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Chapter Objective:
To demonstrate the procedures involved in designing and implementing mapping and monitoring programs based on remotely-sensed data and field data in coastal and coral reef environments.

Provisional Chapter Outline:

1. Information requirements for understanding, monitoring and managing coastal and coral reef environments
2. The role of environmental indicators in monitoring and managing coastal and coral reef environments
3. Linking remotely sensed data sets to environmental indicators, the community and policy-makers.
4. Multi-temporal analysis techniques for mapping and monitoring changes in coastal environments
5. Applications of Remote Sensing in Monitoring Programs - Part 1
   Coral reef monitoring programs using remotely sensed data
6. Applications of Remote Sensing in Monitoring Programs - Part 2
   A combined field and remotely sensed program for mapping a harmful algal bloom
7. Future developments for monitoring coastal and coral reef environments using remotely sensed data

THE ROLE OF INTEGRATED INFORMATION ACQUISITION AND MANAGEMENT IN THE ANALYSIS OF COASTAL ECOSYSTEM CHANGE

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Chapter Objective:
To demonstrate how environmental indicators provide a basis for designing and implementing mapping and monitoring programs using remotely-sensed and field data for coastal and coral reef environments.

1 Information requirements for understanding, monitoring and managing coastal and coral reef environments

1.1 NATURAL RESOURCE MANAGEMENT IN COASTAL AQUATIC ECOSYSTEMS

Coastal aquatic ecosystems are often perceived as a complex and "difficult" area from a management perspective due to their dynamic nature and joint management by multiple local, state and national level government agencies. Collecting information to understand, monitor and manage these ecosystems necessitates the use of spatial information suited to the management agency / agencies (Belfiore, 2003; Treitz, 2003). The material covered in this chapter concerns the application of remote sensing technologies to coastal aquatic systems. seems repetitive . Coastal aquatic ecosystems are defined here as substrate, benthos, water column and water surface features extending from the mean-high water level to the edge of the continental shelf. This definition includes inter-tidal mangroves and saltmarsh, tidal flats, rocky shores, seagrass beds, coral reefs, organic and inorganic water column contents (seston) and water surface characteristics. As an "interface" between terrestrial, atmospheric and aquatic environments this is a highly dynamic area characterised by processes and structures that change on hourly to daily time-scales due to tidal, wind, wave and river processes.

Due to the number of human activities conducted in coastal environments, they are monitored and managed at local, to regional, national and in some cases, international levels. Common activities range from extractive resource use (fishing, tourism), recreation (boating, diving, swimming), and urban development (housing, port, industrial, commercial) to natural functions (habitat, aesthetics, shoreline stabilisation, flood reduction, nutrient sinks/sources). As a result, there is a critical requirement for information to support ecosystem management.

The objective of this chapter is to demonstrate a method for designing and implementing mapping and monitoring programs based on remotely-sensed and field data in coastal environments. This chapter complements Whitehouse and Hutt (2004 – this book), by providing a practical approach for matching remotely sensed data sets within common requirements for monitoring and managing coastal environments.

Numerous types of remote sensing approaches have been used for monitoring coastal environments around the world, mainly through a combination of field survey with aerial photography, and more recently in combination with satellite remotely sensed data (Dadouh-Guebas, 2002; Edwards, 1999a; Green et al., 1996; Joyce et al., 2002). Recent reviews outline the capabilities of remote sensing for environmental monitoring in terms of the data sets and technical approaches applicable for change analysis for terrestrial environments (Coppin, 2003; Treitz, 2003); water quality parameters; and for mapping substrate types, such as coral, seagrass and algae(Dekker et al., 2001b; Edwards, 1999b; Green et al., 1996; Green et al., 2000). This chapter will place the information contained in these reviews within context of typical requirements for managing coastal environments. With the notable exception of (Edwards, 1999a; Green et al., 1996; Green et al., 2000), there is little guidance provided to coastal resource managers on how to practically integrate remotely sensed data within existing field programs for use in monitoring and management activities.

A number of useful surveys covering practical applications or evaluations of remotely sensed data have been published recently. These are often in cooperation with field programs and provide a worthwhile overview of the capabilities of currently available remote sensing technologies (Belfiore, 2003; Dadouh-Guebas, 2002; Edwards, 1999a; Green et al., 1996; Green et al., 2000; Joyce et al., 2002; Malthus, 2003; Phinn et al., 2002a; Phinn et al., 2001b; Phinn et al., 2002b; Trinder, 2003; Wallace and Campbell, 1998). In the surveys of natural resource managers conducted by a number of these reviews, consistent responses were:

- a need for closer integration between existing monitoring programs and remotely sensed data; and
- an onus on demonstrating the effectiveness, accuracy and cost efficiency of remote sensing approaches.

1.2 THE THREE "Ms" FOR MANAGEMENT: MAPPING, MONITORING & MODELLING

A central concept presented in this chapter is that environmental management in coastal zones is part of a continuum of applications. The continuum represents a progression of knowledge necessary for environmental management, and is termed the "three-M" approach. It starts with baseline Mapping and inventory, then progresses to Monitoring and finally to Modelling a coastal environments' processes and structures (Green et al., 1996; McCloy, 1994; Phinn et al., 2003; Smith, 2001; Viles, 1995). The continuum of spatial data collection as it relates to management of coastal aquatic environments can be described as follows:

- ***Mapping*** – Provides a baseline survey or inventory to determine presence and location of features. This most basic application level provides information, at one snapshot in time
- ***Monitoring*** – A comparison of base-line maps of an environmental feature (e.g. substrate type or water depth) collected over a series of different points in time, enabling changes to be mapped and measured.

Mapping and monitoring programs provide information that is combined with scientific knowledge of environments to increase understanding of the environmental function. In some cases this can provide a measure of how different the environment is to a known "healthy" condition.

- ***Modelling*** – The highest level of spatial and non-spatial data integration is based on understanding and then replicating how an environmental system, or one of its components, operates. A model of a coastal environment (e.g. a hydrodynamic circulation model) enables parameters to be modified to determine how the system will change under certain environmental conditions. Models provide critical heuristic and planning tools for resource managers, by enabling "what if?" questions to be posed, e.g., how will key coastal environment structures and processes be altered by certain management activities?

1.3 PRINCIPLES OF ECOLOGICALLY SUSTAINABLE DEVELOPMENT (ESD) - SUSTAINABLE ECOSYSTEM MANAGEMENT AND INTEGRATED COASTAL MANAGEMENT (ICM)

The "three-M" concept for the integration of spatial data in coastal environmental management was derived from the authors' reviews of relevant literature in the field, and their experiences evaluating remote sensing solutions to natural resource management problems in Australian coastal and forest environments. In a number of the application projects discussed in this chapter, ESD and the United Nations Environment Program's pressure-state-response model have been the basis for the adoption of State of Environment reporting frameworks using environmental indicators (Belfiore, 2003; Phinn et al., 2002a; Phinn, 1998a; Phinn et al., 2000b; Trinder, 2003; Wallace and Campbell, 1998). The use of environmental indicators as a central tool for environmental management enables the explicit linkage of the "three-M" approach to remotely sensed for mapping, monitoring and modelling coastal aquatic environments.

1.4 CHAPTER OUTLINE

This chapter presents a progression of concepts and application examples to demonstrate how remotely sensed data can be integrated directly into coastal ecosystem management activities through the use of environmental indicators. The first two sections explain the concept of environmental indicators and their critical roles within coastal monitoring and management programs. The third section provides a worked example of matching suitable remotely sensed data to an environmental indicator for a coastal zone mapping application. This section uses environmental indicators as the key to specifying a component of the environment that can be mapped using remotely sensed data. Change and trend detection techniques are then reviewed, providing a logical expansion of some of the key techniques used for monitoring coastal environments from remotely sensed data. Two case studies are then used to present examples where specific coastal environmental management problems have been addressed by integrating field data, remote sensing techniques and community involvement. The applications covered in the case studies progress in scale from the entire Great Barrier Reef to a local scale harmful algal bloom in southeast Queensland. A concluding section draws attention to the need for integrating remotely sensed coastal environmental indicators within monitoring and management activities from local to national and international scales.

2 The role of environmental indicators in monitoring and managing coastal environments

2.1 ENVIRONMENTAL INDICATORS

Environmental, ecosystem or ecological indicators are variables considered to be representative of the biophysical or socio-economic status of a specific environment. Management agencies and governments from local to international levels commonly adopt the concept of ecological indicators. These are based on the Organisation for Economic Cooperation and Development's (OECD) "pressure-state-response" model, where the indicators are selected for key environmental, economic and social areas of concern (Vandermeulen, 1998). In an environmental context (Bromberg 1990, McKenzie et al. 1992, Australian and Queensland State of the Environment Reports), the indicators can be grouped into:

- ***Response Indicators***: quantify the condition of organisms, populations, communities or ecosystem processes.
- ***Exposure Indicators***: physical, chemical or biological measurements that reflect pollutant exposure, habitat degradation or other causes of poor ecosystem condition.
- ***Stressor Indicators:*** data on human activities and natural processes that can cause changes in exposure indices.

The utility of basing monitoring and management programs around ecological indicators is that agencies agree on a set variable to measure, how to measure them, and then commit to doing this over time. The net result is agreement on a set of variables that can be monitored and used to understand the current state, and short to long-term changes in an environment.

Management agencies with common environmental requirements (e.g. forest conservation? –, maintaining water storage facilities), have met at local, state, national and international levels to agree on common indicators. They then set measurement protocols and develop coordinated mapping and monitoring programs. Examples of this approach include the Montreal Protocol for Sustainable Forests, and within Australia the State of Environment Reporting framework, which is used from national to local government agencies. The definition of environmental variables to measure for each indicator at specific spatial and temporal scales provides a direct link to remotely sensed data (Phinn 1998, Wallace and Campbell 1997, Foody 2003)

2.2 ENVIRONMENTAL INDICATORS FOR COASTAL AQUATIC ECOSYSTEMS

Indicators for coastal ecosystem monitoring have received significant attention in the last ten years, mainly through the global promotion and development of Integrated Coastal Management (ICM) activities (Table 1). A comprehensive summary of coastal ecosystem health indicator development for ICM and their application for monitoring environmental condition, and human impactsis provided in a special issue of Ocean and Coastal Management (Belfiore, 2003). This journal covers key presentations given at the "The Role of Indicators in Integrated Coastal Management Conference" held in 2002. Coastal ecosystem health indicators are considered essential for tracking the implementation of ICM activities. A number of key papers in this special issue define relevant indicators for local, national and global scale coastal monitoring and management programs (Rice, 2003) and successful processes for developing and implementing indicator-based monitoring programs (Kabuta, 2003). Recent reviews have identified several hundred types of environmental indicators with relevance to coastal environments. Selecting an appropriate set of indicators for the environment, monitoring/management issue and decision maker in question, is considered a key task (Bromberg, 1990; McKenzie, 1992; Rice, 2003). The selection of indicators to use for monitoring and management applications should be based on: scientific validity; clear links to management goals; incorporation into the management process; understand-ability; time required for implementation and maintenance; and cost efficiency. The majority of indicators presented in the literature are based on data collected through field surveys, with limited use of remote sensing techniques, except in the case of mapping the extent of surface cover features (e.g. vegetation communities, weeds or algal blooms).

Table 1: Summary of the operational status (column 2) of coastal ecosystem indicators for use with remotely sensed data. Additional columns detail the remotely sensed data (column 3) required and a suitable image processing technique (column 4).

Indicator	Status of RS Estimates	Spectral Resolution	Spatial Resolution	Type of Analysis	Reference
Water Quality - Concentrations TSM/Tripton Chla CDOM	Feasible Feasible Feasible (clear/turbid)	Multispectral Hyperspectral (high, med,low)	High, medium, low	Analytic/ radiative transfer models	(Dekker et al., 2001b)
Algal blooms	Operational (clear water)	Multispectral Hyperspectral (high, med,low)	High, medium, low	Image classification Analytic/ radiative transfer models	
Toxic chemical spills	Feasible	Multispectral Hyperspectral (high, med,low)			
Depth	Feasible (clear water) Operational (clear water)	Multispectral Hyperspectral (high, med) Airborne LADS	High, medium	Analytic/ radiative transfer models Ratio of Ln transformed data	(Green et al., 2000; Stumpf, 2003)
Substrate Type Estuary	Operational (clear water)	Multispectral Hyperspectral (high, med)	High, medium	Image classification Analytic/ radiative transfer models	(Stumpf, 2003)
Substrate Type Coral Reefs	Operational (clear water)	Multispectral Hyperspectral (high, med)	High, medium	Image classification Analytic/ radiative transfer models	(Green et al., 2000; Joyce et al., in press; Palandro et al., 2003b; Palandro et al., 2003c)
Substrate type Rock platforms	Feasible (clear water)	Multispectral Hyperspectral (high)	High	Image classification Analytic/ radiative transfer models	
SAV Density	Feasible (clear water)	Multispectral Hyperspectral (high, med)	High, medium	Image classification Analytic/ radiative transfer models	(Green et al., 2000)
SAV Biomass	Feasible (clear water)	Multispectral Hyperspectral (high, med)	High, medium	Analytic/ radiative transfer models	
SAV Live/Dead	Operational (clear water)	Multispectral Hyperspectral (high)	High, medium	Image classification Analytic/ radiative transfer models	(Green et al., 2000)
Coral Live/Dead	Feasible (clear water)	Multispectral Hyperspectral (high)	High	Image classification Analytic/ radiative transfer models	(Green et al., 2000)

Image Data:
Spectral Characteristics
Multi-spectral = less than 10 broad bands
Hyperspectral = greater than 10 narrow bands
Spatial Characteristics
Low = pixel size > 250m
Medium: pixel size 20m – 250m
High: pixel size < 20m

TSM: Total (organic + inorganic) Suspended Matter concentration in the water column
CDOM: Coloured Dissolved Organic Matter in the water column
Chl *a*: Chlorophyll a concentration in the water column
SAV: Submerged Aquatic Vegetation (seagrass, micro/macro-algae, coral)
RS: remote sensing
A number of local, national and international monitoring and management programs have built successful monitoring and management programs for coastal environments around sets of select indicators. The following list represents recognised coastal ecosystem status indicators and an established monitoring and management program using that indicator:
- Water quality parameters – Moreton Bay Ecological Health and Monitoring Program (Dennison and Abal, 1999) ; (- Algal bloom characteristics – Moreton Bay Lyngbya Task force (Roelfsema et al., 2001);
- Seagrass and benthic substrate community attributes – NOAA-Coastwatch; and
- Coral reef attributes – Great Barrier Reef Marine Park Authority, Global Coral Reef Monitoring Network (Wilkinson, 2000).

2.3 LINKS BETWEEN ENVIRONMENTAL INDICATORS & REMOTE SENSING

Environmental indicators provide one of most useful links from environmental monitoring and management programs to remotely sensed data. The utility of the indicators is that they define a set environmental parameter to be mapped, at a specific spatial scale, and usually over a set time period. This information provides a basis for selecting suitable remotely sensed data sets and processing techniques to deliver map(s) of the requested environmental indicator (Foody, 2003; Phinn, 1998a). The framework proposed by (Phinn, 1998a) and refined to (Phinn et al., 2003; Phinn et al., 2000b) provides a basis for making the link between environmental indicators and suitable remotely sensed data and techniques for processing remotely sensed data. The framework is outlined in detail in the next section and defines the process used in other studies linking environmental indicators to remotely sensed data (Foody, 2003; Green et al., 2000; Trinder, 2003; Wallace and Campbell, 1998) .

3 Linking remotely sensed data sets to environmental indicators, the community and policy-makers

3.1 A FRAMEWORK FOR LINKING ENVIRONMENTAL INDICATORS TO REMOTELY SENSED DATA

The framework described in Parts 1 – 2 below provides a guide to evaluating commercially availableremotely sensed data sets for mapping or monitoring selected environmental indicators. Originally this approach was developed for use in coastal wetlands (Phinn, 1998a), then modified for tropical wetlands and tropical rainforest environments (Phinn et al., 2002a; Phinn et al., 2001b; Phinn et al., 2000b). The key to this approach is linking the spatial and temporal scale(s) of data and information required to remotely sensed data with corresponding dimensions. Explicit consideration is also given to the full costs of processing image data to a map product in terms of necessary hardware, software, ancillary data and skilled personnel. A worked example is provided in Tables 2-5 for monitoring one selected indicator of costal ecosystem health, the extent of seagrass beds in Moreton Bay, Queensland, Australia (Phinn et al., 2001b). Implementation of the framework requires initial specifications of: the indicator to map/monitor, the area to cover and timeframe; available financial; and image processing capability. The framework is then used to select a suitable image data set and to evaluate the cost of various image-processing strategies.

Part 1. Identification of Remotely Sensed Data Sources and Image Processing Operations

This is an inventory stage in the framework, relying on past published work. A comprehensive summary is provided elsewhere for currently available airborne and satellite image data sets suitable for use in coastal aquatic environments (Phinn et al., 2002a; Phinn et al., 2003; Phinn et al., 2000b). These references provide details in a table for each type of commercially available passive and active image data set in terms of:

- the area covered in one image;
- the size of the smallest ground feature able to be mapped;

the type of measurement used to produce the image, e.g., active or passive, and the type of light measured;

- how often the images are collected over the wet tropics; and
- where to obtain the data from and its costs.

The processing methods used to convert airborne and satellite images to maps of relevant environmental indicators (e.g. seagrass extent) are then reviewed in a separate table (Phinn et al., 2001b)., The results of the review will explain type of input data required, their processing assumptions and the forms/reliability of output maps. For reasons of brevity, examples of the tables listing all the remotely sensed data types were not included in the text and the reader is referred to (Phinn et al., 2000a; Phinn et al., 2001b; Phinn, 1998b; Phinn et al., 2000b).

Part 2. Evaluation of Remotely Sensed Data and Processing Approaches for Indicator Monitoring

Each indicator (e.g. seagrass extent) is directly compared to relevant remotely sensed data sets and processing approaches listed in Part 1 to determine the suitability of remotely sensed solutions for monitoring an indicator (i.e., Operational, Feasible, Likely/possible or Unlikely/ impossible).

To arrive at a direct link between the specified indicator(s) and suitable remote sensing data and processing approaches, a three-stage procedure is implemented. At the completion of this procedure, *a clear link is established between each indicator and the remotely sensed data set that could be used for its measurement* (e.g. Table 1). This linkage will include specifications of the most appropriate remotely sensed data, image processing techniques, required personnel, hardware and software to complete the task. An estimated cost of mapping, verification and monitoring for the indicator can be provided for each potentially suitable data type. A final assessment is then able to bemade for each data type and processing operation in terms of its "feasibility" for operational monitoring of select indicators.

The first stage of this process involves determining a direct link between environmental variables that could be mapped, measured and monitored from remotely sensed data, and relevant environmental indicators (Tables 2 and 3). If an indicator can not be matched with a remotely sensed variable or surrogate it is removed from the evaluation process and considered to be in the "Impossible" category. An extensive review of past and current remote sensing applications in coastal environments should be used as a basis for this evaluation (e.g. (Dadouh-Guebas, 2002; Dekker et al., 2001b; Edwards, 1999a; Malthus, 2003). This information is then condensed into Table 3, where the level of match betweenindicators and remotely sensed variable is identified. For example, processing of airborne or satellite image data sets to produce benthic cover maps provides the information required to assess several indicators.

The next stage is to link "appropriate" remotely sensed data sets to each remotely sensed variable. This is achieved in Table 4 by taking all of the commercially available remotely sensed data types and identifying the remotely sensed variable(s) they had been used to derive. Next, the most "appropriate" remotely sensed data set(s) for deriving remotely sensed variables linked to an associated indicator are identified (Table 5).

The final stage specifies the resources required to map and monitor indicators from the most appropriate form of remotely sensed data and image-derived variables. A direct assessment of the feasibility and costs of selected indicators derived through remote sensing is provided. Table 5 contains an example of the results of the assessment. The format of each table first specifies the relevant remotely sensed variable and its spatial and temporal dimensions. The most appropriate data sets selected for each remotely sensed variable are then added, along with their dimensions and a listing of:

- Processing technique(s) required to convert remotely sensed data to the relevant environmental variable and indicator;
- Resources – includes specifications (and costs estimates) for the necessary data, hardware and software systems required to complete the processing of remotely sensed data to map or monitor the to the relevant environmental variable and indicator; and
- Personnel – identifies the type and level of skills required (along with time to complete the task) from staff completing the processing of remotely sensed data to map or monitor the to the relevant environmental variable and indicator

The final table (e.g. Table 5) provides a complete assessment of the types of remotely sensed data suited to monitoring a coastal environmental indicator - seagrass extent in this context - and its accompanying resource requirements. As several remotely sensed data types are often considered at this stage, the summary table provides an effective comparison between the cost:benefit of each data set/approach. In theory, this provides the basis for selecting a suitable type of remotely senses data.

Figure 1: Conceptual framework for integrating remote sensing with environmental monitoring programs.

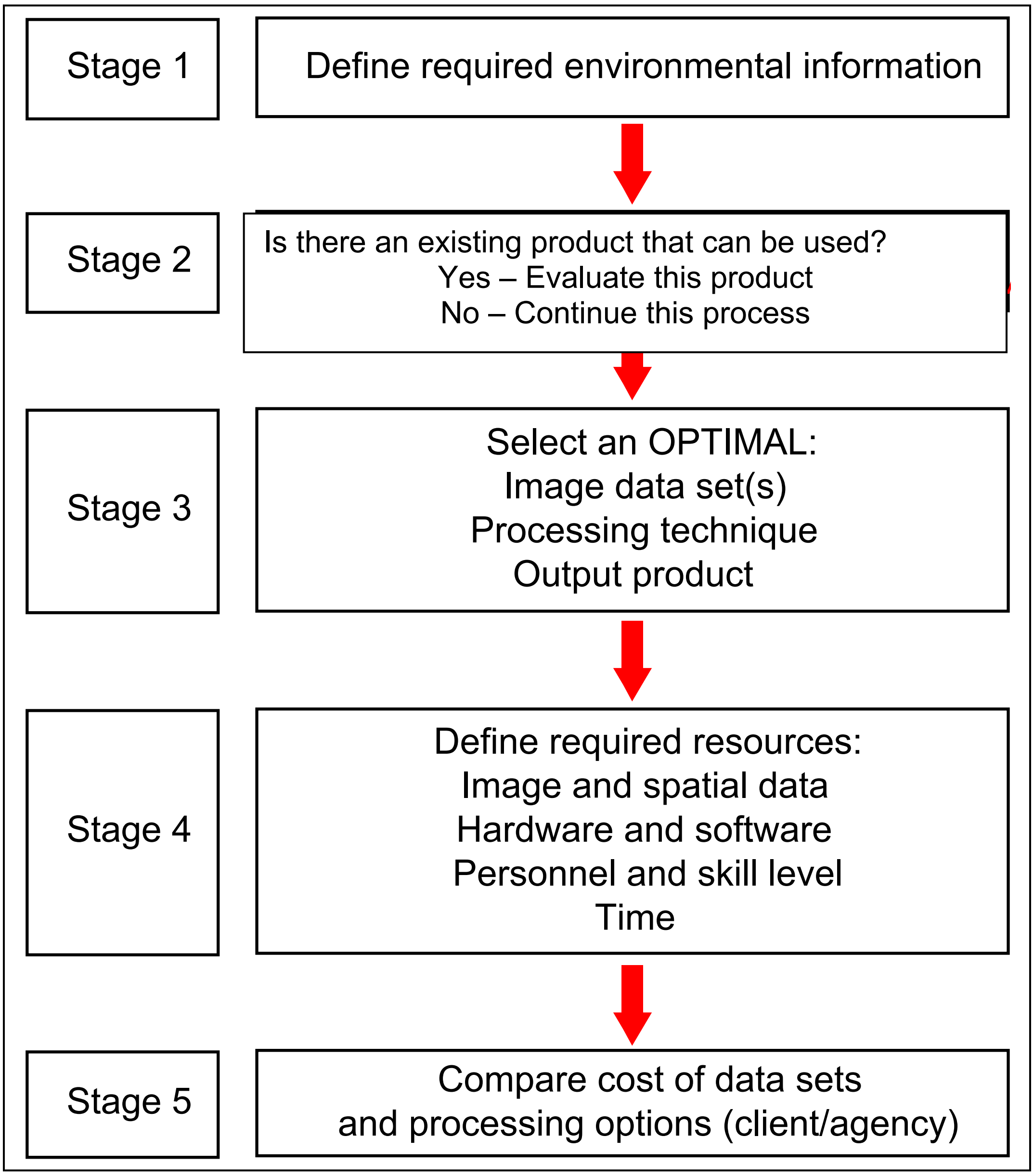


Table 2. Example evaluation matrix for the Moreton Bay indicator – sea grass extent and links to environmental variables that can be measured using remote sensing data and spatial-image analysis techniques.

Indicator ***Surrogate***	**Spatial Scale** **Extent Min.Map Unit**	**Temporal Scale** **Frequency** **Time of Year**	**Remotely Sensed Variable**
Extent of segrass beds	Moreton Bay – 30 x 60km (1000's km^2) < 1ha	Annual e.g. by June for August delivery or event driven	Land/benthic-cover

Table 3. Listing of remotely sensed variables and the indicators they can be used to measure for coastal aquatic ecosystems**.**

Remotely Sensed Variable	**Indicator**
Inherent Optical Properties	Water Quality - Concentrations TSM/Tripton Chla CDOM
Water Surface Characteristics	Algal blooms
Depth	Depth
Substrate Cover Type (benthos)	Substrate Type Estuary Coral Reefs Rock platforms
Image based indices	SAV Density Biomass Live/Dead Coral Live/Dead

Table 4. Assessment of remotely sensed data sets suitability against the spatial, spectral and temporal scales that are linked to selected environmental indicators. The spatial scale section of column has two scales, 1) regional – the extents of Moreton Bay (100 km^2-3000km^2); and 2) local (<100 km^2).

Data Type Sensor (platform)	**Spatial Scale Extent**	**Spatial Scale Min.Map Unit**	**Spectral Scale**	**Temporal Scale Frequency**	**Remotely sensed variable**
Field spectrometers	Site specific	Site specific	Very High	User defined	- Veg. Type - Structure/ Biomass Index
Aerial photographs	Local - Regional	Local - Regional	Low	User defined Cloud restricted	- Land-cover - Land-cover change - Veg. type - Structure - Stanton and Stanton veg. maps
Airborne multi-spectral	Local - Regional	Local - Regional	Moderate - High	User defined Cloud restricted	- Land-cover - Land-cover change - Veg. Type - Veg.Index - Soil Index -Structure/ Biomass Index
Airborne Hyperspectral	Local - Regional	Local - Regional	Very High	User defined Cloud restricted	- Land-cover - Land-cover change - Veg. Type - Veg. Index - Soil Index -Structure/ Biomass Index
Satellite multispectral					
Ikonos (Space-Imaging) Quickbird (Earthwatch)	Local - Regional	Local - Regional	Low	At least 5 days Cloud restricted	- Land-cover - Land-cover change - Veg. Type - Veg. Index - Soil Index -Structure/ Biomass Index
Landsat ETM Landsat TM SPOT XS IRS	Regional	Regional	Moderate	At least 5 days Cloud restricted	As above
SPOT VMI NOAA AVHRR	Regional	Regional	Low	Daily	- Land-cover

				Cloud Restricted	- Land-cover change - Veg. Index - Soil Index - Biomass Index
Satellite hyperspectral MODIS (EOS-AM)	Regional	Regional	High	Daily Cloud Restricted	- Land-cover - Land-cover change - Veg. Index - Soil Index - Biomass Index
Field laser ranging	Site specific	Site specific	N/A	User defined	-Biomass / Structure index
Airborne laser altimeters	Local - Regional	Local - Regional	N/A	User defined	-Biomass / Structure index
Satellite SAR	Regional	Regional-	Low	Minimum of 5 days No cloud or smoke restrictions	- Land-cover - Land-cover change - Veg. Type -Structure/ Biomass Index

Table 5. The remotely sensed variable VEGETATION TYPE (applies to coastal indicators: Substrate Type - Estuary, Coral Reefs, and Rock platforms) and the listing of data types, processing requirements and costs for mapping and monitoring this variable using several suitable types of remotely sensed data. MMU: Minimum mapping unit; GRE: Ground resolution element

VEGETATION TYPE	**Indicator attributes**	**Data type #1** Landsat ETM	**Data type #2** Airborne Hyperspectral	**Data type #3** Aerial Photographs
Spatial Scale **Extent** **MMU/GRE**	Moreton Bay – 30 x 60km (1000's km^2) < 1ha	 185km x 185km per scene 15m panchromatic 30m multi-spectral 60m thermal	 Up to $100km^2$ 0.5 – 10m	 1.3 – $33km^2$ 5m – 250m
Temporal	Annual e.g. by June for August delivery or event driven	Approx 9.45am every 16 days	User controlled (subject to weather and aircraft availability)	User controlled (subject to weather and aircraft availability)
Variable	Land/benthic-cover	Reflectance in up to 7 spectral bands	Reflectance in up to 126 spectral bands	Contact prints (23cm x 23cm) requiring scanning and ortho-correction to produce a digital mosaic
Processing technique **(Output)**		Image classification or feature detection (Vegetation type map and target features) Note: The ability to map specific targets will depend on their growth form and extent.	Image classification or (hyperspectral) feature detection (Vegetation type map and target features) Note: The ability to map specific targets will depend on their growth form and extent.	Manual delineation of SAV types either on hard-copy photographs or on-screen digitizing. (Vegetation type map)
Resource – Equipment		PC Image processing software GIS with image classification module (e.g. Arc-View Image	PC Image processing software capable of hyperspectral data processing.	PC A3 size or larger Scanner Softcopy photogrammetry software

		Analyst)		Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)
Resource – Personnel		Trained in image classification Experience with Landsat data Knowledge of area to be mapped	Trained in image classification and spectral unmixing or matching. Experience with Hyperspectral data Knowledge of area to be mapped	Training in softcopy photogrammetry and image processing. Extensive knowledge of area to be mapped
Estimated task and times		Image pre-processing (1 day) Image classification to SAV Types (15 days per scene) Field/Photo verification for a select number of sample sites: (8 days) Map output production: (2 days) Total = 26 days per scene	Note: This estimate is for a 10km x 10km area Image pre-processing (2 days) Image analysis using classification, un-mixing or matching to define SAV Types: (8 days per area) Field/Photo verification for a select number of sample sites: (3 days) Map output production: (1 days) Total = 14 days per 10km x 10km scene	Note: This estimate is for a 20km x 20km area (10 x 10 photos) Aerial Photograph Scanning (1 day) Digital photographs ortho-correction (5 days) Photograph interpretation and digitizing boundaries (25 days) Build and clean up vegetation type layer Map output production: (2 days) Total = 33 days per 20km x 20km scene
Estimated Cost Note that these are estimates are flexible		Data acquisition: Image data = $1950 Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources	Data acquisition: Image data = $15000 Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources	Data acquisition: Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources = $9000 Ancillary data (topographic map

		Ancillary data (topo sheets)= $200 Processing = 28 days of technical officer @ $150/day = $4200 Total = $7250 Note: This assumes software have been purchased	Ancillary data (topo sheets)= $200 Processing = 14 days of technical officer @ $150/day = $1700 Total = $16900 Note: This assumes software have been purchased	sheets)= $200 Processing = 33 days of technical officer @ $150/day = $4950 Total = $14150 Note: This assumes software have been purchased
Evaluation Result		**Operational**	**Feasible**	**Operational**

3.2 PRESENTING REMOTELY SENSED DATA & DERIVED INFORMATION FOR USE BY POLICY MAKERS AND STAKEHOLDERS

A final consideration is how to present the derived spatial information on the state of selected coastal environmental indicators to decision makers and interested stakeholders. This is a critical consideration and will determine if, and how well the data from a monitoring program are used.

In some cases, the management agency conducting the monitoring may have established reporting mechanisms through formal publications, (e.g. a newsletter series, and monthly or annual reports), or through on-line static websites or interactive internet map servers for delivering various themes of spatial data for an area. The main types of communication products to consider include:

- publications in hardcopy books, reports, newsletters and handouts;
- softcopy static information (e.g. PDF files of reports, newsletters and handouts);
- softcopy interactive information (e.g. internet map servers for delivery of spatial data on digital base maps) for spatial and tabular data
- communications with print (newspaper) and electronic (television and radio) media through press release to draw attention to hard or softcopy publications; and
- posters for public and educational use.

An example communication strategy is provided below to indicate how the results from an on-going coastal waterway monitoring program were presented to decision-makers and the public. The Moreton Bay Healthy Waterways Catchment Partnership (MBHWCP) is responsible for monitoring water quality in Moreton Bay, Queensland Australia. MBHWCP is funded by the 17 local councils with catchments draining into Moreton Bay, and coordinates the Ecological Health and Monitoring Program (EHMP). The EHMP monitors water quality parameters in Moreton Bay and its tributaries on a monthly-annual basis. The communication products used by this program include:

- Quarterly text and graphic reports with maps of key water quality parameters and explanatory text;
- Annual reports presented in a "report card format" where each river and section of the Bay is given a rating from A to D (good – bad), and an indication of improving, stable or decreasing water quality;
- Web-based access to all reports as PDF files at www.healthywaterways.org

4 Multi-temporal analysis techniques for mapping and monitoring changes in coastal and coral reef environments

Effective management and monitoring of coastal environments requires an integrative approach for selecting remotely sensed data to monitor changes to meet the requirements of management agencies as demonstrated in earlier sections of this chapter (Phinn et al., 2001a). The ability of agencies to effect their monitoring requirements is dependant on the availability of timely, accurate and comprehensive information on the type, distribution and rate of change (Phinn et al., 2000a). Remotely sensed data is particularly suitable in change detection applications, as it is relatively cost effective (Mumby et al., 1999) and can provide repeated, non-intrusive sampling over large coastal areas (Green et al., 1996). Remotely sensed data has been used in coastal and aquatic environments to study reef geography and reef form, (Kuchler et al., 1986), assess water quality and benthic and inter-tidal flora (Phinn et al., 2001a) and mapping of littoral and shallow marine habitats, bathymetry and suspended sediment plumes and coastal currents (Dekker et al., 2001a; Dekker et al., 2001b; Dekker and Seyhan, 1988; Green et al., 1996). However, the successful monitoring of change and environmental processes requires significant additional analysis over these "one-off" products (Coppin, 2003; Jensen, 1996b; Treitz, 2003). This section outlines the types of change able to be detected from remotely sensed data, the image pre-processing requirements and change and trend detection techniques required for operational change detection and the presentation of change detection results for managers, agencies and stakeholders.

4.1 TYPES OF ENVIRONMENTAL CHANGE AND PROCESSES ABLE TO BE DETECTED FROM REMOTELY SENSED DATA FOR COASTAL ECOSYSTEMS

The changes and processes that can be distinguished using remotely sensed data can be loosely classified into coastal landcover, water quality and substrate/benthos composition. The following sections outline selected previous work in these ecosystems.

Coastal Landcover

Studies of coastal landcover change have primarily used the Landsat series of sensors. Landsat data provides a synoptic view of landscape processes at a regional scale, however more detailed mapping can be achieved with high spatial resolution airborne and satellite sensors (Phinn et al., 2000a). Multi-temporal post-classification studies using both the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) sensors to detect coastal landscape changes in the Majahual system, along the Mexican Pacific were conducted by Ruiz Luna and Berlanga Robles (1999). They classified change in six land-use classes (mangrove, lagoon, saltmarsh, dry forest, secondary succession, and agriculture) initially using four (Ruiz Luna and Berlanga Robles, 1999) and later six scenes (Berlanga Robles and Ruiz Luna, 2002) to evaluate trends of changes between the classes. Other examples of mangrove mapping include work by Hill, Kelly et al. (1994), who used SPOT to classify mangrove change in the Ba River Delta, Fiji. Jinnahtul Islam et al. (1997) used ancillary data to enhance their change detection of mangrove forest of the Sunderbans region of Bangladesh over a 54 year period using interpreted aerial photography. More specialised work by Trepanier, Dubois *et al.* (2002) used SPOT images to determining the accumulation-erosion budget for a 14 km portion of coastline in Vietnam.

Water Quality

Mapping change in water quality relies on the development of a predictive model relating the water quality variable of interest to the radiance received by the sensor. Early work in this area was completed in the Loosdrecht Lakes in The Netherlands by Dekker and Seyhan (1988), who used qualitative and quantitative assessment of satellite (Landsat TM, SPOT) and airborne (CAESAR-MSS and low-altitude aerial colour photography) remote sensing data to detect and study the temporal and spatial variations in water quality. Further work by Lathrop, Lillesand *et al.* (1991) investigated multi-date water-quality calibration algorithms for turbid inland water conditions using Landsat TM in Green Bay, Lake Michigan to estimate absolute values and change in total suspended solids and Secchi depth. Similar work in Egyptian lagoons using Landsat TM and locally calibrated regression models by Dewidar and Khedr (2001) have also been successful. Multitemporal classification approaches have also been found successful in detecting water quality change. Work by Pal and Mohanty (2002), using IRS-1B data from the Chilka Lagoon, East Coast of India, was successful in predicting selected water quality parameters and lagoon modification over an inter-annual cycle. However, the importance of accurate image calibration was demonstrated in work by Islam Md, Gao *et al.* (2003) in Moreton Bay, Brisbane, Australia. Their estimates of total suspended sediment and Secchi depth, based on empirical models derived from a Landsat TM reference image were found to differ by 35-152% when applied to different images. They concluded that image calibration to like-values could be used to reliably map certain water quality parameters from multitemporal TM images, as long as the water type under study remains unchanged. To avoid the problem of multiple calibrations, more recent semi-analytical and analytic models that account for bottom depth have been developed (Brando and Dekker, 2003). Some, like the model of Lee, Carder *et al.* (2001) have been used to derive accurate estimates of chlorophyll, dissolved organic matter, and suspended sediments concentrations, but they rely on the availability of calibrated hyperspectral imagery. To date, this has been difficult to obtain for multi-temporal studies at regional scales. More recent work by (Dekker et al., 2001b; Phinn, 2003) has addressed imitations of empirical approaches (Islam Md et al., 2003) , and used atmospheric and air-water interface corrected multi-date Landsat ETM data with field measured optical properties to estimate organic and suspended matter concentrations.

Substrate Composition

The measurement of substrate composition and benthic cover is complicated by the spatial variations of water depth and water quality. These variations prevent the normalisation of image data required for accurate mapping, estimation of biophysical properties and change detection (Phinn et al., 2000c). In this sense, the classification of substrate composition, water depth and the measurement of water quality parameters are explicably linked (Lee et al., 2001). In a desktop study using a radiative transfer code to simulate the effect of water column effects, Holden and LeDrew (2002), noted that the classification accuracy of benthic habitat type increased significantly when the effects of the water column were removed. Image based studies confirmed the importance of including depth effects (Mumby et al., 1998).The availability of radiative transfer equations has allowed the development of classification approaches based on simulated spectra derived at different depths (Louchard et al., 2003). Use of a radiative transfer approach allows the retrieval of the seafloor reflectance, which can then be used to classify the benthos or derive biophysical indicators of ecosystem health, such as the leaf area index of seagrasses (Dierssen et al., 2003). However, supervised and unsupervised classification approaches have been successful in mapping benthos at various spatial and temporal scales. Landsat TM and ETM+ have proved valuable for mapping reef characteristics, including morphological and ecological zonation and cover types (Neil et al., 2000) and for mapping change in coral, sand and algae cover (Palandro et al., 2001).

Historically, interpreted aerial photography has been used for fine scale mapping of change in coral reef communities, with this being supplemented in recent years by the advent of higher spatial resolution satellite sensors such as IKONOS and QuickBird (Palandro et al., 2003a). Mapping using these sensors can be quite accurate, with accuracies of 89% reported in a study to map sand, coral reef and seagrass features (Maeder, Narumalani *et al.* (2002). However, substrate mapping, particularly in coral reef ecosystems, is complicated by geometry and scale of reef feature variation, especially in relation to the vertical orientation and location of photosynthetic and productive components (Phinn et al., 2000c), and the spectral resolution requirements of sensor systems (Hochberg and Atkinson, 2003).

4.2 IMAGE PRE-PROCESSING REQUIREMENTS FOR CHANGE AND TREND DETECTION IN COASTAL ECOSYSTEMS

Change and trend detection in coastal ecosystems requires rigorous image pre-processing to ensure that the variable of interest is detected with sufficient signal to noise ratio. At a minimum, multi-temporal analysis requires sub-pixel precision georeferencing, atmospheric correction, multi-date normalization, and ground-truthing for accuracy assessment (Palandro et al., 2001). These processes need to be explicitly considered within the framework used to select the remotely sensed data for the specific monitoring requirement (Phinn, 1998b).

There has been little research on the effects of image mis-registration in aquatic environments on change detection accuracy; although research in terrestrial regions has found that significant and serious classification errors can be induced by a mis-registration of only one pixel. (Phinn and Rowland, 2001; Townshend et al., 1992). These registration errors will become increasingly significant in the move towards higher spatial resolution imagery.

Correction of atmospheric effects is dependant on the analytical methods used in the change analysis. In many cases involving classification and change detection, atmospheric correction is unnecessary, as long as the training data and the data to be classified are in the same relative scale. Atmospheric correction is often unnecessary when using atmospherically resistant indices developed for the application of interest (Jensen, 1996b). Often atmospheric correction alone will not be adequate in images of aquatic environments due to whitecaps and/or sun glint, with the corrected images requiring additional empirical adjustment. Therefore, there is often no substantial benefit in performing an atmospheric correction compared to an empirical correction alone (Andrefouet et al., 2001; Collins and Woodcock, 1996).

However, when the processing is to derive change using semi-analytical modelling, corrections to a common radiometric scale are essential. (Song et al., 2001). Multi-date normalisation is used to minimise radiometric differences among images caused by changes in acquisition conditions, and require the use of reference and subject image pairs along with selected sample points. Normalisation methods include image regression, pseudo-invariant features, histogram matching, radiometric control set and no-change set determined from scattergrams (Tokola et al., 1999). Yang and Lo (2000) found that normalisation methods that used a large number of samples exhibited a better overall performance, but reduced the dynamic range and coefficient of variation of the images and therefore reduced the accuracy of image classification.

4.3 CHANGE AND TREND DETECTION TECHNIQUES

The information requirements of the project and the environment of interest guide the choice of change or trend detection technique. No single change detection technique is suitable for the myriad of monitoring applications, with the various methods often giving differing map accuracy (Rogan et al., 2002). Change detection methods include direct image differencing, spectral index differencing, linear change enhancement techniques (eg. selective principal components analysis not sure if this is where the bracket should be closing), direct multi-date unsupervised classification, post-classification change differencing and decision tree analysis (Coppin and Bauer, 1996; Mas, 1999). Typically, these techniques are applied to imagery collected at two dates, with the differencing and linear change enhancement techniques resulting in a continuous map product that is subsequently thresholded to provide change classes. The classification approaches are either applied individually to each image; where the change can then be classed as change from one cover type one to another, or to the entire image stack. In this case, the output classification will need careful interpretation to develop reliable change classes (Jensen, 1996b). Trend detection methods typically involve the analysis of absolute values of some variable such as a vegetation index or chlorophyll or TSS concentration, and rely on a form of per-pixel time-series analysis through fitting of polynomial functions, Fourier or wavelet analysis (Coppin, 2003; Li and Kafatos, 2000; Ruiz Luna and Berlanga Robles, 1999). These deterministic trend detection models are advantageous, since they can be applied in the same way to a variety of similar trend detection situations, resulting in standardised reporting of the trend in the indicator of interest in different regions.

4.4 PRESENTATION OF CHANGE AND TREND DETECTION RESULTS

Accuracy assessment is an important feature of mapping, not only as a guide to map quality and reliability, but also in understanding thematic uncertainty and its likely implications to the end user (Czaplewski, 2003). Prior to image classification, calibration data must be sampled from appropriate areas, at an appropriate support size (Stehman and Czaplewski, 1998). However, sampling for change detection is more challenging than that found in single-date approaches (Biging et al., 1998). Typically, a first step in this process is to highlight areas of change vs. no-change. This can be accomplished using an optimal threshold value based on similar spectral band comparisons between dates, vegetation indices or texture measures (Lunetta et al., 1998). To ensure appropriate sampling of no-change areas, the stratified adaptive cluster sampling (SACS) approach has been recommended (Brown and Manly, 1998). SACS has particular utility for sampling disturbed locations (changed land-cover and land-use) because they usually represent a minor portion of the target population (most of the land area has not changed) and are often clustered (Rogan et al., 2002).

Following classification, the accuracy of the change maps must be assessed. The total error in a thematic map is the sum of the following: (i) reference data errors; (ii) sensitivity of the classification scheme to observer variability; (iii) inappropriateness of the mapping process or the technological interpolation method; and (iv) general mapping error. General (total) map error conveys map quality, or 'fitness for use' by end users (Chrisman, 1991). The conventional method of communicating 'fitness of use' for map users is the confusion or error matrix (Richards, 1996). The error matrix summarizes results by comparing a primary reference class label to the map land-cover or land-use class for the sampling unit and presents errors of inclusion (commission errors) and errors of exclusion (omission errors) in a classification.

5 Applications of Remote Sensing in Monitoring Programs – Part 1 - Coral reef monitoring programs using remotely sensed data

In the following two sections, information is presented from two perspectives to illustrate practical applications of the concepts discussed in the preceding sections for linking remote sensing and multi-temporal analysis techniques to coastal and coral reef environmental indicators. In the first section, the status of remote sensing for mapping and monitoring coral reefs is reviewed. A local scale example is then provided, demonstrating the development and transfer to a government agency of a combined field and remotely sensed system for mapping toxic algal blooms.

5.1 POTENTIAL CORAL REEF MONITORING CAPABILITIES USING REMOTE SENSING

Given the large and often inaccessible areas of reef ecosystems globally, remote sensing remains the only way to obtain synoptic data about ecosystem composition and dynamics. This information provides a mapping capability that would be impossible to replicate using traditional field survey techniques. Remote sensing permits construction of baseline maps depicting reef location, extent, structure and composition. It can also be used to provide information about water quality, temperature and hydrodynamics, all of which may affect reef processes and health.

Landsat image data has been used for reef mapping applications since the mid 1980s (Jupp, Mayo et al. 1985; Kuchler, Jupp et al. 1986; Bour 1988). It is commonly accepted that these data are well suited to geomorphic and reef zonation studies, but finer description of reef habitats (eg. coral and algal definition) requires higher spatial and/or spectral resolution imagery (Mumby and Edwards, 2002). However, to analyse changes in reef substrate composition over time, the opportunities available with Landsat data are yet to be fully exploited (except see (Palandro et al., 2003a; Palandro et al., 2003c)). The Landsat time series and frequency of image acquisition provides an information source incomparable to other data types. However, while this is a more cost-effective option than high-resolution data, it cannot provide the spatial or spectral information required to map small-scale dynamics relevant to individual coral patches.

More recently, the increased availability of high spatial resolution satellite data (eg. Ikonos, Quickbird) has presented the opportunity to map reef habitats in greater detail. Where analysis of Landsat imagery may be able to generate a benthic habitat map with up to eight classes, Ikonos can increase the definition to around thirteen classes with a similar accuracy level (Andréfouët et al., in press; Mumby and Edwards, 2002). However, this high spatial resolution still may not be sufficient to provide information about many reef processes operating on a finer scale. For example, (Andréfouët et al., in press) suggests a pixel size of as little as 15cm is needed to detect coral bleaching. In mass bleaching events, however, such as those occurring in early 1998 and 2002, timely Ikonos data should be sensitive enough to detect a benthic change (Andréfouët et al., in press).

5.2 EXISTING CORAL REEF MONITORING APPLICATIONS WITH REMOTE SENSING

In a survey of 64 organisations involved in coral reef management and research conducted in 2001, 62% of respondents reported using remote sensing in some capacity for research, mapping, monitoring or management activities (Joyce et al., 2002). The number of years using these data were relatively equally distributed between new users (less than 2 years) and longer term users. Remote sensing is used for a variety of purposes in coral reef environments, though the most common applications are benthic habitat mapping, coastal zone management and change detection. The least common response was rehabilitation monitoring. Given the inherent difficulties in mapping submerged ecosystems, for example water column attenuation, spectral similarity between features and high levels of heterogeneity, it is not surprising that the more complex tasks of rehabilitation monitoring are yet to be employed in reef environments.

Of note were the responses received from representatives of research and development organizations including educational institutions, stating that remote sensing cannot as yet be used for effective monitoring of reef systems due to the current state of knowledge and lack of understanding of light interactions in these environments. The difficulties are primarily related to the lack of algorithms that can be used to measure reef properties related to health, especially due to the spectral similarities of corals and algae in the limited portion of the spectrum able to penetrate the water column. Further questions were raised, asking 'what is reef health?', and it was noted that there is a need for a greater understanding of reef processes and a quantification of reef condition other than presence and absence of algae, and detection of coral bleaching. Once an effective indicator of reef health is established, then the process outlined in section 3 can be used to identify the most appropriate form of remotely sensed data to address monitoring and management of the ecosystem.

Remote sensing has been used most effectively in indirect coral reef monitoring, such as the sea surface temperature data used for developing the degree-heating week hot spot maps or coral bleaching index maps. These data are readily available to the public via the National Oceanic and Atmospheric Administration's (NOAA) website. These types of information and data are used extensively by reef management agencies, e,g, Great Barrier Reef Marine Park Authority (GBRMPA). At present GBRMPA conducts extensive annual field surveys along set transects covering the entire reef. However, the samples are limited to dive-based video along set transects and do not provide spatially extensive coverage. GBRMPA is currently mapping simple substrate types from Landsat ETM+ mosaic over the entire Great Barrier Reef and is investigating the use of multi-temporal data for mapping disturbance impacts.

5.3 DEVELOPING REMOTE SENSING FOR INCREASED USE IN CORAL REEF MONITORING

Effective monitoring of any environment requires reliability, repetition and cost-effectiveness. In tropical environments prone to cloud cover, repeatable remote sensing image acquisition becomes a challenge. In addition, many reef locations are inaccessible for extensive and repeated field validation, so the validity and consistency of image-derived maps is a particularly pertinent question. The remoteness of some reefs also means that airborne data is either prohibitively expensive or logistically impossible, thus satellite imagery remains the only option. However, some satellite systems do not systematically acquire data over oceanic regions, thus specific tasking is required (eg. Quickbird).

Effective field validation methods for image classifications remain a challenge in reef environments due to scales of heterogeneity from individual coral patches to entire reef ecosystems. Neither field campaigns nor image data can capture all scales, and integrating the two is difficult. Although global standards for reef substrate monitoring have been developed (e.g. Reef Check), using this classification scheme or field method for calibrating and validating image data presents problems with scaling and accuracy(Joyce et al., in press) . The Reef Check methods are simple and able to be implemented as a rapid assessment scheme by volunteers with little training (Mumby et al., 1995), thus are ideal for assisting with image data classifications, however the scaling challenges related to the differences between image and field data resolutions need to be overcome.

According to the aforementioned survey, (Joyce et al., 2002), the main limitations to the use of remotely sensed data in coral reef environments were perceived to be cost of image acquisition and inadequate spectral resolution. Increased utilisation of these data requires better integration with GIS and a greater capacity (human and computer ability) to effectively process and extract this information. Although the majority of respondents identified the cost of remotely sensed data sets as a major limitation, most were unsure of the cost of their data, due to government provisions, special research allowances, or infrequency of purchase. This would suggest a limited knowledge of the full costs of acquiring and processing images for their purpose, or a limited knowledge on actual prices of image data sets. In either case this is an indication of the lack of detailed knowledge of the cost, time and possible accuracy involved in applying remote sensing for coral reef monitoring activities. An example of this is aerial photography, where the cost of acquisition is not indicative of the total cost to integrate fully into a GIS database.

Improved remote sensing technologies (eg. data set development, higher spatial and spectral resolution) will be welcomed by the majority of coral reef monitoring and management agencies, however cost was noted as a potential constraint, with only 14% believing they would have both technical and financial capabilities to fully utilise new remotely sensed data sets. The majority believed they would have neither the technical nor financial capacity, while other organizations believed that finance would prove to be the only constraint.

One of the most commonly identified limitations of remotely sensed data is the high degree of user expertise required to understand and extract the required information. A common theme observed in the results was the strong need for further research into, and development of techniques to best use remote sensing as a monitoring tool. Cost was another major factor in remote sensing being under-utilised or not considered at all for monitoring work. As a large portion of the world's coral reefs occurs in the waters of developing countries, financial constraints are a significant factor in the methods employed for coral reef management.

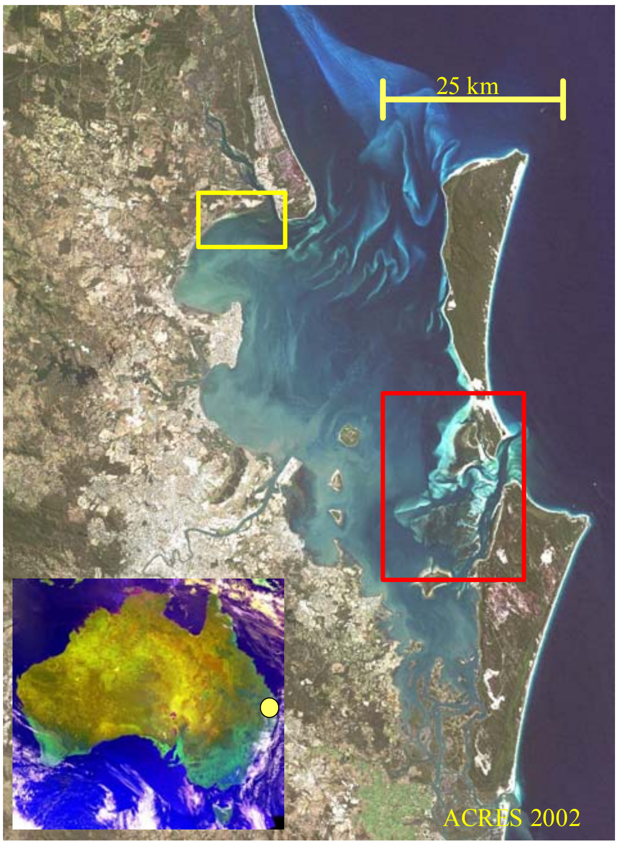
Based on the results of this survey, it seems the combination of a greater range of image data sets now available, an inability to consistently identify indicators of reef condition and to produce reliable change detection approaches have placed coral reef remote sensing in a developmental stage. Recommendations for furthering the utility of remote sensing in coral reef environments should focus on: (i) The identification and development of algorithms (and related spectral resolution) to relate reef bio-optical properties with relevant biophysical controls; (ii) Further development of techniques to remove the attenuating effects of the overlying water column; (ii) Greater incorporation of biogeochemical cycles (eg. climatic and oceanographic data) with remote sensing data to understand the processes that influence the biology of reefs and their subsequent bio-optical properties; and (iv) Evaluation and increased utilisation of a greater range of image data sources (eg. MODIS, IKONOS, SeaWiFS).

6 Applications of Remote Sensing in Monitoring Programs -
Part 2 - A combined field and remotely sensed program for mapping harmful algal blooms

6.1 CHARACTERISTICS OF *Lyngbya majuscula* AS A HARMFUL ALGAL BLOOM

Blooms of the toxic cyanobacteria *Lyngbya majuscula* have become a significant problem in Moreton Bay, southeast Queensland, Australia due to the large size of blooms that have been occurring since 1997 (Figure 2) (Dennison, 1999). As the algae produces skin and respiratory reactions, it has forced the closure of several net-fisheries in the Bay, and also forced the closure and clean up of beaches used for recreational purposes. From an ecological perspective, the smothering effect of the algae on seagrass may be impacting the health of turtles and dugongs in the area that feed from the seagrass (Dennison, 1999; Preen, 1995; Watkinson, 2000). *L. majuscula* is a toxic, filamentous, non-heterocystous marine cyanobacteria that fixes nitrogen. It is found attached to seagrass, algae and coral, and may rise to the water's surface by internal accumulation of gas bubbles (Watkinson, 2000). The *L. majuscula* blooms in Moreton Bay occur over areas from 8 - 80 km^2, with varying amounts of projected cover and vertical thickness (i.e., up to one meter thick). The blooms may last over periods of days to months (Roelfsema, 2001; Watkinson, 2000). *L. majuscula* blooms in the Moreton Bay region have most recently been observed in large areas (>1ha) on the seagrass beds of Deception Bay and the clear waters of the Eastern Banks, though they have also been observed in most locations throughout the Bay (Figure 2). Blooms have been observed in other locations along the Australian coastline and other tropical coastal regions throughout the world (e.g. Hawaiian islands, Cook Islands, Fiji, Eastern Africa).

Figure 2: Landsat 7 ETM image of Moreton Bay collected on March 21, 2002. The main L. majuscula bloom sites at Deception Bay and Eastern Banks are shown. Yellow box = Deception Bay, Red Box = Eastern Banks. Image source: Geoimage/Geosciences Australia.



6.2 SCIENTIFIC AND COMMUNITY MONITORING REQUIREMENTS

The negative impacts of *L. majuscula* blooms on fisheries, beach conditions and native marine fauna in Moreton Bay Marine Park were recognised quickly by the Local Councils and State Government Agencies responsible for managing Moreton Bay. These groups collaborated to form a "Lyngbya Taskforce" to collect baseline information, monitor, understand and manage the blooms. Baseline mapping of the bloom extent and density for use in monitoring its changes was critical information. This spatial information was used by scientists attempting to understand the causes and dynamics of the bloom, and for the Marine Park Managers to restrict use of affected sites. For example, the baseline mapping information was used to:

- provide Marine Park Managers with a basis for initiating mitigation (e.g. which beaches or areas to close and clean);
- produce "Lyngbya Alert" maps on the Environmental Protection Agency's website to enable local residents to decide where to safely swim, fish or boat; and
- provide scientists with information to understand the bloom characteristics (e.g. dynamics, origin).

Hence, the monitoring program needed to meet multiple requirements, in addition to being an accurate, cost effective and repeatable approach so that management and monitoring agencies could implement it on a regular basis using their staff and resources.

6.3 REMOTE SENSING FOR MAPPING *L.majuscula*

Due to the extensive area covered by Moreton Bay, mapping the extent and density of *L. majuscula* on a daily or weekly basis cannot be done using standard field survey techniques (e.g. video transects, diver transects or diver quadrats). Remotely sensed data from airborne or satellite imaging systems provides an alternative for synoptic coverage and can be used to map the location and density of *L. majuscula* to a depth of 3m in clear water (Roelfsema, 2001; Roelfsema, 2002). Maps of *L. majuscula* collected over time can then be examined to assess bloom dynamics and potential controlling factors. A procedure to map *L. majuscula* in the Eastern region of Moreton Bay was developed from field-spectrometry of key substrate types, radiative transfer modelling to assess water depth effects on the ability to discriminate Lyngbya, and field data to verify the results of image based mapping (Roelfsema, 2001; Roelfsema, 2002). The result of this work was a mapping program for use with Landsat TM/ETM+ data that could be used to map *L.majuscula* in areas of clear water < 3m deep. The mapping approach relies on coincident field survey data to train an image classification. A geometrically registered and dark-pixel corrected Landsat TM/ETM+ image dat, is then required with the aid of field survey to map the location of *L. majuscula*. This work was implemented as a joint monitoring program, combining local field expertise of Marine Park authorities (Queensland Parks and Wildlife Service), with remote sensing capabilities of a research group at the University of Queensland. The aim of the program was to provide regular baseline maps, integrating field and image based approaches to present *L.majuscula* density and distribution in one section of Moreton Bay, Eastern Banks.

6.4. INCLUSION OF COMMUNITY-INFORMATION WITHIN THE FIELD AND IMAGE BASED MAPPING PROGRAM

Community groups (e.g. oyster lease owners, seagrass watch groups) in Moreton Bay were informed about the characteristics of *L.majuscula* via websites, handouts and public presentations. In each form of communication explicit instructions were provided on how information on bloom sightings (e.g., percent cover, colour, location) was to be recorded and then submitted to Queensland Parks and Wildlife Service (QPWS) for analysis.

A field-monitoring program was developed to provide a repeatable GPS based field survey to improve on an earlier QPWS subjective and non-geolocated survey technique. Boat driven survey tracks were first located over the sections of the Bay to be monitored, taking into account the most recent bloom locations and expected changes. Data were then collected at regular spatial and temporal intervals along these tracks. Data collected included: GPS coordinates for each sample point; substrate type; visual estimate of substrate percent cover; and digital images captured for those sites having *L. majuscula*. The digital images were used to confirming the field estimated of the % *L.majuscula* cover. These data were used to verify substrate cover estimates and as archival information. The collected information was then processed in a GIS to produce quantitative field map of *L. majuscula* distribution.

Field data collection activities were scheduled to coincide with overpasses of the Landsat TM/ETM+ sensors. This enabled the use of field data for both calibration and validation purposes. Depending on the severity of the bloom, the field and image acquisitions were scheduled on a monthly or fortnight basis. The satellite images used for the classification of *L.majuscula* blooms were subsets of map-oriented, dark pixel corrected Landssat 7 ETM+ scenes (path 89, row 79) recorded at 9:45 am (AEST) on dates when field data collection and cloud free imagery coincide.

Mapping of *L.majuscula* patches followed a multistage process that ensured only those areas in which *L.majuscula* could be reliably mapped were extracted from the image and used for mapping. The blue, green and red bands were selected for use in image classification because of the comparatively limited depth-related light attenuation effects and maximum signal from submerged features. Variations in light attenuation are particularly acute in this environment, due to the mixture of oceanic and coastal/estuarine water bodies (Morel, 1977). ERDAS Imagine software was used to process the imagery. Once geometrically corrected, the subset was corrected for additive path radiance by applying dark pixel subtraction (Jensen, 1996a).

Image classification to map L. majuscula

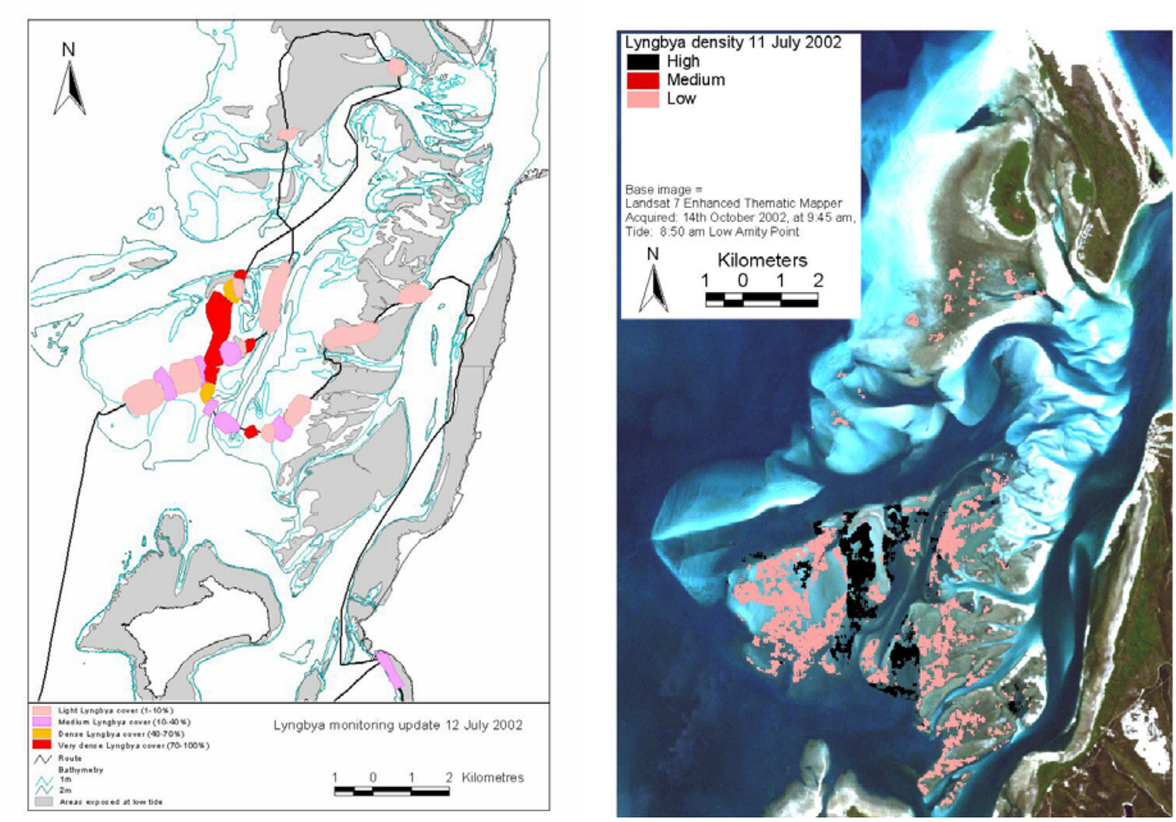
The field data collected by Marine Park authorities together with substrate coverage maps produced from previous studies (e.g., (Dennison, 1998)) were used to apply a supervised classification to map *L. majuscula* coverage. The substrate information used to select training pixels for classifying the Landsat TM or ETM+ image data were collected as close to the field survey date as possible. Statistics on substrate reflectance values were extracted from the image for field sites known to correspond to different *L. majuscula* density levels. The masked image of Eastern Banks was then subject to a “minimum distance to means” clustering routine to group pixels with similar reflectance values into three classes of varying *L. majuscula* cover and all other substrate. The final map for presentation to QPWS and for inclusion in their GIS, was made in Arcview 3.2, presenting the classification image results overlaid on the original image.

A pseudo "error matrix" was used to assess the accuracy of the classification and quantify the level of agreement between the classes identified from the image classification and the field data. The "pseudo" label is applied as a true reference set would have consisted of independently selected sites where *L. majuscula* cover had been measured and not used to train the image classification process. Hence, the error matrix is only a measure of how well the classification correctly identified the training data, not the whole study area.

6.5 MAINTAINING THE MAPPING PROGRAM

Currently the field component of this program is implemented on a regular basis, coinciding with Landsat 7 ETM+ over flights. The remote sensing component is part of a *L. majuscula* bloom contingency plan is initiated when the results of the field monitoring show medium to high levels of Lyngbya. At this time, a cloud free image of the study area will be purchased if available, and a classification using QWPS and community field data will be conducted. The results (in map and report format) of field and/or remote sensing monitoring are present on a website to be accessible for the community (figure 3). The data itself is still analysed on a yearly basis and will be used as one of the parameters for a report card presenting the health of the local coastal areas. The presence, size and duration of a bloom are regarded as key indicators of coastal ecosystem health in Moreton Bay.

Figure 3: *Lyngbya majuscula* monitoring results: a) field data collected by Marine Park rangers; and b) classification of satellite imagery resulting from field data and cloud free Landsat 7 ETM image.



7 Future developments for monitoring coastal and coral reef environments using remotely sensed data

7.1 CURRENT STATUS OF REMOTELY SENSED DATA/PROCESSING TECHNIQUESFOR MONITOIRNG CHANGE IN COASTAL AND CORAL REEF ECOSYSTEMS

Other authors in this text (e.g. …….) and review papers (Andréfouët et al., in press; Coppin, 2003; Dekker et al., 2001b; Green et al., 2000; Joyce et al., 2002; Malthus, 2003) demonstrate that remote sensing techniques are operational for mapping and monitoring selected components and processes of coastal aquatic environments. In this context, the following applications from commercially available image data and image processing software are operational:

- mapping and monitoring changes of substrate type in relatively clear waters < 10m deep;
- mapping depth in shallow clear waters < 10m deep;
- mapping selected water quality parameters related to optical properties of water (e.g. total suspended matter, suspended organic material (e.g. Chlorophyll) and dissolved organic material (e.g. CDOM); and
- mapping sea-surface skin temperature.

Substrate and water quality mapping applications have been shown to perform accurately in clear, oceanic case 1 waters. The accuracy and reliability of these mapping techniques is reduced significantly in coastal and estuarine waters, which are often a mix of case 1 and case 2 waters.

The majority of coastal management and monitoring programs are centred around measurement of ecosystem health indicators. Hence, it makes sense to focus on the indicators as a basis for selecting suitable remote sensing approaches towards the monitoring and management procedures of a region. Ecosystem health or status indicators often refer to environmental parameters that can be mapped directly or indirectly from passive and active image data sets. In this chapter we have presented a framework for developing remote sensing applications to map and monitor coastal ecosystem health or status indicators. The framework ensures explicit consideration is given to selection of an image data set suited to the indicator and its use in management. In addition, all of the considerations for using remotely sensed data are included in the evaluation process (data cost, software, hardware, personnel etc). A key component of the use of remote sensing data for monitoring is the implementation of change and trend detection techniques. Our chapter indicated the key pre-processing requirements and large range of processing options are now available. The framework and change/trend detection sequence is an "ideal" approach and coastal managers and remote sensing practitioners will often be faced with a gap that persists between the expectations of both groups pertaining to the use of data. Our experience in this area, as demonstrated through the *L. majuscula* project, is to select one indicator and run through a trial project. It is critical that the trial project involves management and remote sensing scientist working together on image and field data collection, data analysis, error assessment and presentation of results. This approach enables remote sensing to fit in with existing activities and to be actively understood by those who will use the results.

Remotely sensed data continues to become more easily available in a range of different scales and data types, some of which are inherently suited to coastal environments. Continued uptake of these technologies within integrated coastal management programs will not occur passively and requires demonstration that these data provide accurate, useful, timely and cost effective information – that meets the needs of management agencies. Careful application of the framework suggested in this chapter, along with cultivation of cooperative relationships with management agencies should enable this to occur.

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