and laboratory spectroradiometric measurements.
5.6 Parameterisation and simulations of reflectance using the SAMBUCA model

The present version of the SAMBUCA model is fully parameterized as presented in Figure 5.10.

\[ r_s(\lambda)_{\text{modelled}} = f \left[ C_{\text{CHL}}, C_{\text{CDOM}}, C_{\text{TR}}, X_{\text{CHL}}, X_{\text{TR}}, Q, H, S_{\text{CDOM}}, S_{\text{TR}}, a^*_{\text{TR}}(\lambda) \right] \]

- \( C_{\text{CHL}} \) = concentration chlorophyll range limited
- \( C_{\text{CDOM}} \) = concentration coloured dissolved organic matter range limited
- \( C_{\text{TR}} \) = concentration tripton (=lifeless TSM component) range limited
- \( X_{\text{CHL}} \) = backscattering chlorophyll
- \( X_{\text{TR}} \) = backscattering tripton
- \( Q \) = fractions of 2 benthic substrate(s) contributing to bottom reflectance
- \( H \) = depth of water column range limited
- \( S_{\text{CDOM}} \) = slope of CDOM absorption
- \( S_{\text{TR}} \) = slope of tripton absorption
- \( a^*_{\text{TR}}(\lambda) \) = specific tripton absorption
- \( a^*_{\text{chl}}(\lambda) \) = specific algal pigments absorption

**FIGURE 5.10** Parameters in the SAMBUCA model

As previously explained the model applies corrections for all relevant optical properties of column that influence light transmission in the water column including bathymetry. In actual fact it does not remove these influences but incorporates these effects on the final spectrum at the surface as it is matched with the measured CASI spectrum.

Figures 5.11, 5.12 and 5.13 illustrate the spectral pigment absorption characteristics of the pelagic algae =phytoplankton (the primary pigment being chlorophyll), CDOM and tripton (the non-algal particulate matter) as measured from samples taken during the field campaign in November 2003 during the CASI November 2003 flights.

**FIGURE 5.11** Phytoplankton pigment spectral absorption curves of the in situ samples, measured by CMR (Lesley Clementson)
Note the Chlorophyll absorption features around 440 and 676 nm. The highest values are measured near the Bolivar WWTP effluent area. The lowest values are measured near the southern ACWS waters.

FIGURE 5.12 CDOM spectral absorption curves of the in situ samples

The two samples with high CDOM were taken near the Bolivar WWTP; the low CDOM values all apply to the Adelaide Coastal Waters from Outer Harbor to Glenelg. CDOM mainly absorbs light in a decreasing exponential manner with increasing wavelength.

FIGURE 5.13 Non algal particulate matter spectral absorption curves of the in situ samples

The absorption of this material has a similar exponential decreasing absorption with increasing wavelength as the CDOM spectra; however, the slope is less than for CDOM.
FIGURE 5.14 The light backscattering (m$^{-1}$) measured in situ using the HydroScat-6

The backscattering decreases with increasing wavelength. The least backscattering samples are the clearest waters in the southern part of the ACWS.

FIGURE 5.15 The inherent optical properties (all symbols without a * superscript) and the specific inherent optical properties (with a * superscript) as used for the SAMBUCA parameterization

Specific inherent optical properties are those inherent optical properties that are divided by either chlorophyll concentration or tripton concentration, thus becoming concentration specific.

With the parameterisation spectral curves of Figs 5.11 to 5.15 and using the SAMBUCA model in forward (=spectral simulation mode) it was now possible to simulate the effect of varying
concentrations of optically active substances on the reflectance of the water column. The results for such simulations varying the concentrations between the ranges measured in the ACWS are presented in Figs 5.16-18.

**FIGURE 5.16** The effect of varying CDOM values on subsurface irradiance reflectance within the range found in the ACWS region

As CDOM increases the reflectance decreases as CDOM absorbs light only.

**FIGURE 5.17** The effect of varying chlorophyll values on subsurface irradiance reflectance within the range found in the ACWS region

As chlorophyll increases, the reflectance decreases in the blue because chlorophyll absorption in the blue light supercedes the associated increase in algal biomass (that leads to more backscattering of light). Beyond 600 nm these effects are in balance.
As tripton increases the reflectance increases as tripton scatters light more than it absorbs light.

Now we were able to simulate the effects of varying concentrations on reflectance for optically deep waters (Figs 5.16-5.18) we could also use the SAMBUCA forward model for simulating the effect of varying water depth on the reflectance over a location where a substratum or seagrass or macro-algae is visible. Figures 5.19 and 5.20 show such simulations over a Posidonia bed and over sand respectively.

From a depth of 10 m onwards the difference is imperceptible with respect to the deep water column spectrum.
FIGURE 5.20  The effect of varying water depth on subsurface irradiance reflectance over a sand substratum

From a depth of 12 m onwards the difference is imperceptible with respect to the deep water column spectrum.

Now we have full insight into (through simulations) the effect of water column depth and substratum type and cover on the reflectance we need to demonstrate that it is possible to measure this subsurface irradiance reflectance from the CASI airborne imaged spectrum.

FIGURE 5.21  The effect of atmospheric correction on CASI at sensor measured spectra (CASI radiance) to subsurface irradiance reflectance over a few targets in a strip of CASI data shown right in the image

Figure 5.22 is a plot of atmospherically corrected CASI data and in situ subsurface irradiance measured using the RAMSES submersible spectroradiometer over a deep water site. Using a deep water site obviates any confusing influences from benthic substrates and so allows a critical
comparison between CASI derived and RAMSES field measurement derived irradiance data. The symbols on the CASI data plot represent the positions of the spectral band centres.

**FIGURE 5.22** Comparisons of CASI atmospherically corrected data and in situ subsurface irradiance data over a deep water site

For atmospheric correction the full range of spectra was used. The close match between the two data sets indicates the high degree of accuracy of cross calibration of the airborne and field instruments and demonstrates a high degree of confidence in the use of CASI data for the quantification of subsurface irradiance. This level of removal of atmospheric and air-water interface effects is not possible with aerial photography.

### 5.7 CASI imagery based feature and change maps for the Bolivar region

These maps have been produced from March 2001 and November 2003 CASI and some qualitative discussion of the 1999 CASI imagery (derived from a different instrument) is also given.

First we discuss the results for the Bolivar region as it illustrates the use and power of multi-temporal hyperspectral airborne imaging as an objective change detection tool requiring no local expert knowledge once the initial parameterisation is established. CASI data was flown in 1999, 2001 for method development and as demonstration of the airborne hyperspectral imaging capability. In November 2003 the ACWS RS1 Task flights were carried out over both Bolivar and the four ACWS areas depicted in Fig 5.2. Another reason for discussing the Bolivar results first is that it is possible to visualize the detail of information possible with the CASI imagery as it is a limited spatial area. The results for the four ACWS areas (roughly 40 by 4 km) are necessarily compressed in the printed figures of this report and much detail is lost.

The 1999 data coverage is discussed only in qualitative terms as it appeared impossible to obtain the raw CASI data so we could process it exactly the same as the 2001 and 2003 CASI data. The 1999 data was flown courtesy of Ball-AIMS (a now defunct Australian business closely associated with Ball AeroSPACE). Unfortunately we could not access any necessary raw data and metadata anymore for this flight. Therefore the quantitative change detection focuses on the 2001 and 2003 image products.

Figure 5.23 shows an end-result for the mapping of the Bolivar area for the November 2003 CASI image. It depicts the amalgamated classes (see Figure 5.9. for all the substratum classes mapped) of *Posidonia* spp., Zosteraeaceae, macro-algae spp and sands. The black colours on the intertidal
area depict areas where there was no classification possible as we did not have the representative spectral library of whatever vegetative cover was present. The field survey boat was unable to access these shallow intertidal areas. The *Zostera* and macro-algae cover in the intertidal area may be detrital *Zostera* and macro-algae cover or it may be a confusion with another unidentified cover type. The SAMBUCA inversion method can distinguish only between the substratum types with which it is parameterized. One of the advantages of this new method is that in future if more spectral information on substratum types becomes available it is possible to rerun the classification without too much effort. The map shows a 2 km wide subtidal strip where a lot of sand is present (presumably due to a loss in *Posidonia* cover).

**FIGURE 5.23** The final SAMBUCA derived classification of the Bolivar November 2003 CASI coverage at 2 m resolution for the final amalgamated classes

This result is repeatable by any operator and is objective. The classes are aggregated from the 11 originally discriminated classes and are presented in terms of the dominant substratum type or cover (i.e. more than 50% presence) as SAMBUCA calculates the relative distribution of the two most likely substratum types or covers within one pixel: the so-called “subpixel unmixing”.

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FIGURE 5.24 The final SAMBUCA derived *Posidonia* spp. classification in relative abundance per pixel of the Bolivar March 2001 CASI coverage at 2 m resolution.

The classes are aggregated from the 3 originally discriminated *Posidonia* classes (*P. australis* bright, *P. australis* dark and *P. sinuosa*). The zero to ten percent cover class type may have no *Posidonia* at all and this is certainly the case for intertidal areas. These results can be directly compared with Fig. 5.25 which depicts the same classification for the 2003 CASI imagery.
The final SAMBUCA derived Posidonia spp. classification in relative abundance per pixel of the Bolivar November 2003 CASI coverage at 2 m resolution

The classes are aggregated from the 3 originally discriminated Posidonia classes (P. australis bright, P. australis dark and P. sinuosa). The zero to ten percent cover class type may have no Posidonia at all and this certainly the case for intertidal areas. These results can be directly compared with Fig. 5.24 which depicts the same classification for the 2001 CASI imagery.
FIGURE 5.26 Changes in *Posidonia* cover 2001 to 2003, CASI data

This image has resulted from applying a change detection algorithm to the results of the SAMBUCA derived *Posidonia* spp. classification in relative abundance per pixel of the Bolivar March 2001 and November 2003 CASI coverage at 2 m resolution. The classes are aggregated from the 3 originally discriminated *Posidonia* classes (*P. australis* bright, *P. australis* dark and *P. sinuosa*). The zero to ten percent no change cover class type may have no *Posidonia* at all. The outlined areas labeled A and B are shown in detail in Figure 5.27 and 5.28 respectively which show the obvious decreases in overall cover of *Posidonia* during the period 1999 to 2003.
TABLE 5.3  Changes in *Posidonia* cover for the Bolivar region, 2001 to 2003.

<table>
<thead>
<tr>
<th>Subtidal <em>Posidonia</em> Percentage Change Results</th>
<th>2001 to 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>91 to 100% gain</td>
<td>0.3%</td>
</tr>
<tr>
<td>81 to 90% gain</td>
<td>0.5%</td>
</tr>
<tr>
<td>71 to 80% gain</td>
<td>0.3%</td>
</tr>
<tr>
<td>61 to 70% gain</td>
<td>0.4%</td>
</tr>
<tr>
<td>51 to 60% gain</td>
<td>1.6%</td>
</tr>
<tr>
<td>41 to 50% gain</td>
<td>2.4%</td>
</tr>
<tr>
<td>31 to 40% gain</td>
<td>3.1%</td>
</tr>
<tr>
<td>21 to 30% gain</td>
<td>4.0%</td>
</tr>
<tr>
<td>11 to 20% gain</td>
<td>3.4%</td>
</tr>
<tr>
<td>No change (+/- 10%)</td>
<td>29.9%</td>
</tr>
<tr>
<td>11 to 20% loss</td>
<td>15.6%</td>
</tr>
<tr>
<td>21 to 30% loss</td>
<td>7.8%</td>
</tr>
<tr>
<td>31 to 40% loss</td>
<td>6.8%</td>
</tr>
<tr>
<td>41 to 50% loss</td>
<td>3.8%</td>
</tr>
<tr>
<td>51 to 60% loss</td>
<td>6.1%</td>
</tr>
<tr>
<td>61 to 70% loss</td>
<td>4.4%</td>
</tr>
<tr>
<td>71 to 80% loss</td>
<td>11.7%</td>
</tr>
<tr>
<td>81 to 90% loss</td>
<td>0.9%</td>
</tr>
<tr>
<td>91 to 100% loss</td>
<td>6.9%</td>
</tr>
<tr>
<td>Ratio of avg gain to loss</td>
<td>25.0%</td>
</tr>
</tbody>
</table>

The results of *Posidonia* mapping and the change detection for the period of 2001 to 2003 indicate a gain of *Posidonia* in the subtidal area near to the intertidal area, a loss in the next area and possibly a gain in the deeper area. It should be noted here that the gain in the area near to the intertidal may be due to *Posidonia* detritus (or any other matter with a similar spectrum); also the deeper water gain in the southwest may be less reliable as the depth of the water column and the overall higher concentration of optically active attenuating substances make the assessment of substratum cover less reliable.

*Posidonia* is the major benthic macrophyte in the ACWS study area. Losses of this seagrass offshore of Bolivar have been reported from remote sensing studies covering the period 1949 to 1993 (Kinhill Metcalf and Eddy 1994; KME 1996, Kinhill 1998b, Kinhill Engineers 1998, Kinhill Metcalf and Eddy 1994) – refer to figure 4.2.

The initiatives by SAWater and United Water to reduce marine discharge flows and nutrient loads from the Bolivar WWTP do not seem to have had a pertinent effect based on these results. In order to check this result, figures 5.27 and 5.28 depict full resolution rectangles of pseudo-true colour imagery showing that indeed there is a net reduction of substratum vegetation in this area. The estimated percentage change in cover has been plotted in figure 4.2, although it should be made clear that the areas analysed in 2001 to 2003 CASI imagery do not represent a complete coverage of those analysed in aerial photography (the 16 sq. km study area considered in Chapter 4).
FIGURE 5.27 Details of substratum cover in Area A of figure 5.26 (extracts only)
FIGURE 5.28 Details of substratum cover in area B of Figure 5.26
Another method to assess changes in all 10 identified and mapped substratum type/cover occurrences is to create a radarplot as shown in Fig. 5.29 where the change in occurrence in each species as calculated by SAMBUCA for the entire Bolivar area is presented.

![Radarplot showing changes in occurrence](image)

**FIGURE 5.29** A radarplot showing the net result in change in occurrence over the entire Bolivar image for all substratum types and covers analysed

Adding up the occurrences of all ten cover types for each year results in an occurrence of up to 200% as we identify two substratum types/cover per pixel and thus twice as many occurrences as pixels are identified. The plot reads as follows: Red branching algae class had a 22% occurrence in 2001 but no occurrence in 2003; *P. australis* dark increased in occurrence from 53% to 60% in 2003. Note that a higher occurrence may result in a lower overall cover as the per pixel amount of a cover may decrease whilst the amount of pixels with any cover may increase. In both BMA Sand and the Sand no BMA class there was a net increase indicating a loss of vegetation cover.

### 5.8 CASI imagery based feature maps for the metropolitan region

The following figures (Figures 5.30 to 5.35) show the cover percentages of benthic features for the CASI coverage south of the Bolivar region. The mapped features are:

- *Posidonia* spp.
- Zosteraceae
- *Amphibolis*
- Macroalgae
- Bare sediments

The red vector on the maps indicates the high water mark, or nominal coastline. The black mask over the Outer Harbor region indicates an area where SAMBUCA interpretation was not possible or irrelevant because of the existence of the deep water shipping channel and the persistent high suspended sediment eddy feature documented later in Chapter 6.
FIGURE 5.30 Percentage cover of *Posidonia*, 2003 CASI data.
FIGURE 5.31 Percentage cover of Zosteraceae, 2003 CASI data

FIGURE 5.32 Percentage cover of Amphibolis, 2003 CASI data
Although *Amphibolis* was added at a later stage to SAMBUCA it was relatively little work to add another class to SAMBUCA. The results are very promising as *Amphibolis* was mapped using the SAMBUCA software fully objectively and came up with a seemingly correct distribution using only no groundtruth data. The results have been compared to some minimal data, in particular observations made during the 2003 field survey south of Brighton and some point data provided by SARDI for four locations off West Beach and the agreement is good (within a few metres GPS located accuracy and field observation data-surface and underwater).

Because *Amphibolis* cover represents less than 2% of total seagrass cover between Outer Harbor and Seacliff, it is barely visible in the previous figure. Accordingly a detail of *Amphibolis* cover between West Beach and Seacliff has been produced with cover classes divided into 10 percentiles. This more detailed map is shown in Figure 5.33.

![Figure 5.33](image)

**FIGURE 5.33** *Amphibolis* cover percentages between West Beach and Seacliff based upon objective interpretations of 2003 CASI data

The black line towards the eastern boundary of the figure represents the high water mark.

In this region *Amphibolis* is most abundant on firm substrates (shelly sands and cobbles). It does occur as scattered patches and narrow marginal communities along the landward edges of *Posidonia* beds. It has been described as a colonizing species in areas of high wave energy and sediment disturbance and this agrees with our observations from CASI, aerial photography over the Marino rocks area and field surveys.
FIGURE 5.34 Percentage cover of macroalgae (incl. algae on *Spirographis*), 2003 CASI data

FIGURE 5.35 Percentage cover of bare sediments, 2003 CASI data
The cover percentage statistics for the 2003 CASI study area are summarized in Table 5.4.

From this Table it can be seen that the dominant feature type (when sparse cover to dense cover are combined) is *Posidonia*. Macroalgae are overall more abundant than *Zosteraeae* (largely due to their extensive distribution on intertidal flats near Bolivar, shallow subtidal areas near Bolivar and along the Adelaide metropolitan coastline where they are associated with *Spirographis* (as epizoic organisms) and cobble reefs from Glenelg to Marino Rocks.

**TABLE 5.4** Benthic feature class cover percentages from 2003 CASI data, full coverage area

<table>
<thead>
<tr>
<th>FEATURE NAME</th>
<th>Percent cover class</th>
<th>Class area (ha)</th>
<th>Percent of total for this feature</th>
<th>Percent of total for classes in this feature compared to whole study area</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Posidonia</em></td>
<td>0-10 i.e. absent</td>
<td>6887</td>
<td>46.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11-25 very sparse</td>
<td>141</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26-50 moderately dense</td>
<td>234</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51-75 quite dense</td>
<td>625</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76-100 very dense</td>
<td>6989</td>
<td>46.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total area with sparse or greater</td>
<td>7989</td>
<td>53.62</td>
<td></td>
</tr>
<tr>
<td><em>Zosteraceae</em></td>
<td>0-10 i.e. absent</td>
<td>13538</td>
<td>90.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11-25 very sparse</td>
<td>22</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26-50 moderately dense</td>
<td>90</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51-75 quite dense</td>
<td>329</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76-100 very dense</td>
<td>912</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total area with sparse or greater</td>
<td>1353</td>
<td>9.08</td>
<td></td>
</tr>
<tr>
<td><em>Amphibolis</em></td>
<td>0-10 i.e. absent</td>
<td>14778</td>
<td>99.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11-25 very sparse</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26-50 moderately dense</td>
<td>21</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51-75 quite dense</td>
<td>32</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76-100 very dense</td>
<td>46</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total area with sparse or greater</td>
<td>102</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td><em>Macroalgae</em></td>
<td>0-10 i.e. absent</td>
<td>12994</td>
<td>87.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11-25 very sparse</td>
<td>970</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26-50 moderately dense</td>
<td>528</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51-75 quite dense</td>
<td>332</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76-100 very dense</td>
<td>31</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total area with sparse or greater</td>
<td>1861</td>
<td>12.49</td>
<td></td>
</tr>
<tr>
<td><em>Sand</em></td>
<td>0-10 i.e. absent</td>
<td>8563</td>
<td>57.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11-25 very sparse</td>
<td>804</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26-50 moderately dense</td>
<td>1372</td>
<td>9.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51-75 quite dense</td>
<td>1108</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>76-100 very dense</td>
<td>2987</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total area with sparse or greater</td>
<td>6271</td>
<td>42.09</td>
<td></td>
</tr>
</tbody>
</table>
5.9 Airborne and satellite remote sensing solutions for monitoring

This study has used historical and recent aerial photographs, supported by field measurements collected over the period 1993 to 2003 as well as airborne imaging spectrometry imagery.

It is recommended that a range of instruments and platforms and methodologies be considered for ongoing monitoring programs. Some possible systems are:

- Hyperspectral
  o CASI airborne imagery spectrometer with up to 72 discrete and tuneable spectral bands covering blue to nearby infrared wavelengths
  o HyMap airborne imaging spectrometer with fixed 15 nm wide spectral bands from the blue to the mid infrared
  o Hyperion hyperspectral satellite
- Multispectral
  o Satellites including Quickbird II, IKONOS, Landsat and Aster,
- Photography
  o Digital cameras with band pass filters e.g. the Vexcel Ultracam with red, green blue and near visible infrared sensitivity
  o Aerial photography (though problems with this medium and its limitations are discussed below.

New earth observation satellites planned for launching in the next year or two, between them covering blue to infrared bands with various spectral band sensitivities and resolutions may change this palette of options in the near future.

Consideration of the most appropriate remote sensing application will have to be done with regard to:

- Levels of spectral discrimination required for benthic and water column features
- Instrument availability:
  o Satellite overpass frequency,
  o Aircraft availability
- Spatial resolution required
- Sensitivity (radiometric resolution)
- The ability to correct imagery for atmospheric effects using objective physics based algorithms.

A cost –benefit analysis should be carried out.

5.9.1 Analogue aerial photography

Aerial photography using colour film suffers from a number of disadvantages which have been described above, but it has the advantage of being able to provide a long historical record. Until mid 2003 aerial photography in South Australia was available through the Department for Environment and Heritage. Since that time, with outsourcing aerial photography has been available only through interstate contractors, more than doubling the cost of acquisition of this imagery.

Aerial photography has the advantage of being able to acquire large area coverages in each frame – a photograph taken at 1:16,000 scale typically covers an area 4 km by 4 km and most coverages relevant to a study area like that of the ACWS require a single flight line. A disadvantage with aerial photography is that it is not practical to take photographs with more that about 60% forward overlap. The result is that inevitably there are contrast mismatches between successive frames, and the removal of these is a complex and time consuming process and if significant sun glint is involved, ideal contrast matching may not be possible.
5.9.2 Digital aerial photography

A recently developed digital airborne camera system, the Vexcel Ultracam has 14 charge coupled device sensors (CCDs), is able to acquire red, green, blue and near visible infrared imagery at very high resolution. For example from a height of 300m it can capture images with a pixel size of 5 cm, from 1000m the pixels are 15 cm. It is capable of taking one frame every second, meaning that there is a high degree of overlap between successive frames (greater than 90%), thus greatly reducing problems of frame to frame contrast and panoramic distortion. The images are photogrammetrically corrected, that is georeferenced using GPS and corrected for panoramic distortion and aircraft bank, pitch and yaw.

Some trials have recently been run in South Australia with this instrument and an example of the quality of the imagery is given in Figure 5.36. This image is a mosaic of four frames and the lack of contrast mismatches as compared to analogue aerial photography is evident. Like analogue aerial photography coverage suitable for a study area requires just one flightline.

A local company (Aerometrex) has purchased the instrument and has test flown some tens of thousands of scenes in a Cessna Citation aircraft based at Adelaide airport.

The Ultracam has the same CCDs as the Fuji S7000 digital SLR camera and the particular CCD is the only one with IEEE certification, as a result of its high spatial and spectral resolution. David Blackburn has a Fuji S7000 camera with a single CCD identical to those in the Vexcel Ultracam and expects soon to conduct trials with ground level imagery (of seagrasses, mangroves etc), with GPS fixes and taken at the same time as airborne Ultracam coverage is obtained. This should provide very detailed imagery and ground truthing data to prove the system’s accuracy and versatility.

FIGURE 5.36 Vexcel Ultracam image over Hallett Cove, January 2005.
5.9.3 Airborne hyperspectral imaging

CASI is a tried and tested system for providing high spatial and high spectral resolution imagery, allowing the derivation of quantitative data on feature types, water quality and water depths. The merits of and outputs from CASI have been discussed previously in this report. CASI has four significant disadvantages over systems like the Ultracam:

- The instrument has to be flown in from interstate and its availability is dependent upon its usage nationally and internationally, potentially leading to months of delay in being able to acquire local coverage
- It has an effective swathe width of about 1 km for 2.5 m resolution, meaning that numerous flight lines are required (40 for the ACWS Task RS 1 coverage)
- It is expensive – a result of mobilization costs and data analysis costs
- Is limited by spectral absorption of the water column for objective image analysis – but this can be overcome by subjective and feature association based analyses.

It however remains the most superior instrument for high spatial and particularly spectral resolution and provides data which can allow objective interpretation of benthic features. Objective interpretation provides not only highly discriminatory map products, but also the ability to statistically derive estimates of errors in classifications.

An alternative airborne hyperspectral instrument is HYMAP. It can provide data sets equivalent to CASI and for 28 spectral bands of 16 nm band width at fixed positions in the visible to near infrared bands. The deployment costs are in the same order of magnitude as the CASI. It also is difficult to plan missions with this instrument in Australia – it spends a great deal of time overseas.

5.9.4 Satellite multispectral and hyperspectral systems: recommendations

Satellite systems such as Quickbird II, IKONOS, Aster, and Hyperion provide multispectral data sets in between about 4 to 30 bands at spatial resolutions between 1 m and 90 m. The older satellites such as the LANDSAT series (operational since 1972) and SPOT (operational since 1986) provide data in 3 to 7 spectral bands (SPOT and LANDSAT respectively), with pixel sizes of 30 and 20 m respectively and are suited to ACWS scale mapping if 20 to 30 m pixels are sufficient for monitoring purposes. A recent publication by Dekker et al (2005), using a precursor approach to the CASI SAMBUCA work described here, demonstrates that retrospective mapping of seagrass and macro-algae species was feasible for Wallis Lake (NSW) over the period 1988 to 2002 using archived Landsat data. They demonstrated that the Posidonia beds were stable over this period, whereas the Zostera and Ruppia/Halophila classes were transient.

SeaWifs, MODIS and MERIS satellite data as used by Peter Petrusevics (ACWS Task PPM 2) have pixel sizes of about 1km by 1km and are suited to broadscale mapping of sea surface temperatures and chlorophyll and total suspended matter concentrations, but are not useful for mapping small scale benthic features.

Of the new satellite systems Quickbird II and IKONOS seems to be the most relevant to ongoing monitoring of marine and coastal ecosystems. Quickbird flies in a circumpolar orbit and has a return period of two days over any part of the world (due to its pointing capacity in space, its nominal revisit time is once every 60 days). An example coverage over the Adelaide region is shown in Figure 5.37. The pixel sizes for the source of this image is 2.5 m (4 m for IKONOS), though it has been resampled to 40 m pixels to reduce the file size for inclusion in this document. The image is a compilation of four spectral bands. Data from this satellite are available through a number of Australian and overseas companies and missions can be ordered to cover specific areas on specific dates with image quality being specified (e.g. cloud cover, sun glint, sea state conditions).

Some of the other existing systems have long lead and follow up times for data acquisition and provision. In the next few years about 5 new earth observation satellite systems are expected to be launched and start providing data sets. These developments should be watched.
For an integrated remote sensing based monitoring of the Adelaide coastal waters substratum types and covers it is advisable to:

1. Use QuickBird and or IKONOS imagery for regular (once or twice a year) monitoring.
2. Use airborne (and in future spaceborne) hyperspectral imaging once every two to five years to detect shifts in species and as an environmental baseline.
3. Enhance the spectral library to include all relevant substratum cover types and species
4. Acquire a detailed bathymetry model as input to SAMBUCA so that one variable can be constrained and thus used to search for anomalies.
5. Be clear on what information is essential and what information is non-essential.

**FIGURE 5.37** Quickbird II satellite imagery taken over the Adelaide metropolitan coastline January 16 and 18, 2004
5.10 Comparisons of CASI and aerial photography feature interpretations and field observations

This Section provides information on cross comparison between CASI, aerial photography and field observations acquired in November 2003.

Thirty five locations which were inspected during field surveys on November 2003 and March 2004 are listed in Table 5.5.

There is generally a close correspondence between feature types and covers identified from the three sets of observational and interpreted data.

Site coordinates are listed in Appendix 2. Each location was examined using a circular mask 10 m in diameter centered upon the recorded coordinates and this mask included 20 pixels at the nominal resolution of 2m by 2m resulting in some 700 pixels being critically examined for some 5 feature classes.

The root mean square (RMS) error for GPS located sites was generally about +/- 5m, given that 10 to 12 satellites were consistently acquired during the field surveys. A small area mask provides a very stringent test of the two image classification types. RMS errors due to limitation of the GPS are not the only source of positional errors e.g. drift of the survey boat while observations were made and the extent of underwater surveys (up to about 50 m from the boat) both add to positional uncertainty. Field based estimates of cover types and percentages are also subject to sea state conditions (for surface observations) and the ability of a diver to accurately estimate cover percentages in variable water depth and water clarity situations.

For practical monitoring and management of marine ecosystems a resolution of +/- 20 m may be more appropriate and the scale dependency of remote sensing and more conventional ecological surveys has been the matter of some debate in various ACWS Scientific Committee meetings.

Fewer features than those described in Appendix 2 have been used in the following table. There is variability in the discrimination of species using the different observational methods and this occurs especially when there are mixed communities and features. The main feature classes used below are those agreed to occur by the ACWS Scientific Committee as being of greatest ecological and management importance, namely:

- Posidoniaceae (Posidonia australis and P. sinuosa)
- Zosteraceae (Zostera mucronata and Z. muelleri, Heterozostera tasmanica)
- Macroalgae (species of red and green algae grouped)
- Amphibolis
- Bare sediments (i.e. with less than about 10% macrophyte cover).

In interpreting the following tables the cover percentages of all species of Posidonia should be summed, likewise for all species of Zosteraeaceae and macroalgae where they are separately mentioned in the tables. Halophila has been included with Posidonia because of its relatively limited distribution and because it proved impossible to discriminate from the remotely sensed data.

The greatest degrees of misclassifications have occurred with highly mixed features, particularly where seagrasses and macroalgae occur together. The small scale patterning of these features (patchiness on scales of a few metres) and their spectral complexity make it difficult or nearly impossible to separate individual substrate types.
### TABLE 5.5 Comparisons of remotely sensed data interpretations and field observations of substrate features

<table>
<thead>
<tr>
<th>SITE No.</th>
<th>CASI FEATURES</th>
<th>AIR PHOTO FEATURES</th>
<th>FIELD OBSERVATIONS</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ND</td>
<td>PS 100</td>
<td>PS 100</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>ND</td>
<td>PS 50, BS 50</td>
<td>PS 50</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>P 95, BS 5</td>
<td>PS 100</td>
<td>PS 100</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Z 75, M25</td>
<td>Z &amp; M 100</td>
<td>Z, HZ, U, GR, AS, BS</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Z 95, BS 5</td>
<td>Z &amp; M 100</td>
<td>Z 75, BS 25</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>P 50, BS 50</td>
<td>PA 15, BS 75</td>
<td>PA 25, BS 75</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>P 90, BS 10</td>
<td>PS 85, BS 15</td>
<td>PS 100</td>
<td></td>
</tr>
<tr>
<td>14a</td>
<td>P 90, BS 10</td>
<td>PS 90, BS 10</td>
<td>PS 90, BS 10</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>P 80, BS 20</td>
<td>PS 75, BS 25</td>
<td>PS 50, BS 50</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>BS 100</td>
<td>BS 100</td>
<td>BS &gt;90, sparse SC, SA</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>P 95, BS 5</td>
<td>PS 80, BS 20</td>
<td>PS 90-100</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>BS 100</td>
<td>BS 100</td>
<td>Outer Harbour Navigation channel - no seagrass</td>
<td>Assumed – not visible in imagery</td>
</tr>
<tr>
<td>25</td>
<td>BS 70, A 30</td>
<td>BS 50</td>
<td>All dead seagrass rhizome (south east inside of OH breakwater)</td>
<td>Anomalous ID of Amphibolis – no dead rhizome spectral were data collected</td>
</tr>
<tr>
<td>26</td>
<td>P 30, BS 60</td>
<td>PS 50, BS 50</td>
<td>PS 60, BCS 40</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>P 50, BS 50</td>
<td>PS 60 + ?</td>
<td>PS 40, A (minor), HA (v. minor), H, D, BSS (coarse&lt;10% carbonate)</td>
<td>Mixed features &amp; overinterp. of PS from aerial photo</td>
</tr>
<tr>
<td>56</td>
<td>ND</td>
<td>PS 40, BS 75</td>
<td>Uneven bottom, A (100% in patches, CY locally 20%, SC scattered, PS locally 20%, BSS &lt;10 carbonate)</td>
<td>Mixed features, Amphibolis not discriminated from Posidonia in air photos</td>
</tr>
<tr>
<td>55</td>
<td>ND</td>
<td>PS 10, R &amp; BS 80, M 10</td>
<td>Coblies with U and sparse SC</td>
<td></td>
</tr>
<tr>
<td>55a</td>
<td>ND</td>
<td>PS 70, BS 30</td>
<td>PS 50, CB/BSS 50</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>ND</td>
<td>PS 50, BS 50</td>
<td>PS &lt;20, BSS &gt;80</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>ND</td>
<td>PS 30, BS 60, MA 10</td>
<td>CB, SC patches on ridges, PS 100% cover in patches, sparse SA</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>ND</td>
<td>PS 70</td>
<td>PS 80 with some brown epiphytes</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>M 55, R 45</td>
<td>M 75, R 25</td>
<td>G on rocks (50% cover), U, BS</td>
<td>Macroalgae spp. not separated</td>
</tr>
<tr>
<td>42</td>
<td>PS 85, BS 15</td>
<td>PS 70, BS 30</td>
<td>PS 100</td>
<td></td>
</tr>
<tr>
<td>42a</td>
<td>PS 100</td>
<td>PS 100</td>
<td>PS 100, bare sand patches adjacent</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>P 95, BS 5</td>
<td>P 90</td>
<td>PS 100</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>P 65, BSS 35</td>
<td>PS 50, BS 50</td>
<td>PS 15, HA 40, BSS &gt;40</td>
<td>Halophila and Posidonia not separated in rem. sens imagery</td>
</tr>
<tr>
<td>S3</td>
<td>P 30, M 30, BS 40</td>
<td>PS 20</td>
<td>PS 20</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>P 95, BS 5</td>
<td>P 100</td>
<td>PA 50, PS 50</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>P 85, BS 15</td>
<td>P 70</td>
<td>PA 40, PS 40, BS 20</td>
<td>No spp. discrimination in airphoto</td>
</tr>
<tr>
<td>S6</td>
<td>P 100</td>
<td>PS 85, BS 15</td>
<td>PS 90</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>P 30 + ?</td>
<td>PS 35</td>
<td>PS 20, HA 1, HZ 5, sections of reef</td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>P 70, M 30</td>
<td>PS 50</td>
<td>PS 80</td>
<td></td>
</tr>
<tr>
<td>S9</td>
<td>P100</td>
<td>ND</td>
<td>PS 100</td>
<td>Air photo obscured, PS patches within 5m - 10m of site.</td>
</tr>
<tr>
<td>S10</td>
<td>P 87, M13</td>
<td>PS 50 + ?</td>
<td>PS 50 + ?</td>
<td>Macroalgae not discriminated in airphotos, or recorded in field notes.</td>
</tr>
</tbody>
</table>

**ND means that no useful remote sensing coverage was acquired for this site.**  
**BS = essentially bare sediments, mostly sands.**  
**M = macroalgae grouped.**  
**P = Posidonia species grouped.**  
**DR = dead seagrass root matte**  
**R = reef and cobble bottoms grouped.**  
**? means a feature component could not be identified or was not recorded in field notes.**
Note that decisions about whether Posidonia species mapped from aerial photography were P. sinuosa or P. australis were based upon the expected depth distributions of these species (refer to Chapter 3, Table 3.1). Where it was considered that mixed communities might have occurred the species have been grouped as Posidonia.

Posidonia cover estimates for airphoto versus CASI interpretations are plotted in Figure 5.38, with an associated regression line, $r^2$ coefficient, the F statistic and significance of F.

Under the null hypothesis that the regression coefficient of the sample populations for dependent and independent variables (e.g. cover estimates from different sampling techniques) is not significantly different from zero, then the following $r$ and $r^2$ values need to be exceeded for the probability that the variables are correlated by chance with a probability of less than 1%:

- 23 degrees of freedom (n-2), $r = 0.51$
- 32 degrees of freedom (n-2), $r = 0.42$
- 23 degrees of freedom (n-2), $r = 0.51$.

For the data sets the relevant statistics are given in Table 5.6

Estimated standard error of the means are all less than 15, meaning on average the “independent” variables are good estimators of cover within about 15%. The F statistic is highly significant in all cases. Statistical testing used the methods and tables from Sokal and Rohlf, 1981 (1) and Rohlf and Sokal, 1981 (2).

### TABLE 5.6 Regression statistics for estimated Posidonia cover percentages.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Degrees of freedom</th>
<th>$r$</th>
<th>$r^2$</th>
<th>SE (mean)</th>
<th>F statistic</th>
<th>F significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASI vs airphoto cover</td>
<td>23</td>
<td>0.94</td>
<td>0.88</td>
<td>12.6</td>
<td>174</td>
<td>3.27E-12</td>
</tr>
<tr>
<td>Airphoto vs field cover</td>
<td>32</td>
<td>0.93</td>
<td>0.87</td>
<td>14.5</td>
<td>210</td>
<td>1.28E-15</td>
</tr>
<tr>
<td>CASI vs field cover</td>
<td>23</td>
<td>0.94</td>
<td>0.89</td>
<td>13.7</td>
<td>180</td>
<td>2.38E-12</td>
</tr>
</tbody>
</table>

These statistics need to be treated with some caution as the variables (i.e. cover estimates from the different methodologies are certainly not independent). That is, each of the data sets has influenced the others by iteration. This means simply that field data and remote sensing data have been used to aid image classifications, particularly in the case of aerial photography interpretations.

To explain further: Aerial photography interpretations were based upon the rule based and expert knowledge methods described in Chapter 3. Feature map classifications were seeded by observations form field surveys and established knowledge of the distributions of species and sediments. Where there were apparent anomalies the feature classifications were locally masked and reiterated. In many cases anomalies were a result of contrast and water surface and water column differences between adjacent aerial photograph frames. The possibility of correcting these anomalies has been discussed and demonstrated in Chapter 2 (figures 2.1, 2.2 and associated text). Interpretations of CASI data have also relied upon collection of spectral characteristics of benthic features, the distributions of those features and validation of interpretations of the imagery against real world observations. No remote sensing technology or methodology can produce completely objective classifications, so the iterative process is essential to reliable classification. There is no logical circularity in this approach.

A completely independent set of classifications may have some attractiveness for statistical robustness, but realistically such an approach would be impractical – models cannot be divorced from reality and the aim has been to produce acceptably reliable map products.

Estimates of cover (with fitted regression lines) for the three methodologies are illustrated in figures 5.38 – 5.40

![Graph](image)

**Figure 5.38** CASI cover estimates vs air photo cover estimates for *Posidonia* cover
Figure 5.39  Airphoto estimates vs field observation estimates for *Posidonia* cover.

Figure 5.40  CASI estimates vs field observation estimates for *Posidonia* cover.
In conclusion the high degree of correspondence between the three data sets suggests that in combination (or even paired) they are able to produce useful and reliable classifications of benthic features with high degree of feature discrimination and spatial resolution. Only *Posidonia* has been subjected to this statistical analysis, but this is justified in that:

- *Posidonia* is the dominant macrophyte of the ACWS region of interest;
- It is strongly negatively correlated with bare subtidal sediment features, so cover of dense *Posidonia* is a good estimator of bare subtidal cover (highly negatively correlated);
- Intertidal macrophytes (Zosteraceae and macroalgae) are seasonally and spatially highly variable and are not good indicators of long term environmental impacts (both natural and anthropogenic);
- *Amphibolis* represents a small part of the total seagrass cover and has proven difficult to unambiguously identify in remotely sensed data. However the *Amphibolis* mapping results from the CASI imagery look promising, but need validation (ref Figs 5.32-5.33).

Estimates of the relative cover of *Posidonia* and bare sediment features for the RS 1 study area have been derived from interpretations of 2003 CASI and aerial photography images. Details of these are given in Chapter 3 and Chapter 5, but are summarised here.

- Dense *Posidonia* cover approx. 54% of study area (CASI), 59% (aerial photos)
- Bare sediments cover approx 37% of study area (CASI), 32% (aerial photos)

The close correspondences between these cover estimates again demonstrates that for major, relatively homogeneous feature classes both the CASI and aerial photography analytical methods can provide comparable estimates of cover.
6  Land-based impacts

Discharges from Wastewater Treatment Plants, stormwater outfalls and flows from the Port Adelaide River have been mapped using remotely sensed data sets so as to allow the characterization of patterns of land-based discharge plumes in the marine environment.

The source data sets are from aerial photography, Quickbird II satellite imagery and HYMAP and CASI hyperspectral airborne imaging spectrometers. Where possible the remotely sensed data interpretations have been verified using field surveys and water quality samples.

The intent of this study of land-based discharge plumes is to provide input for the calibration and verification of hydrodynamic models (Task PPM 2 of the Adelaide Coastal Waters Study) and to provide reference data for other tasks in the ACWS – notably Tasks IS 1 and EP 1.

Some of the plume data are quantitative (Bolivar and Glenelg). The remainders are qualitative and provide only snapshots of plume trajectories and dimensions.

In total for this report there are the following numbers of plume feature maps and images:

- Bolivar WWTP discharges 8
- Outer Harbor /Port Adelaide River discharge 5
- Port Adelaide WWTP sludge discharge 1
- River Torrens discharges 8
- Glenelg WWTP wastewater discharge 3
- Patawalonga discharges 5
- Glenelg WWTP sludge discharge 1

6.1 Bolivar Wastewater Treatment Plant discharge plumes

Bolivar Wastewater Treatment Plant discharged, until early 2002, on average about 130 ML per day of treated wastewater derived from domestic and industrial sources and stormwater infiltration to the sewerage system. Since that time average daily discharges have been about 100ML per day as a result of re-use of water for irrigation and aquifer injection.

The discharge i.e. the outflow at the last weir in the discharge channel is characterised for the period 1993 to 1998 by total dissolved solids (TDS) concentrations of about 1,300 mg/L, total Kjeldahl nitrogen (TKN) concentrations of about 40 mg/L and total chlorophyll (TChl) concentrations of about 2 mg/L. These concentrations are highly variable over time. Following WWTP upgrades in 2000, to reduce nutrient loads and increase use of wastewater for irrigation and aquifer injection purposes, the loads of TDS, TKN and TChl have decreased substantially (Total N reduction of about 30% has been achieved) – further details are available in IS 1 study reports.

A study conducted for SA Water (Kinhill 1998b) acquired water quality data between 1993 and 1994 from within the Bolivar WWTP discharge plume and at sites further distant and offshore. Aerial photography was acquired in December 1993 over the Bolivar WWTP discharge region while field studies were being conducted to collect TDS, TKN and chlorophyll data. These concomitant studies have allowed the development of a model for estimating plume dilutions using a red/green spectral model which has been correlated, with a high degree of statistical significance, to chlorophyll concentrations ($r^2 \approx 0.85$ for red/green reflectance index vs. measured chlorophyll concentrations – 9 degrees of freedom).

The general region for which Bolivar plume studies have been conducted, with an overlay of a reference calibrated plume from September 1993 is shown in Figure 6.1.
FIGURE 6.1 Bolivar WWTP discharge, tidal creeks, mangroves, intertidal flats, subtidal seagrasses and bare sediment, overlaid by a calibrated dilution plot for a 1993 discharge

Quantitative maps of plume dispersion and dilution, based upon the predictive chlorophyll “greenness/redness” model are shown below in Figure 6.2. Tidal and wind conditions are indicated on the plots. A dilution of 1 means no dilution of the wastewater, a dilution of 2 means 50% dilution by ambient seawater. In other words if the discharge salinity was 1,300 mg/L and the receiving water salinity was 35,000 mg/L a dilution of 2 results in a salinity within the plume of 16,850 mg/L i.e.35,000-((35,000-1,300)/2).

The plume trajectory and dilution field is very stable over a range of wind and tidal conditions. This is probably due to the plume being controlled by small scale intertidal topography (see Figure 6.7) and the fact that the intertidal flats are generally covered by shallow water with a maximum depth of about 1.3 m at the highest tidal levels. This results in tidal flow directions which tend to be perpendicular to the coastline.

The images shown in Figure 6.2 are from Blackburn 2001b.

FIGURE 6.2 Bolivar WWTP plume trajectories and dilutions for a range of tidal and wind conditions, based upon interpretations of chlorophyll concentrations from 1985 to 1998 aerial photography
A qualifier for the interpretations presented in figure 6.2 is that the plots may not represent in all cases, chlorophyll concentrations but almost certainly include CDOM. The 1993 plot was based upon 10 samples collected during the 1993 airphoto flight and these samples were analysed for chlorophyll, plus salinity and nitrate. A model of the ratio of green band pixel values to red band pixel values produced a plume dispersion map that resembled quite well in a subjective sense. The same green/red model was applied to other periods and the close correspondence between the plumes in figure 6.2 suggest it is not greatly sensitive to whether the coloured material is dominated by chlorophyll or CDOM – both seem conservative within the extent of the plume. What the dominant coloured components are, seems to be academic – the plume shape is remarkably consistent and it is likely that coloured components are reasonable surrogates for estimating salinity and nutrient concentrations within the plume field.

CASI and Quickbird data also show similar dispersions of coloured plumes from Bolivar.

CASI images of the Bolivar discharge for April 8 1999 and March 14, 2001 are shown in Figures 6.3 and 6.4 and November 25, 2003 CASI imagery is shown in Figure 6.6. Quickbird II imagery is shown in Figure 6.5.

FIGURE 6.3 CASI Bolivar WWTP plume image, April 8, 1999
Figure 6.4 is from Quickbird II satellite data acquired in February 2003. It reflects the persistence of a distinctive plume dispersion pattern that has been observed in aerial photography and CASI imagery, the most recent of which is from November 2003.

Figure 6.5 is from Quickbird II satellite image of the Bolivar WWTP plume, February 2003.
FIGURE 6.6  Limited plume from Bolivar WWTP, November 25, 2003, with dense seagrass and algal cover over intertidal flats (CASI data)

The November 2003 plume was not clearly visible in airborne imagery and this may be a result of several factors:

- A late onset of summer resulting in the persistence of Zosteraceae on intertidal flats, on the margins of the intertidal channel which controls plume discharges
- A late onset of summer resulting in low microalgal cell counts and therefore low chlorophyll and CDOM concentrations in the plume
- The dissolved air flotation and filtration system plant (DAFF plant) which came on-line in mid 2003, reducing nutrient and suspended solids discharges to the facultative lagoons of the Bolivar WWTP.

The dispersion of treated wastewater from the Bolivar WWTP is controlled by intertidal topography, tidal currents and wind. However the consistent patterns of dispersion shown in figures 6.2 to 6.6 suggest that topography is the main control of dispersion patterns. The general trajectory of the Bolivar plume follows a shallow intertidal channel and this is evident in Figure 6.7 which is a 3D representation of the intertidal and subtidal topography. The base imagery is from a December 1993 false colour infrared aerial photograph.

FIGURE 6.7  Bolivar WWTP plant discharge (December 1993) and 3D model of intertidal and subtidal topography. View from the north west.
6.2 Impacts of Bolivar WWTP discharges on seagrasses

Losses of seagrass beds in the Bolivar WWTP outfall region appear to be related to the patterns of wastewater plume dispersion. This may be coincidental, but there is compelling evidence that progressive seagrass loss has occurred in areas where the relatively undiluted wastewater plume reaches subtidal *Posidonia* beds and that this loss started within 12 months of the Bolivar WWTP marine discharge commencement in 1965 (KME 1986, Kinhill Metcalf and Eddy 1994, Kinhill Engineers Pty Ltd 1998, Kinhill Pty Ltd 1998b).

The discharge from Bolivar WWTP has an average salinity of about 1,300 mg/L. The discharge plume follows a consistent pattern and there are times when the dilution 1 km offshore of the discharge creek is 4 times or less. A dilution of 4 times of a 1,300 mg/L discharge into a receiving water body of salinity about 38,000 mg/L results in salinity of about 29,800 mg/L. While this may seem to be still fairly saline it is well below the range of 38,000 mg/L to 43,000 mg/L found in coastal waters in Gulf St Vincent.

Further study of the impacts of low salinity discharges is required and this will be dependent upon long term studies of the tolerance of *Posidonia* to reduced salinity. Preliminary, short time scale studies of low salinity impacts on *Posidonia* survival have been conducted by SARDI as part of Task EP 1 and these have suggested little impact upon *Posidonia*, but these studies have been inconclusive – most of the SARDI trials have been conducted over time scales of a few days to a few weeks.

The issue of long term chronic impacts of low salinity water on *Posidonia* needs to be further investigated within the scope of Task EP 1.

Losses of subtidal seagrasses have been observed in the Bolivar WWTP discharge region and two examples from 1974 and 1997 aerial photography interpretation are illustrated in Figure 6.8.

6.3 Impacts of Bolivar WWTP discharges on mangroves

There is circumstantial, but compelling evidence that the WWTP discharge has impacted indirectly upon mangrove (*Avicennia marina* var. *resinifera*) communities. There has been some 150 ha of mangrove dieback within several kilometers north and south of the discharge since the WWTP came on line in 1965. Examples of the severity of the dieback are shown in Figures 6.9 to 6.11.
Detailed studies of mangrove communities have been excluded from the ACWS, however the extensive dieback in the region from St Kilda to Chapman Creek (north of Bolivar) suggests (Kinhill, 1998, Natural Resource Services 2004) that loss of seagrasses has an impact on intertidal and coastal vegetation due to increased wave action and sediment transport (both accumulation and erosion) see Figures 6.12 and 6.13.

**FIGURE 6.9** Mangrove dieback between the Bolivar discharge location and St Kilda attributed to accumulation of seagrass detritus (foreground) smothering the pneumatophores

**FIGURE 6.10** Mangrove dieback between the Bolivar discharge location and St Kilda attributed to smothering of pneumatophores by fine, organic sediments
FIGURE 6.11 Mangrove dieback between the Bolivar discharge location and St Kilda attributed to smothering of pneumatophores by water impounded by sediment “dams”

FIGURE 6.12 Erosion of the pneumatophore zone, restricting the roots to a small crown at the base of the tree

Erosion results in a narrow crown of pneumatophores, in this case 2 m in diameter, with a canopy diameter of about 6 m. Inevitably trees affected are likely to topple during storms. A study conducted for the Corporation of the City of Salisbury (Kinhill Engineers, 1995a) investigated tidal range and sediment conditions in which mangroves occurred. The tree shown in Figure 6.12 was one of the individual trees investigated. In a revisit of this location 3 months later the tree had toppled following a storm and the foliage at least was already dead.

Such severe erosion was exacerbated by substantial waves (up to 50 cm high) and during a similar storm event in 1996 active erosion was clearly visible with as much as 2 cm per hour reduction in sediment levels within mangrove communities. An example of waves surging across shallow intertidal flats during the 1996 is given in Figure 6.13.
FIGURE 6.13  Storm generated waves (30 to 50 cm high) entering the seaward mangroves, south of the Bolivar WWTP outfall

Direct impacts of the Bolivar WWTP discharge on mangrove communities, specifically extensive dieback and sediment erosion are shown in Figure 6.14.

FIGURE 6.14  Mangrove dieback at the mouth of the Bolivar WWTP discharge creek, attributed possibly to changes in sediment sodicity

Reduced sodicity in marine organic silts can lead to a loss of soil structure, the collapse of infaunal (crab, prawn, worm, and mollusc) burrows and a reduction in available sediment oxygen (Peri Coleman, Delta Environmental Consultants, pers. comm. December 2004). Sediments so affected also become more susceptible to erosion and the erosion scarp at the mouth of the discharge creek is quite evident in this photograph.

Figure 6.15 shows a prograding shelly beach ridge smothering mangrove pneumatophores. This image has been separated from those taken near Bolivar as it is on the West side of Point Grey, the northern end of Torrens Island, adjacent to the Port Adelaide River shipping. Development of this beach ridge is attributed to waves generated by large ships sailing along the River. It is unlikely to be due to natural storm or wind-fetch related process since the fetch at this location is no more than about 1 km. However it does illustrate the importance of wave action in sediment dynamics in intertidal and shallow supratidal areas.
Normal, healthy mangroves and scenarios for mangrove dieback are summarized in Figure 6.16, in particular illustrating the effects on pneumatophores suffocation by sediments and standing water and the effects of erosion on the lateral extent of mangrove pneumatophores (Figure from Kinhill 1998).

FIGURE 6.15 Shelly, sand, beach ridge smothering mangrove pneumatophores, Point Grey, Torrens Island

FIGURE 6.16 Mangrove pneumatophore and sediment dynamics

Normal, healthy mangroves have spreading surficial root systems supplying oxygen through the aerenchyma in their spike-like pneumatophores and deeper cable root systems. Loss of pneumatophores whether through erosion or suffocation by sediments, anoxic water or organic detritus can lead to rapid death of these trees which grow in essentially anoxic sediments. Erosion and smothering in the general
region of the Bolivar WWTP discharge increased between 1965, when the wastewater treatment plant started marine discharges of wastewater, and 1993 which was the time of the latest data used in the Kinhill 1998 report. This increase in mangrove loss is circumstantially related to offshore loss of seagrasses, resulting in increased wave action and increased sediment mobility.

6.4 Outer Harbor/Port Adelaide River suspended sediment plumes

A persistent feature of the ebb tide discharge from the Port Adelaide River at Outer harbor is an anticlockwise gyre. This gyre is shown very clearly in the next set of images derived from aerial photography, Quickbird II satellite imagery and CASI data.

The persistent nature of this feature is reflected in the pattern of seagrass distributions south of and close to the Outer Harbor shipping channel breakwaters i.e. seagrasses are virtually absent from the region of influence of the plume. It is a large scale feature and so information on its persistence and trajectory may provide useful input to ACWS task PPM 2.

It has not been possible to quantify the suspended sediment concentrations in this plume as no data on TSS are available for the location and various time periods shown for this feature. If samples were taken of the plumes for the concentration specific inherent optical properties CSIRO Land and Water can estimate concentrations in the plume retrospectively on all available digital remote sensing data.

Figures 6.17, 6.18 and 6.20 illustrate the plume visible in 1970, 1983 and 2003 aerial photography. Figure 6.19 illustrates the plume visible in Quickbird II satellite imagery. Figure 6.20 illustrates the plume visible in 2003 CASI airborne hyperspectral imagery.

![Figure 6.17: Outer Harbor sediment plume visible in 1970 aerial photography](image)

Smaller gyres or eddies are quite clearly visible on the western side of the plume.
FIGURE 6.18 Outer Harbor sediment plume visible in 1983 aerial photography

Although indistinct due to low suspended sediment concentrations, this plume map is interesting in that there is apparently a “puff” of sediments offshore (near the 1983 label), probably from a previous tidal event.

FIGURE 6.19 Outer Harbor sediment plume visible in February 2003 Quickbird II satellite imagery

This image shows the fine scale complexity of the eddy patterns.
Again fine scale eddy complexities can be seen.

The absence of seagrass within the general region of the plume trajectory is particularly apparent in figure 6.21 (light blue is bare subtidal sand and dark blue is medium to dense seagrass cover). This suggests that suspended sediment loads may be correlated (though not necessarily causally related) to seagrass dieback (although the persistence of the sediment plume and bare sediments suggests causality).
6.5 Port Adelaide Wastewater Treatment Plant sludge plume

The sludge plume from this plant was visible only in 1983 aerial photography. The usual discharge was at night-time and so not visible from the air. This visible plume has been overlaid on 1999 aerial photography to show its relationship to the well documented loss of seagrass around the outfall (Figure 6.22).

FIGURE 6.22 Port Adelaide WWTP sludge discharge plume, 1983
6.6 River Torrens discharge plumes

The River Torrens discharges stormwater across the beach at Henley Beach. In all of the imagery studied (1949, 1970, 1977, 1980, 1983, 1995, 1999, 2002) the plume is narrow, has a northward trajectory and stays within, or close to the surf zone and does not disperse offshore to seagrass beds. Even in 1949 some 15 years after the Torrens was redirected to discharge to the beach, the near shore edge of seagrasses was about 400m offshore. The discernible plumes are shown below (in red) as feature maps (Figures 6.23 to 6.30) overlaid on contemporaneous aerial photography.

FIGURE 6.23 River Torrens discharge sediment plume visible in 1949 aerial photography

FIGURE 6.24 River Torrens discharge sediment plume visible in 1970 aerial photography
FIGURE 6.25 River Torrens discharge sediment plume visible in 1977 aerial photography

FIGURE 6.26 River Torrens discharge sediment plume visible in 1983 aerial photography
FIGURE 6.27 River Torrens discharge sediment plume visible in 1995 aerial photography

FIGURE 6.28 River Torrens discharge sediment plume visible in 1999 aerial photography
None of the observed plumes extended more than 200 m offshore of the high tide mark, well inshore of any seagrass beds. These observations have important consequences for understanding mechanisms of seagrass dieback.
6.7 Glenelg Wastewater Treatment Plant dye plume

The Glenelg WWTP discharges secondary treated wastewater through 2 submarine outfalls some 400m offshore of the plant. A study commissioned by SA Water in 1998 and conducted by Kinhill used Rhodamine WT dye as a tracer for characterising the dispersion of the discharged wastewater. The study report has not been completed, but the results of the dye tracing study were presented in 2001 (Blackburn, 2001 a).

Rhodamine WT was injected into the surge sumps of the two discharge pipelines. Flow proportional metered pumps were used to ensure known concentrations (12 ug/L) in each of the outflows for a period of two hours.

After 30 minutes when the dye discharge from the discharge pipelines was clearly evident, marine water samples were collected for return to a laboratory for fluorescence measurements of dye concentrations. 50 surface and 50 subsurface (1.5 m depth) samples were obtained. At the same time as water samples were being collected, oblique, airborne video from a helicopter was obtained by Channel 10 TV station. Two video frames were digitised and georeferenced using landbased structures and navigation and pipeline features – the accuracy is somewhat indeterminate because of the nature of the pitch and yaw of a helicopter, but fortunately the survey vessel was identified and its position was GPS fixed to about +/-10m.

Using the laboratory results for dye concentrations, the digitized video imagery was calibrated using a “redness/greenness” model to produce contours of dye concentrations.

The results are summarised in Figure 6.31 as contours of dye dilutions at the surface, in Figure 6.32 as dye dilutions at 1.5 m depth and in Figure 6.33 as a model of surface and subsurface dilutions at distances along the tidal and wind vectors.

FIGURE 6.31 Glenelg WWTP discharge surface dilutions estimated from Rhodamine dye concentrations and a spectral “redness/greenness” index
Wastewater dilution isopleths (equal concentration contours) shown in this figure range from 50:1 to 1000:1.

**FIGURE 6.32** Dye dilution isopleths from samples taken from 1.5 m depth

**FIGURE 6.33** Surface and subsurface (1.5 m depth) Glenelg WWTP discharge dilutions model

The buoyant wastewater plume under conditions of a neap tide (+/- 50 cm tidal elevation over 12 hours) and low wind speeds (2 m/s) was diluted by 50:1 within 100 metres of the discharge pipe and 100:1 within 200 m of the discharge pipe. The tidal and wind conditions represented a “worst case” for mixing and
dilution. Estimated dilutions at the sea floor for this experiment were approximately 3000:1 in the near-field (within 50 m of the discharge) and 5000:1 in the far-field (500 m from the discharge). Given that seagrasses even at the time of commencement of the Glenelg WWTP activated sludge plant discharge (1942) were some 600 m offshore it is unlikely that the Glenelg WWTP treated water discharge had a significant impact upon seagrass communities. The sludge discharge is a different matter.

6.8 Glenelg Wastewater Treatment Plant Sludge Plume

The sludge discharges from both Port Adelaide and Glenelg WWTPs have now ceased, but they have been implicated in causing seagrass dieback, in particular the former discharge. For operational and aesthetic reasons sludge was generally discharged at night. No aerial images of the Port Adelaide sludge discharge were found. A single photograph taken on 24th February 1985 over the Glenelg discharge shows a sludge plume with a southerly trajectory from the end of the sludge pipeline. The plume is barely visible but appears to be aligned along the axis of an area of seagrass dieback extending several kilometres to the south of the end of the pipe (see Figure 6.34).

The plume extents have been manually digitized as there are no data available for suspended sediment and coloured dissolved organic matter for the date and time of the photograph. Tide and wind conditions for the time of the photography are yet to be determined.

FIGURE 6.34 Glenelg WWTP sludge plume, Feb. 1985, with nearby areas of seagrass dieback
6.9 Patawalonga Plumes

Discharge plumes from the Patawalonga boat haven/creek are illustrated below. The feature mapped plumes are illustrated in red, showing trajectories, but do not quantify suspended sediment or coloured dissolved organic matter concentrations as no such field data were available for these parameters for the dates and times of the imagery.

These maps are very conservative. There have certainly been more significant discharge events but these have not been captured in available aerial photography except for an event on March 29, 1983.

FIGURE 6.35 Patawalonga Creek plume from 1949 aerial photography

The plume was constrained within 200m of high water mark i.e. within the surf zone.

A major stormwater event and subsequent release of water from the Patawalonga boat haven occurred in late March 1983. The low salinity, buoyant plume extended some 500 m offshore. Only one aerial photo frame was found capturing this discharge event and it is illustrated in Figure 6.36. The plume front is clearly visible due to foam and detritus being driven at the plume front. The plume extends over seagrass beds, but being buoyant it is likely to have been highly diluted at the seafloor but representing a transient reduction in seafloor illuminance due to the high concentrations of probably both CDOM and TSS.
This plume extended further offshore than that apparent in the 1949 imagery (figure 6.35), because by this time the boat haven and associated navigation channel and 300 m breakwaters had been constructed.
FIGURE 6.38 Patawalonga plume, April 2002 aerial photography

The dark greenish features north of the breakwaters are cobbles with macroalgae cover (observed by David Blackburn) and accumulations of drift organic detritus possibly from channel dredging operations in the “lee” of the breakwaters. Although the dredged spoil has generally been deposited offshore, observations of the bucket dredge in operation by David Blackburn are that considerable spillage from the bucket occurred and seagrass detritus was clearly apparent north of the end of the Patawalonga channel.

FIGURE 6.39 Patawalonga plumes combined for 1949, 1983 and 2002 airphoto data
Figures 6.35 and 6.37 to 6.39 show that in general, discharges from the Patawalonga are confined to the near shore, surf zone. The March 1983 (Figure 6.36) event is the most exceptional we have been able to find in aerial photo imagery. The frequency and duration of such events is unknown and therefore the effects upon seagrasses are also unknown. The issue of effects of extreme events is worthy of further study, but this has not been possible within the scope of the present study or with available remotely sensed data, to further investigate this.

6.10 Stormwater Drains

Stormwater drain discharges were investigated, however maps of these have not been produced as:
• They are small discharges when compared to the other land based discharges considered above
• Their peak discharges generally follow rain storms when conditions for acquiring remotely sensed data are not suitable, so there are few aerial photographs that show these discharges
• The durations of the discharges are relatively short (from a few days to perhaps a week) – unlike the major discharges
• At 2m pixel resolution they were barely visible, at the accepted working pixel size of 10 m they were invisible.
• In the limited available imagery they are consistently constrained to the littoral zone, occasionally entering the surf, but always being adverted northward within less than a couple of hundred metres of the shore.

The first three assertions are substantiated by information from Task IS 1 (Input Studies).

By comparison to long term discharges from Bolivar WWTP, the Port Adelaide River, the River Torrens and the Patawalonga stormwater discharges are probably of little significance in terms of impacts along the Adelaide coastline (though admittedly they have aesthetic and potential health and other amenity impacts). It is accepted that the assertion of their ecological impacts may be debated.

6.11 Coastal dynamics

The study of coastal sand budgets and the impacts of urbanisation of what was, prior to European settlement a coastal dune dominated coast, is essentially outside the scope of the RS 1 contract.

The Department for Environment and Heritage (through its Office of Coast and Marine) is engaged in beach rehabilitation, by carting sand to replenish metropolitan beaches. It is proposed that seabed levels have dropped along the metropolitan coastline and that indeed around Glenelg and Henley Beach there are virtually no self sustaining sandy beaches. Offshore of Glenelg and West Beach, basal calcrites and shelly estuarine clays are exposed where once there were sandy substrates thick enough to sustain seagrass communities.

This Task will not consider coastal dynamics in detail however, some historical images are presented to show the scale of development of the West Beach dunes and sand plains (which have now almost completely disappeared).

Aerial photography from 1929, 1949, 1977 and 2003 (West Beach and Grange/Tennyson regions) show dramatic changes in the development of the dunes and sand plains.
Figure 6.40  Aerial photograph taken in 1929, looking seawards towards West Beach

This image is of West Beach, 1929, photographed by Darian Smith from a DH-60 Gypsy Moth using a hand held 6" by 4" plate camera. It comes from a collection of several hundred photographs taken by him during the 1920s and 1930 covering Adelaide, the southern vales and the Barossa. The collection is held by Atkins Technicolor and is being curated and digitised by Denis Parlsow. Thanks to them for permission to use this image.

The bare sand areas show the beginnings of development in this area, with levelling of dunes. Substantial development did not commence until the 1950s. The dark rectangles on the dunes are areas that were sprayed with oil to stabilise the sand. Until the early 1960s Military Road was often blocked by drifting sands.

Figure 6.41  Aerial photograph taken in 1949 over West Beach
There had been essentially no development of the West Beach area, by 1949 even 20 years after Darian Smith took his photos.

By 1977 much of this stretch of coast was under housing (and drive-in theatre developments as can be seen in figure 6.42). By that time most of the Adelaide coastal dunes had suffered a similar fate. 1977 or thereabouts seems to be pivotal for a rapid increase in losses of seagrasses.

**Figure 6.42** Aerial photograph taken in 1977 over West Beach

The Grange to Tennyson regions have suffered similar fates. Extracts of aerial photography taken in 1949 and 1983 are shown below.

**Figure 6.43** Aerial photograph taken in 1949 over Tennyson and the old Port River reach
It is interesting that the older imagery was of exceptionally high quality, whereas with more modern technology in 1983 the resolution is quite poor because the aircraft were able to fly at much higher altitudes and cover greater areas. Fortunately things have improved since then.

Seagrass beds from Henley to Semaphore South have suffered some of the biggest losses of cover and experienced the largest seaward regressions for the metropolitan coastline. Interestingly there are no major stormwater drains or other landbased discharges in this coastal stretch, with the exception of:

- the River Torrens, the plumes of which do not appear to transport high sediment, nutrient or freshwater loads to seagrasses and
- The discontinued Port Adelaide WWTP sludge outfall which discharged some 4km offshore, far seaward of the nearshore seagrass edge.
7 Conclusions

This report presents a compilation of aerial photography, airborne hyperspectral and satellite multispectral images for the period 1949 to 2004, covering mapping of benthic biotic and abiotic features and plumes (characterised by high chlorophyll, coloured dissolved organic matter and suspended sediments) from land-based discharges.

The quantification of locations, areas and cover percentages which can be derived from the feature maps plus the data on plume dispersion and dynamics are expected to be valuable inputs for the design and calibration of other ACWS research tasks.

The methodologies and instruments used in this study potentially provide a basis for long term monitoring of the marine environment.

The spatial and temporal effects of land-based discharges and natural processes on marine biota have been considered through image analysis and field investigations.

The general conclusions and recommendations of this study are:

There are several different ecological and land-based discharge influence zones, namely the region north of Outer Harbor, Outer Harbor to Largs Bay, the region from Largs Bay to Grange, the region from Grange to Glenelg, the region from Glenelg to Seacliff and the region from Seacliff to Marino Rocks;

The nature of benthic features (defined as species composition, cover, density and spatial patterning) in each of these regions differs, both inshore (within 1 km of high the tide mark) and offshore (1 km to 4 km from the high tide mark);

Land based discharges (with the exception of the Bolivar WWTP outfall, the Port Adelaide River discharge at Outer Harbor, and the Port Adelaide WWTP and Glenelg WWTP effluent and sludge discharges) are unlikely to have had a significant impact upon seagrass decline, except for perhaps prior to the 1940s when seagrass beds grew within a couple of hundred metres from the shoreline;

The Bolivar WWTP discharges are typified by low salinity and high nutrient and chlorophyll concentrations and a near linear decline in seagrass cover occurred between 1964 and 1993 within an area of some 16 km$^2$ in the vicinity of the discharge creek and that despite major engineering works to reduce the concentrations and loads of nutrients this decline continues.

Discharges from the Port Adelaide River at Outer Harbor are typified by high suspended sediment concentrations and persistently follow an anti-clockwise gyre which reflects closely the patterns of bare sediments and seagrasses, indicating that the loss of seagrass in this region is likely to be related to high suspended solids concentrations and the subsequent reduction of light reaching the seabed.

Port Adelaide and Glenelg WWTP sludge discharges have been clearly associated with seagrass loss (Neverauskas 1984, 1987a, 1987b). This is most likely attributable to high suspended solids and nutrient loads. The patterns of seagrass loss around these now discontinued discharges reflect tidal and current advection patterns of the sludge plumes.

Storm water discharges from the Torrens River, the Patawalonga and numerous urban storm water outfalls are consistently advected northwards and are constrained within a few hundred metres of the shoreline so it is unlikely for these discharges to have had acute impacts on seagrass beds; unless the aerial photography and airborne imaging spectrometry datasets (from the 1940’s to 2003) are not representative of all conditions.

Sediment dynamics, particularly the loss of beach and subtidal sands have been considered as possible causes of seagrass loss. The changes to the Adelaide metropolitan coastline due to urban development (construction of seawalls, roads, housing) affecting the sediment budget that existed prior to European settlement on the coastal sand dune systems have been addressed by Dr Murray Townsend (DEH Office of Coasts and Marine) and the conclusion is that these changes have not contributed significantly to seagrass losses.
There are potential future alternatives for acquiring airborne and satellite imaging spectrometry to discriminate to much more detail the benthic species and assemblages per pixel than has been possible with conventional aerial photography in an inherently objective and repeatable manner. These alternatives are discussed in Section 5.9.

Now the SAMBUCA model has been parameterized for the CASI datasets available, it can be used for any other type of digital remote sensing dataset with relatively little work. Moreover, any additional fieldwork will enhance the SAMBUCA inversion accuracy. Once it is parameterized to a sufficient degree no more fieldwork is necessary for remote sensing data analyses.

The CASI data allow the calculation, pixel by pixel of abundance or cover of multiple substrate covers and therefore presents a much more detailed pixel by pixel analysis than aerial photography where detailed local expert knowledge is required to merge pixels into large groups based on *a priori* knowledge and assumptions about continuity and homogeneity.

From the 2003 CASI images it was possible to make a potential distribution map of relative presence of *Amphibolis* across the entire 160 km$^2$ area. This is a significant finding and needs to be quantitatively validated.

The advent of an increasing range of multispectral high spatial resolution satellite sensors such as IKONOS and QuickBird and experimental satellite hyperspectral sensors such as Hyperion, and studies of their applications indicate that the monitoring of the Adelaide Coastal Waters would benefit considerably from the findings of this research. The data from these sensors is easier to acquire than colour aerial photography and cheaper than airborne imaging spectrometry campaigns. In addition airborne digital camera systems should also be investigated as an alternative. For all of these remote sensing approaches, (note that the systems mentioned here are only a fraction of what will be available in five years time) availability, cost effectiveness, resolution and spectral characteristics relevant to monitoring these coastal marine environments must be determined.

A cost effective alternative to remote sensing instruments used for this study might be to use the IKONOS/QuickBird type data for regular (possibly seasonal) monitoring of gross changes and to acquire airborne imaging spectrometry data once every three to five years to discriminate more subtle changes in benthic assemblages. Operational hyperspectral satellite sensors could take over these detailed analyses if and when available.
REFERENCES


Kinhill Engineers Pty Ltd 1995a. MFP Barker Inlet Wetland mangrove accession study. Corporation of the City of Salisbury.

Kinhill Engineers Pty Ltd., 1995b. Mapping historical changes in distributions of mangroves in the vicinity of the Penrice Soda Products bitterns discharges. Penrice Soda products Pty Ltd.


Kinhill Stearns, 1985b. *Wasleys to Adelaide pipeline looping project supplementary environmental studies*. Pipelines Authority of South Australia.


KME, 1996. *Assessment of Marine Environmental effects near the Bolivar Wastewater Treatment Plant reclaimed water discharge*. Engineering and Water Supply Department, South Australia.


**Uncited bibliography**


Appendix 1 - Data from field observations of benthic features

Data sets are from November 25 to November 27, 2003 (Table A1.1) and March 9, 2004 (Table A1.2).

The data in Table A1.1 were collected specifically for the Adelaide Coastal Waters Study and these data were used to provide information for calibration of CASI data to allow for water column property corrections and identification of benthic features and their cover percentages.

The data in Table A1.2 were collected for the Coast Protection Board of DEH for the purpose of studying the effect of potential sand mining on Section Bank and are not as detailed as those data for the ACWS.

**DATA DESCRIPTORS**

Water depth measurements are provided as measured in the field (m from water surface to substrate) and with corrections to predicted tide heights based upon National Tidal Facility tide predictions using Outer Harbour, Adelaide, South Australia as the tidal level reference location. Absolute water depth references are to Indian Spring Low Water (ISLW) which is 0.15m above the lowest astronomical tide level. ISLW is 1.6 m below Mean Sea Level (MSL) which is equivalent to the Australian Height Datum (AHD).

Time Zone: Central Standard Time (CST) - corrected for daylight saving - subtract 1 hour for local time.

Coordinates are in Latitude South and Longitude East (degrees and decimal minutes and seconds) and AMG Northings and Eastings (m) for Zone 54S (UTM projection)

**Key to species and substrates**

<table>
<thead>
<tr>
<th>Code</th>
<th>Species</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA</td>
<td><em>Posidonia australis</em></td>
<td>(seagrass)</td>
</tr>
<tr>
<td>PS</td>
<td><em>Posidonia sinuosa</em></td>
<td>(seagrass)</td>
</tr>
<tr>
<td>A</td>
<td><em>Amphibolis antarctica</em></td>
<td>(seagrass)</td>
</tr>
<tr>
<td>ZM</td>
<td><em>Zostera muelleri</em></td>
<td>(seagrass)</td>
</tr>
<tr>
<td>ZU</td>
<td><em>Zostera mucronata</em></td>
<td>(seagrass)</td>
</tr>
<tr>
<td>HZ</td>
<td><em>Heterozostera tasmanica</em></td>
<td>(seagrass)</td>
</tr>
<tr>
<td>HA</td>
<td><em>Halophila australis</em></td>
<td>(seagrass)</td>
</tr>
<tr>
<td>U</td>
<td><em>Ulva lactuca</em></td>
<td>(green alga)</td>
</tr>
<tr>
<td>G</td>
<td><em>Gelidium</em> sp.</td>
<td>(red alga)</td>
</tr>
<tr>
<td>GR</td>
<td><em>Gracilaria</em> sp.</td>
<td>(red alga)</td>
</tr>
<tr>
<td>D</td>
<td><em>Dictyota</em> sp.</td>
<td>(brown alga)</td>
</tr>
<tr>
<td>H</td>
<td><em>Haliplton roseum</em></td>
<td>(red alga)</td>
</tr>
<tr>
<td>SC</td>
<td><em>Scaberia</em> sp.</td>
<td>(brown alga)</td>
</tr>
<tr>
<td>CY</td>
<td><em>Cystophora</em> sp.</td>
<td>(brown alga)</td>
</tr>
<tr>
<td>SA</td>
<td><em>Sargassum</em> sp.</td>
<td>(brown alga)</td>
</tr>
<tr>
<td>SP</td>
<td><em>Sabella (Spirographis)</em></td>
<td><em>spallanzanii</em> (polychaete worm)</td>
</tr>
<tr>
<td>AS</td>
<td><em>Ascidians</em></td>
<td></td>
</tr>
<tr>
<td>BCS</td>
<td>Bare carbonate sand &gt; 50%</td>
<td>carbonate</td>
</tr>
<tr>
<td>BSS</td>
<td>Bare silica sand &gt; 50%</td>
<td>silica</td>
</tr>
<tr>
<td>IR</td>
<td>Intertidal reef</td>
<td></td>
</tr>
<tr>
<td>SR</td>
<td>Subtidal reef</td>
<td></td>
</tr>
<tr>
<td>CB</td>
<td>Cobble reef (unaggregated</td>
<td>cobbles &gt; 20 cm in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>diameter)</td>
</tr>
</tbody>
</table>

Length and width ranges for seagrass leaf blades are provided where these data were collected. Measurements were based upon a minimum of 10 leaf blades for each species.

The tidal ranges for the November 2003 field surveys are shown in Figure 5.8. These are based upon tidal predictions from Outer Harbor and published by Transport SA (2003 Tide Tables for South Australian Ports).
The tidal data were used to correct in-field water depth measurements to a standard ISLW datum for reference to standard bathymetric charts and characterisation of typical water depth ranges for benthic biota. For water depth corrections of CASI data, the actual measured depths at the times of flights were used.

**TABLE A1.1** Field observational data from November 2003 surveys.

<table>
<thead>
<tr>
<th>Site No</th>
<th>Latitude (South)</th>
<th>Longitude (East)</th>
<th>Northing</th>
<th>Easting</th>
<th>Date</th>
<th>Time (CST)</th>
<th>Depth measured</th>
<th>Depth (ISLW)</th>
<th>Features</th>
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<td>1</td>
<td>34.38770</td>
<td>138.23956</td>
<td>6163118</td>
<td>261633</td>
<td>25/11</td>
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<td>1.9</td>
<td>-0.7</td>
<td>PS 100% (Leaves 1200mmx7mm)</td>
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<td>3</td>
<td>34.39683</td>
<td>138.22764</td>
<td>6161381</td>
<td>259855</td>
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<td>10:42</td>
<td>6.3</td>
<td>-5.9</td>
<td>PS 50% (Leaves 800mmx5mm)</td>
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<td>8</td>
<td>34.42607</td>
<td>138.25947</td>
<td>6156084</td>
<td>264169</td>
<td>25/11</td>
<td>12:15</td>
<td>3.4</td>
<td>-3.2</td>
<td>PS 100%</td>
</tr>
<tr>
<td>10</td>
<td>34.42646</td>
<td>138.27281</td>
<td>6156082</td>
<td>266894</td>
<td>25/11</td>
<td>12:25</td>
<td>2.0</td>
<td>-1.7</td>
<td>PA 50%</td>
</tr>
<tr>
<td>11</td>
<td>34.42627</td>
<td>138.28088</td>
<td>6156148</td>
<td>268125</td>
<td>25/11</td>
<td>12:45</td>
<td>2.0</td>
<td>-1.7</td>
<td>PA 50%</td>
</tr>
<tr>
<td>13</td>
<td>34.43537</td>
<td>138.28088</td>
<td>6154465</td>
<td>268168</td>
<td>25/11</td>
<td>13:15</td>
<td>2.3</td>
<td>-2.0</td>
<td>PA 50%</td>
</tr>
<tr>
<td>14</td>
<td>34.44114</td>
<td>138.27024</td>
<td>6153357</td>
<td>266571</td>
<td>25/11</td>
<td>13:50</td>
<td>4.8</td>
<td>-4.3</td>
<td>PS 100% (Leaves 500mmx6mm)</td>
</tr>
<tr>
<td>14a</td>
<td>34.44111</td>
<td>138.27050</td>
<td>6153364</td>
<td>266610</td>
<td>26/11</td>
<td>7:27</td>
<td>6</td>
<td>-3.4</td>
<td>90%, BCS - medium grain</td>
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<tr>
<td>18</td>
<td>34.46011</td>
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<td>6149843</td>
<td>266373</td>
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<td>8:55</td>
<td>8.3</td>
<td>-6.0</td>
<td>BSS</td>
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<tr>
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<td>6151039</td>
<td>266384</td>
<td>26/11</td>
<td>9:03</td>
<td>5.4</td>
<td>-3.2</td>
<td>BSS, sparse SC, SA</td>
</tr>
<tr>
<td>20</td>
<td>34.46410</td>
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<td>6149150</td>
<td>268170</td>
<td>26/11</td>
<td>9:20</td>
<td>4.3</td>
<td>-2.3</td>
<td>PS 90-100% (Leaves 600mmx5mm)</td>
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<td>138.27286</td>
<td>6147128</td>
<td>267129</td>
<td>26/11</td>
<td>9:52</td>
<td>11.5</td>
<td>-10.6</td>
<td>Outer Harbour Navigation channel - no seagrass</td>
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<tr>
<td>25</td>
<td>34.47421</td>
<td>138.28489</td>
<td>6147300</td>
<td>268960</td>
<td>26/11</td>
<td>11:05</td>
<td>3.4</td>
<td>-2.9</td>
<td>All dead seagrass rhizome (south east inside of OH breakwater)</td>
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<tr>
<td>26</td>
<td>34.48613</td>
<td>138.28838</td>
<td>6145109</td>
<td>269548</td>
<td>26/11</td>
<td>12:05</td>
<td>3.4</td>
<td>-3.2</td>
<td>PS 60% (Leaves 400mmx5mm), BCS</td>
</tr>
<tr>
<td>27</td>
<td>34.49730</td>
<td>138.28361</td>
<td>6143026</td>
<td>268873</td>
<td>26/11</td>
<td>13:20</td>
<td>5</td>
<td>-4.7</td>
<td>PS 30% (Leaves 600mm), A (minor), HA (v. minor), H, D, BSS (coarse&lt;10% carbonate)</td>
</tr>
<tr>
<td>56</td>
<td>35.02735</td>
<td>138.30352</td>
<td>6229983</td>
<td>269768</td>
<td>27/11</td>
<td>7:30</td>
<td>3.2-4.7</td>
<td>-1.2 -2.4</td>
<td>Uneven bottom, A (100% in patches, CY locally 20%, SC scattered, PS locally 20%, BSS &lt;10 carbonate</td>
</tr>
<tr>
<td>55</td>
<td>35.02500</td>
<td>138.30519</td>
<td>6119498</td>
<td>272751</td>
<td>27/11</td>
<td>8:45</td>
<td>1.9</td>
<td>-0.2</td>
<td>Cobbles with U and sparse SC</td>
</tr>
<tr>
<td>55a</td>
<td>35.02196</td>
<td>138.29656</td>
<td>6120028</td>
<td>271425</td>
<td>27/11</td>
<td>8:50</td>
<td>12</td>
<td>-10.4</td>
<td>PS 50%, CB/BSS 50%</td>
</tr>
<tr>
<td>54</td>
<td>35.01945</td>
<td>138.28772</td>
<td>6120458</td>
<td>270068</td>
<td>27/11</td>
<td>9:00</td>
<td>14.4</td>
<td>-12.9</td>
<td>PS &lt;20%, BSS</td>
</tr>
<tr>
<td>52</td>
<td>35.01326</td>
<td>138.29935</td>
<td>6121814</td>
<td>271835</td>
<td>27/11</td>
<td>9:12</td>
<td>7.5</td>
<td>-6.1</td>
<td>CB, SC patches on ridges, PS 100% cover in patches (30-50cm sediment level above bare sand), sparse SA</td>
</tr>
<tr>
<td>51</td>
<td>35.00940</td>
<td>138.30253</td>
<td>6122373</td>
<td>272274</td>
<td>27/11</td>
<td>9:25</td>
<td>4.2</td>
<td>-2.9</td>
<td>PS 80% with some brown epiphytes</td>
</tr>
<tr>
<td>48</td>
<td>34.59057</td>
<td>138.30352</td>
<td>6125858</td>
<td>272338</td>
<td>27/11</td>
<td>10:00</td>
<td>3.5</td>
<td>-2.3</td>
<td>G on rocks (50% cover), U, BSS</td>
</tr>
<tr>
<td>42</td>
<td>34.56966</td>
<td>138.29076</td>
<td>6129675</td>
<td>270299</td>
<td>27/11</td>
<td>10:50</td>
<td>4.2</td>
<td>-3.4</td>
<td>PS 100% (Leaves 500mmx6mm), bare sand patches adjacent</td>
</tr>
<tr>
<td>42a</td>
<td>34.56969</td>
<td>138.29201</td>
<td>6129674</td>
<td>270489</td>
<td>27/11</td>
<td>11:15</td>
<td>5</td>
<td>-4.4</td>
<td>PS 100% (Leaves 400mmx5mm), bare sand patches adjacent</td>
</tr>
</tbody>
</table>

*Note: Where cover percentages do not sum to 100%, the remainder is assumed to be bare sediments.*
Field sample sites, locations, water depths and descriptions of dominant features from 2004 surveys are given in Table A1.2.

**TABLE A1.2** Field observational data from March 2004 field surveys.

<table>
<thead>
<tr>
<th>Site No</th>
<th>Latitude (South)</th>
<th>Longitude (East)</th>
<th>Northing</th>
<th>Easting</th>
<th>Depth (ISLW)</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>S 34 44.283</td>
<td>E 138 27.637</td>
<td>6153069</td>
<td>267514</td>
<td>5.3</td>
<td>PS 100%</td>
</tr>
<tr>
<td>S2</td>
<td>S 34 43.845</td>
<td>E 138 27.771</td>
<td>6153884</td>
<td>267698</td>
<td>3-4</td>
<td>PS 15%, HA 40%</td>
</tr>
<tr>
<td>S3</td>
<td>S 34 43.942</td>
<td>E 138 28.289</td>
<td>6153724</td>
<td>268493</td>
<td>4</td>
<td>PS 20%</td>
</tr>
<tr>
<td>S4</td>
<td>S 34 43.811</td>
<td>E 138 28.750</td>
<td>6153984</td>
<td>269191</td>
<td>3</td>
<td>PA 50%, PS 50%</td>
</tr>
<tr>
<td>S5</td>
<td>S 34 44.185</td>
<td>E 138 29.118</td>
<td>6153307</td>
<td>269770</td>
<td>3</td>
<td>PA 40%, PS 40%</td>
</tr>
<tr>
<td>S6</td>
<td>S 34 45.738</td>
<td>E 138 28.008</td>
<td>6150393</td>
<td>268148</td>
<td>3</td>
<td>PS 90%</td>
</tr>
<tr>
<td>S7</td>
<td>S 34 45.009</td>
<td>E 138 27.657</td>
<td>6151727</td>
<td>267579</td>
<td>4-5</td>
<td>PS 20%, HA 1%, HZ 5%, sections of reef</td>
</tr>
<tr>
<td>S8</td>
<td>S 34 43.704</td>
<td>E 138 27.632</td>
<td>6154139</td>
<td>267479</td>
<td>3</td>
<td>PS 80%</td>
</tr>
<tr>
<td>S9</td>
<td>S 34 43.450</td>
<td>E 138 27.798</td>
<td>6154615</td>
<td>267721</td>
<td>3</td>
<td>PS 100%</td>
</tr>
<tr>
<td>S10</td>
<td>S 34 41.595</td>
<td>E 138 25.895</td>
<td>6157416</td>
<td>264743</td>
<td>4</td>
<td>PS 50%</td>
</tr>
<tr>
<td>S11</td>
<td>S 34 39.463</td>
<td>E 138 23.967</td>
<td>6161837</td>
<td>261682</td>
<td>4</td>
<td>PS 90%</td>
</tr>
</tbody>
</table>

*Note: Where cover percentages do not sum to 100%, the remainder is assumed to be bare sediments.*
Appendix 2 – Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHD</td>
<td>Australian Height Datum – for Gulf St Vincent closely approximates mean sea level.</td>
</tr>
<tr>
<td>Backscatterometer</td>
<td>An instrument for measuring light reflected from the seabed – see Hydroscat-6.</td>
</tr>
<tr>
<td>Benthic features</td>
<td>What occurs on the seabed e.g seagrasses, macroalgae, bare sediments (with and without surficial microalgal cover – BMA), reefs.</td>
</tr>
<tr>
<td>BMA</td>
<td>Benthic microalage such as diatoms which occur as a film on the surface of most otherwise bare sediments, especially in low energy environments where the sediment surface is not frequently disturbed by wave or tidal forces.</td>
</tr>
<tr>
<td>CAP</td>
<td>Colour aerial photography – analog red/green/blue – sometimes with visible near infrared.</td>
</tr>
<tr>
<td>CASI</td>
<td>Airborne digital spectrometer (Compact Airborne Spectrographic Imager) with 30 discrete spectral bands used in this study.</td>
</tr>
<tr>
<td>CDOM</td>
<td>Coloured dissolved, non-particulate organic matter, typically tannins from decayed plant matter.</td>
</tr>
<tr>
<td>DAFF Plant</td>
<td>A water quality improvement technology which uses dissolved or bubbled air to float solids from sewage to allow their removal by filtration – employed at the Bolivar WWTP.</td>
</tr>
<tr>
<td>DEH</td>
<td>Department for Environment and Heritage (South Australian State Government Department).</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System- A network of 25 Satellites which provide positional information for microwave receivers. A low cost receiver can acquire positional data from up to 12 satellites to determine the X,Y location of the receiver to within about 5m horizontally and the Z location to within about 2m vertically.</td>
</tr>
<tr>
<td>Gyre</td>
<td>A rotational water circulation feature.</td>
</tr>
<tr>
<td>Hydroscat-6</td>
<td>An instrument for measuring light reflected from the seabed back to the surface (uses 6 discrete spectral wavebands).</td>
</tr>
<tr>
<td>Hyperspectral data</td>
<td>Digital image data which is acquired for a large number of discrete spectral bands – for CASI 30 bands spanning the visible spectrum were used in this study.</td>
</tr>
<tr>
<td>ISLW</td>
<td>Indian Spring Low Water – typical lowest tide level based upon astronomical i.e solar and lunar tide levels – approximately 1.6 m below AHD for the Adelaide region.</td>
</tr>
<tr>
<td>Map datums</td>
<td>AMG (Australian map grid- based upon rectangular areas of the continent with scale 1 metres, WGS, AGD, GDA datums are different projections based upon world and Australian geodetic datums. Their interconversion is not trivial, but spatial software such as TntMips can make these conversions. Georeferencing data derived from topographic and orthocadastral maps needs to be converted to a common projection and datum.</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean Sea Level – equivalent to the Australian Height datum in the Adelaide region (+/- a few centimetres).</td>
</tr>
<tr>
<td>Multispectral data</td>
<td>Digital image data which is acquired for a number of discrete spectral bands. Existing satellite sensors acquire data in about 5 to 9 bands.</td>
</tr>
</tbody>
</table>
RAMSES Submersible spectroradiometer instruments.

RGB Red, green and blue bands typical of normal colour aerial photography – overlapping and without discrete spectral characteristics such as is characterised by digital hyper and multispectral data.

SAMBUCA Semi-analytical model for Benthic Unmixing, bathymetry and Concentration Assessment – a suite of computer programs for classifying CASI data after removal of atmospheric and water column effects and incorporating field and laboratory measurements of the spectral characteristics of benthic feature types.

Tripton Inorganic matter suspended in the water column – differs from the often used term “Total Suspended Solids” (TSS which includes both organic and inorganic particulates.

WWTP Wastewater Treatment Plant- a facility which treats domestic and industrial sewage using solids and nutrient removal or reduction.