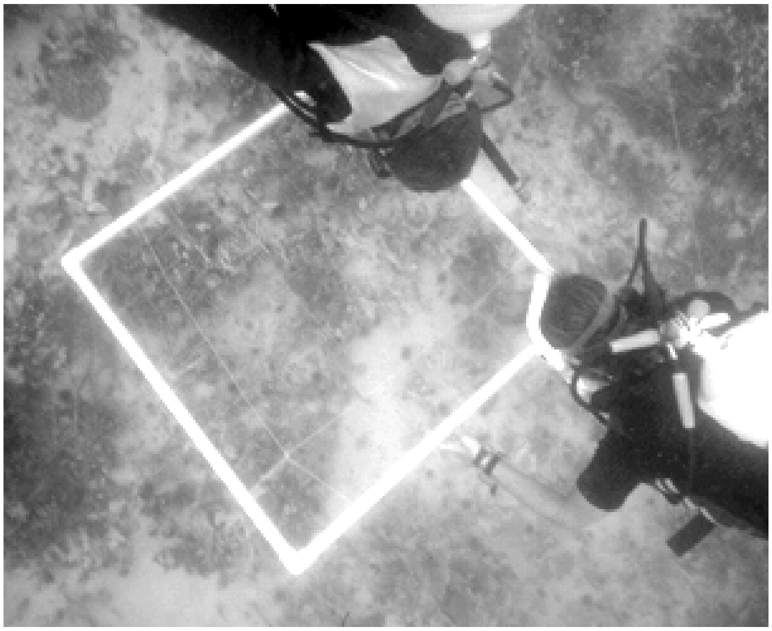

A PILOT STUDY OF THE USE OF SATELLITE OCEAN COLOUR IMAGERY FOR WATER QUALITY MONITORING IN OPTICALLY SHALLOW TROPICAL COASTAL ENVIRONMENTS

The Watershed Reef Interconnectivity Scientific Study

(WRIScS) Report E1

1997 – 2002

Changing land-use practices and their impact on nearshore environments, Belize Barrier Reef (Phase II)
EU Project No. B7-6200/97-02/VII/ENV

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This document is a part of a Report Series which contains the following modules.

- **M1. Project Leaflet**
- **M2. Executive Summary**
- **M3. Technical Report**
- **M4. Methodologies**
- **M5. Presentations and Newsletters**

And (Project Extension Series)

- **E1. This Report**
- **E2. Soil Erosion And Sediment Delivery In The Stann Creek District of Belize**
- **E3. RoxAnn Acoustic Mapping of the Cay Caulker Reserve**
- **E4. Water Column Monitoring in the Belize Northern Marine Reserves**
- **E5. WRIScS Phase II Hydrological Cooperative Program**

Full report sets and databases are lodged with the following organisations in Belize (members of the WRIScS Working Group).

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EXECUTIVE SUMMARY

The Watershed-Reef Interconnectivity Scientific Study (WRIScS, 1997 – 2001) has the objective of promoting a balance between sustainable land-use development and reef conservation in Belize, Central America. This technical report deals with the findings of a one year marine research programme funded by the European Union as an extension to the main project.

The initial WRIScS programme addressed the effects of changing land-use on environmental conditions along the Barrier Reef, specifically investigating sediment-related effects. In arriving at their conclusion that to date there has been minimal impact on the reef, the WRIScS team and Working Group were anxious to emphasise the need for continued monitoring of the interconnectivity between human activity in the watersheds and impacts within the coastal zone. The positive result of the study was not seen as an excuse for complacency, but rather as a guide to the focus and prioritisation of future studies of the Belize aquatic environment.

This extension programme has addressed one such potential exercise – the use of ocean colour satellite imagery for effective monitoring of water quality in the coastal zone. Water colour is the result of the action of light on the materials suspended and dissolved in it. The relation between water quality and water optical properties is a long-established open-ocean science. The benefits to Belize of the development of such a tool would be the daily acquisition of data relating to a range of water quality issues, covering the whole of the Belize marine zone, and at minimal cost.

Remote sensing is not yet used in water quality assessment in the coastal zone because of the problem of optical shallowness. This term describes the condition where sunlight can penetrate all the way to the seabed and be reflected back upwards and out again through the water surface. This bed-reflected light adds another element of colour to the water surface, and masks the colour due to water quality.

This project has addressed a range of feasibility issues concerned with setting up a marine remote sensing facility in Belize (including awareness and training, use of image acquisition software, the impact of cloud cover, and validation of the image-derived data). It has been primarily involved however with an examination of the bed reflectance problem. A basic strategy has been to move away from 'whole image' analysis, which is the major advantage of satellite imagery, but which presents an unresolvable complexity when dealing with bed reflectance. The classical spot sampling approach has been used to create time series data over a six month period at some 40 stations along W-E aligned transects at contrasting sites in north and south Belize coastal waters. Each 'site' is one satellite image pixel, $1km^2$. The SeaWiFS satellite has been used, which provides daily images, at no cost to developmental projects.

At each of these sites, *in situ* water quality has been recorded at 1-2 week intervals, and the seabed mapped twice. The field measurements were carried out by Raleigh International volunteers, based on two island 'dive-sites' from March to June and July to September 2001. Water quality measurements included secchi-depth observations and sampling for suspended particulate matter, plankton, chlorophyll-a and coloured dissolved organic matter. Samples were preserved and sent to the UK for analysis. SCUBA transect surveys were used to map the bed types and depth, and to collect information on bed colour using digital cameras and Munsell cards. In addition to this basic measurements, scientists used the dive-team facilities to make more complex observations, including RoxAnn acoustic mapping of pixel zones, CTD profiles of salinity, temperature and turbidity, and a Profiling Reflectance Radiometer to measure light attenuation through the water column.

From the wealth of data generated over two three-month expeditions (covering both the wet and dry seasons), descriptive models have been developed of the light-reflective properties of the seabed within each pixel-station, and of the seasonal variation of water quality within zones incorporating stations of similar conditions.

The three types of data (satellite, water column and seabed) have been interrelated using a simple optical equation developed by earlier researchers, which breaks down the light reflecting from the ocean surface into water-column (quality) and bed-sourced components. The equation has been developed into a simple interactive model which can be used to test the sensitivity of the reflected light output to the effects of the various contributing components. This model has underlined the importance of the attenuation properties of the water column in determining the influence of bed-reflected light. It has also demonstrated that peak reflection from bed occurs between 490 and 555nm, and that hardly any light is reflected back at the spectral extremes of 412 and 665nm. Detailed inspection of the output from the model at a range of sites of different bed conditions show that although the general responsiveness of the model is good, it gives unrealistic results under certain conditions. At the close of the investigation, three new objectives have been prioritised to carry the project forward. These tasks are:

1) to develop an algorithm for reliably predicting the diffuse attenuation coefficient of water at 412 or 665nm from satellite data
2) to better characterise the reflectance properties of biological surfaces, including the shading effects of relief and vegetation under-storeys and
3) to investigate and develop the optical theory within the light model.

The project concludes on an optimistic note that although a solution to water quality monitoring in optically shallow water has not been fully revealed in this pilot study, an excellent database has been generated for continuance of the investigation, and there is much enthusiasm and good-intention to continue with the research. Actual steps forward have been made in the revelation that the 665 and 412nm bands are effectively optically deep in most of the Belize coastal zone and can be used without correction for bed reflectance in monitoring for suspended sediment and Coloured Dissolved Organic Matter respectively. Hardware and software for acquiring and processing SeaWiFS images have been donated to the Coastal Zone Management Institute. The WRIScs team recommend that all who can should take advantage of this facility, with the intention that familiarity with the data and system will give confidence for the future development of this tool for water quality monitoring.

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1. INTRODUCTION

1.1 Background to the Study

1.1.1 Continuity from WRIScS Phase 1.

The Watershed-Reef Interconnectivity Scientific Study (WRIScS, 2000 A) has the objective of promoting a balance between sustainable land-use development and reef conservation in Belize, Central America. Phase 1 (1997-2000) was primarily concerned with the collection and analysis of field data pertaining to the transport of fine sediments and associated contaminant through the river systems and coastal zone of the Stann Creek district of Southern Belize.

The Phase 1 study concluded that there is no evidence to suggest that changed sedimentary processes resulting from farming activity to date in the Stann Creek area are having a negative impact on the Barrier Reef. The natural coastal system would appear to be effective in dealing with the impact of increased sediment yield and sediment contaminant loading produced by current land usage.

In arriving at this conclusion, the WRIScS team and the WRIScS Working Group were anxious to emphasise the need for continued monitoring of the interconnectivity between human activity in the watersheds and impacts within the coastal zone, in particular the Barrier Reef. The positive result of the study was not seen as an excuse for complacency, but rather as a guide to the focus and prioritisation of future studies of the Belize aquatic environment.

In discussing the results of Phase 1 with the members of the WRIScS Working Group, the following points emerged relating to future effort in the marine field.

1) There is a critical need for awareness and technical education within Belize Institutes concerned with the management of the coastal zone.
2) As a result of both lack of technical expertise and lack of physical resources, it would be difficult for Belize Institutions to repeat further studies using the same approaches to field data collection as employed in the WRIScS project.
3) The WRIScS study was geographically limited to the Stann Creek area and to the effects (primarily) of the citrus industry. Future investigations and monitoring should be concerned with the whole of the Belize coastal zone and with the full range of land use.
4) The WRIScS study was focussed on sedimentary effects, and did not consider the impact of loading and contamination in the dissolved phase. Future investigations and monitoring should include dissolved loads, and therefore address the concerns relating to nutrient inputs.

These observations were embodied into the recommendations of the WRIScS Phase 1 report.

In December 2000 the European Union funding committee granted a year's extension to the WRIScS project. On the marine side, the extension was to address sustainable use of the techniques introduced by WRIScS (see reports E3 and E4), and was to explore methodologies whereby Belizean Institutes could expand their investigations and monitoring of coastal water quality in relation to points 2-4 above. This report (E1) is concerned with the latter activity.

[Note: Report E2 addresses research on terrestrial aspects of soil erosion and delivery to rivers. Report E5 addresses project assistance provided by WRIScS to the Hydrology Section in the National Meteorological Service.]

1.1.2 Coastal Water Quality Concern in Belize.

A comprehensive review of coastal zone water quality issues in Belize can be found in Grimshaw and Wade (2001), a study initiated and part-financed by WRIScS as part of the National Marine Environmental Quality Monitoring Plan initiative (WRIScS, 2000 C).

Five broad geographical zones of potential water quality impairment can be defined:

1) Coastal waters arriving from Mexico, Guatemala and Honduras, as a result of (largely unknown) coastal currents, and affected by a variety of agricultural and urban sources.
2) River discharge to Chetumal Bay. Large watershed areas are in Mexico and Guatemala. Sugar cane production affects much of the watershed area, and there is a substantial urban population. The waters mix with the ocean within the shallow shelf lagoon environment in the vicinity of Ambergis Cay, Cay Caulker and Cay Chapel, each of which contains local point sources of urban contamination.
3) The Belize River discharge, with a variety of agricultural and urban inputs, notably that of Belize City. Dispersion is principally involved with the Belize River delta plume.
4) The Stann Creek District, dominated by Citrus and Banana plantation effects.
5) The Toledo district, dominated by Banana and Shrimp farm effects.

Agricultural inputs are calculated to provide by far the greatest contribution to 'contaminant' loading in the coastal zone. Impairment of water quality is possible due to the effects of

1) Increased turbidity levels due to sediment inputs (with effects on light availability and benthic nutrition)
2) Plankton blooms, stimulated by increased nutrient levels (with a variety of effects, notably modification of community structure and eutrophication in extreme cases) .
3) Toxic effects due to pesticides etc (with potential impacts on reproductive capabilities).

The Coastal Zone Management Institute conducts water quality monitoring at some 75 sites throughout the Belize coastal zone, where dissolved oxygen, turbidity, nitrate, phosphate, and chlorophyll-a measurements are routinely made. Results (since 1992) indicate a general absence of contamination problems to date (CZMI, 1999).

1.1.3 The Use of Satellite Imagery in Water Quality Monitoring.

Remote-sensing from Ocean Colour satellites can provide direct evidence on sediment, plankton and (coloured) dissolved organic matter concentrations in near-surface waters (Michalek *et al*, 1993), and thus potentially offers a practical, cost-effective means for study and monitoring of many aspects of water quality.

Although satellite imagery needs to be validated by the collection of in-situ field data, its use offers the advantages of:

1) Reducing the amount of resources that have to be directed to field sampling programmes.
2) Covering the whole of the Belize coastal zone.
3) Providing spatially continuous data, rather than information relating only to sampling points.
4) Providing extreme-weather data, when normal field sampling would be impractical.

The use of ocean colour imagery in a coastal zone monitoring context also has its problematic side. The shortcomings relate to:

1) Staff training and hardware/software resources.
2) The long-term cost of image purchase. For research projects (such as this,) images are often provided for free. At what point such projects cease to become 'research' is a woolly area. The politics and economics of image sales is a controversial and (hopefully) changing arena however; once the policy of selling data by the pixel rather than by scene becomes acceptable, use of imagery for providing time-series data will become an economic practicality (Bukata, 2001).
3) Cloud cover. At critical times of the year (the rainy season) cloud cover may inhibit data acquisition over prolonged periods.
4) The effect of optically shallow water (where satellite images 'see' the seabed instead of just 'seeing' the water column). Ocean colour satellite programmes were developed for use in oceanic waters. Use of these images in 'optically shallow' waters is still in its infancy. (Maffione, 2000)

The WRIScS Phase 2 marine programme has been directed towards investigation of these problems, in order to evaluate the potential use of satellite imagery as one tool for future monitoring of coastal water quality in Belize.

The SeaWiFS programme, operated from a NASA satellite, currently provides the most practical source of ocean colour images and has been used in this study.

1.2 Project Aims

1.2.1 Broad Objectives

The purpose of WRIScS Phase 2 is

"increased Belizean capacity to incorporate watershed-reef connectivity considerations into policy, planning, management dialogue and decision-making"

The overall objective of this pilot Ocean Colour study is

"to evaluate the feasibility (scientific practicality and economic sustainability) of the use of ocean colour satellite imagery for long-term water quality monitoring in the Belize coastal zone"

1.2.2 Scientific Aims

The project has four specific aims.

1) Training. To provide an awareness of the capabilities and limitations of ocean colour satellite imagery for water quality monitoring in the Belize coastal zone (wider scientific audience). To provide specific training on the acquisition and processing of SeaWiFS images (restricted technical audience).
2) Computing Facilities. To evaluate the minimum hardware requirements for practical acquisition and processing of SeaWiFS images.
3) Cloud Cover. To quantify image availability during the six-month pilot study.
4) Seabed Reflectance. To conduct a pilot scientific study of the effect of seabed reflectance on colour recorded by satellite images of the Belize coastal zone, and investigate the possibility of removing seabed reflectance effects to reveal colour associated with water quality.

Fulfilment of these four specific aims is intended to provide coastal zone management with the basic information necessary for evaluation of the practicality of ocean colour imagery as a water quality monitoring tool.

Most of the project activity during the WRIScS extension period has been directed towards Aim 4, evaluation of the possibilities of working within optically shallow water. The results of this investigation are covered in this technical report.

1.3 Logistics

1.3.1 *Team Structure*

The WRIScS Phase 2 Ocean Colour Project has been a partnership between three United Kingdom organizations:

Raleigh International, a youth development organization, provided the co-funding with the European Union. Raleigh has been operating expeditions in Belize throughout the life of the WRIScS project and has organized the volunteers who participated in much of the marine fieldwork. In addition, Raleigh has provided the administrative, financial and logistical framework within which the WRIScS project has operated.

Ambios Ltd., a not-for-profit company operating in the field of Coastal Zone Research and Education, provided the original concept for the project and designed and directed the marine aspects of the research programme.

University of Plymouth – Institute of Marine Studies, designed and directed the marine optical measurements and the satellite imagery processing.

Raleigh International and Ambios, together with the Geography Department of the University of Exeter, comprise the WRIScS management team.

The WRIScS project was implemented by a full-time staff based in Belize, consisting of a Project Manager and a series of (shorter-term) Project Assistants . Ambios also provided staff to fulfill some marine fieldwork and training requirements.

The project has been developed in association with a range of institutions in Belize. The objectives of the programme were developed in response to inputs from these institutions, and they have provided guidance to the project during its active life through a ***Working Group***. The membership of the Working Group has been :

WRIScS, Coastal Zone Management Authority and Institute, Fisheries Department, Hydrology Section in the National Meteorological Service, Agriculture Department, and the Department of the Environment and the Physical Planning Unit of the Ministry of Natural Resources and the Environment.

1.3.2 Timing

The project officially commenced in February 2001 and concluded in February 2002. Scientific data collection and monitoring activities extended over two Raleigh International expeditions, spanning the period March to September 2001.

1.4 Report Structure.

Two training sessions have been provided as part of the WRIScS Phase 2 Ocean Colour study. These took place at the Radisson Fort George Hotel, Belize City, on the 18th-20th April and 31st July and 1st August 2001. These sessions covered the wider background to ocean-colour imagery and its validation, the acquisition and processing of SeaWiFS data using dedicated software, and hands-on practical sessions concerned with marine optical measurements and satellite image analysis. The training sessions were issued as two inter-active CD-roms, which have been provided to all participating institutions.

This Technical Report contains the following Sections.

1. **Introduction.** Provides the preamble to the study.
2. **Methodologies**. The protocols used for making all measurements used are described in detail here.
3. **Results**. This sections contains a factual description of the data (field and satellite) obtained during the study. It is divided into Water Column Properties, Seabed Characteristics, Optical *In-Situ* Observations and Satellite Images.
4. **Discussion**. Here the data are synthesised and the results evaluated.
5. **Conclusions and Recommendations.** Relates to all the scientific aims of the project.

2. *METHODOLOGY*

2.1 *Overview*

2.1.1 *Definition of the Research Task*

A basic introduction to the elements, processes, terminology and measurement techniques involved in ocean colour studies is provided in Figure 2.1_1.

Sunlight (solar irradiance) penetrates the ocean surface and continues downwards into the water column. In the absence of encounters with any solid matter, the light energy is totally absorbed by the water and its dissolved components.

Most ocean water contains particles in suspension. Some of the light hits these particles and is reflected (scattered). Most light is scattered in a forward direction (further down into the water column), but some is 'backscattered' upwards, and re-emerges from the water surface. This backscattered light is what gives the ocean surface its colour. Different types and concentrations of suspended particles and dissolved matter ("water quality") have different effects on the scattering and absorption of light at different wavelengths (colours). Thus from examination of the colour of the ocean, deductions can be made about water quality.

The loss of light energy with depth in the water column through the combined processes of absorption and scattering is known as attenuation.

Sometimes sunlight can penetrate all the way to the seabed, to be reflected from the seabed and return to the sea-surface to also affect to affect the ocean surface colour. When this happens, the water area is defined as "Optically Shallow". This definition depends both on the water depth, and the clarity of the overlying water (which controls the depth of light penetration). As the latter can vary, a zone may be optically shallow for only certain periods of time. Also, as the attenuation (penetration) of light varies with different wavelengths (colour), a site may be optically deep for some wavelengths and optically shallow for others.

To make deductions about water quality in optically shallow water, it is necessary to be aware of the elements of the ocean colour which derive from seabed reflectance. Examining the feasibility of doing this in the Belize coastal zone is the primary task of this project.

Success in completing this task is not simply a 'yes we can' or 'no we can't' situation. It is possible to recognise a series of steps between presently accessible usage of satellite imagery which can help in understanding processes affecting coastal water quality, through to an optimum level of development which would take many years of research to complete. These steps are:

Use Imagery only in CASE 1 waters (open ocean situations where colour is effectively a function of chlorophyll alone). This restricts use of ocean colour images to the open Caribbean Sea area , east of the Belize reefs and north of the Honduran reefs. This option is immediately available, and would provide information on plankton blooms entering and leaving Belize coastal waters.

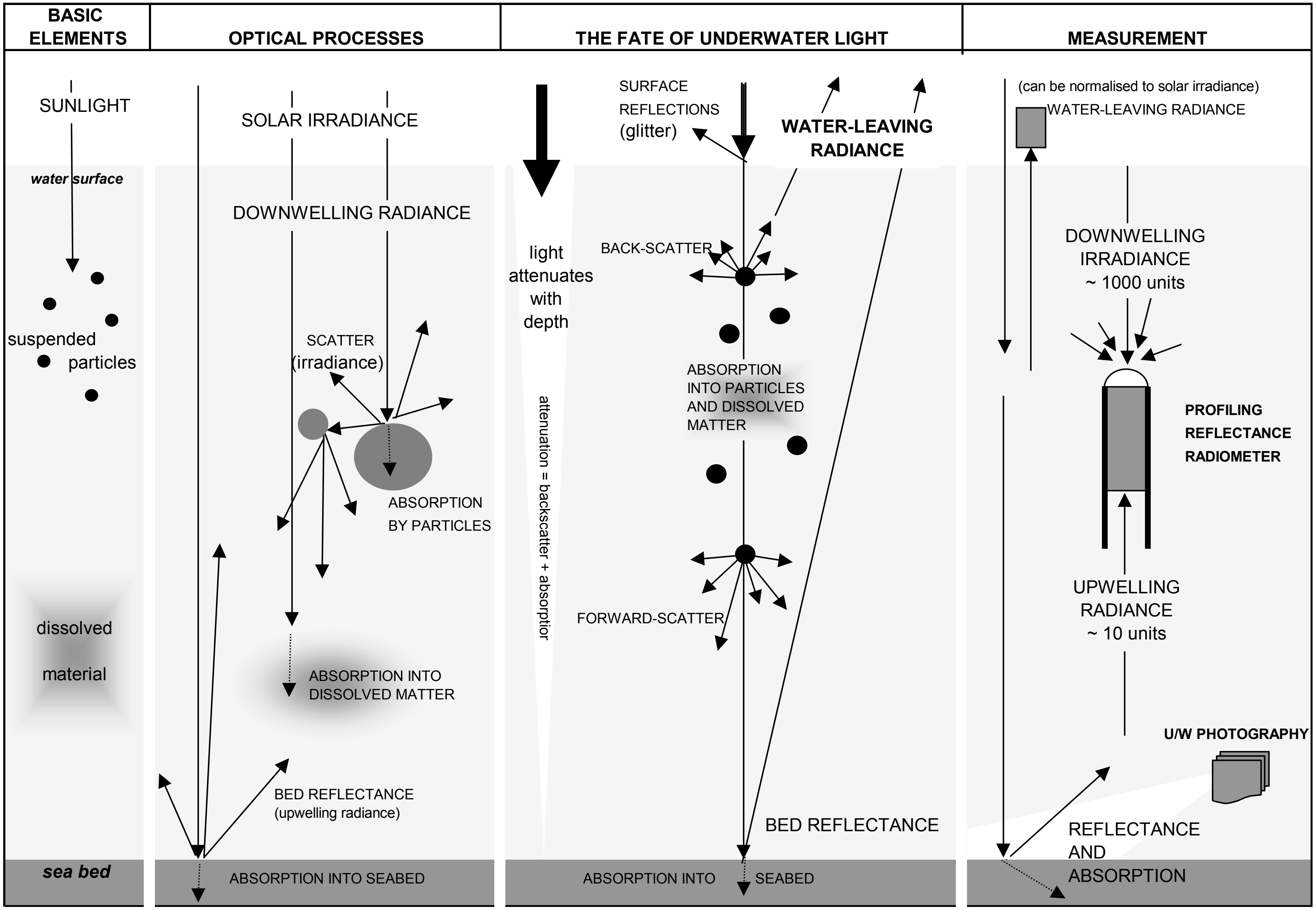


Figure 2.1_1. An introduction to Ocean Colour processes and terminology.

Use Imagery only in optically deep water. A readily attainable output of the WRIScS Phase 2 study is to define water areas that are always optically deep, in terms of bathymetry and geographical location. On the basis of this a mask could be produced, leaving only optically deep areas visible from which ocean colour data can be acquired. Almost all of northern inshore Belize (north of Belize City, on and inside the reef) would be masked out. Thus this scenario would add to the previous by allowing sediment plumes and plankton blooms to be identified in certain deeper areas of the coastal waters of Belize.

Use Imagery at selected points in optically shallow water. The objective of the WRIScS Phase 2 study is to develop algorithms which allow seabed effects to be removed from the ocean colour images at some forty or so *in-situ* sampling stations observed during the project. This scenario would allow Ocean Colour images to be used to provide time-series of chlorophyll and suspended sediment data at many 'monitoring' points in optically shallow water, in addition to the uses described in the two situations above.

Use imagery at all points in optically shallow water. The arrival at this level of usage would require a model to be developed based on the WRIScS Phase 2 data, which would allow the algorithms determined at specific points to be applied to all areas. This model would need to relate the optical properties of the seabed to basic seabed characteristics which are well mapped, eg depth, aspect, geographic location, distance from reef or river etc. The development of such a model would allow full use of ocean colour imagery throughout Belize coastal waters ie the realisation of spatially-continuous datasets, enabling plume definition etc. It is a long-term goal however, and would require research beyond the capacity of the present study.

2.1.2 Investigative Strategy

In theory, it may be possible to use a time series of ocean-colour images as the sole basis for identification of effects due to seabed reflection, with minimal recourse to field investigations. Such a study would probably take many years of image analysis, to arrive at a statistically acceptable level of confidence in the results, and may never be achieved if temporal variation in water quality and/or seabed conditions is complex.

A holistic approach, taking account of all the aspects of the problem through direct observation of field conditions, should provide a more robust appreciation of the problem, and has been relied upon in the project.

Three types of investigation have been completed all at the same selected sites within the Belize coastal zone – measurement of the characteristics of the seabed (bathymetry, habitat and the optical properties of the bed), measurement of water column conditions (water quality and optical properties) and analysis of satellite imagery. At the data-collection level, each investigation has been pursued in an effectively independent manner. Confidence in the results of the project will be enhanced if, in the synthesis of the results of the three approaches, they come together to tell a consistent story.

A final thread in the planning of the project was a resolve to minimise, as far as was practical, dependence on high-technology field equipment. This approach not only reflected the limited financial resources of this project, but importantly that further study should be encouraged both in Belize and in other areas of the developing world, where financial constraint would undoubtedly apply.

2.1.3 Study Site Selection.

Raleigh International was equipped to operate two camps of volunteer divers on remote cays in the Belize coastal zone. These camps could be widely separated, but needed to be accessible from a supply site on the mainland coast.

For purposes of the study, the sampling sites needed cover as wide a range as possible of the conditions found in the Belize coastal zone. These conditions related to both:

1) Water bodies – in terms of sources, active processes and water quality characteristics.
2) Seabed conditions – in terms of depth, morphology and habitat type.

Two contrasting survey areas were selected (Figure 2.1_2). From each of these sites it was planned to service some 20 sampling stations at up to 20km distance from the base-camps.

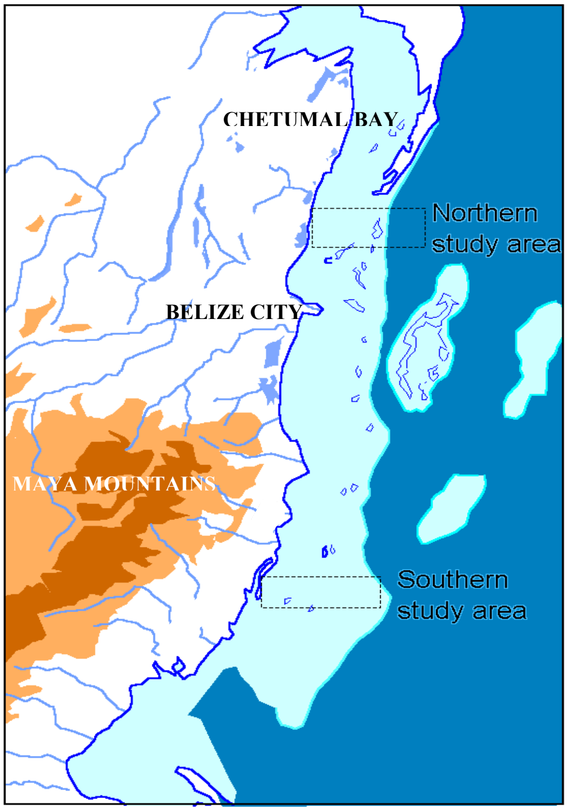


Figure 2.1_2. Location of the survey areas in the Belize Coastal Zone

NORTHERN AREA. The camp was based on Long Cay and serviced from Belize City. The study area is a shallow-water environment, terminating along its seaward margin in the reef and drop-off zones. This is a critical area in terms of water bodies, where the discharge from Chetumal Bay enters the sea. The Belize River plume may possibly also extend northwards to affect this area at certain times.

SOUTHERN AREA. The camp was based on Cary Cay and serviced from Placentia. This is a deeper water area, with extensively developed localised reef zones and two major channels. Waters bathing this zone are known to be of a much more oceanic character than in the northern study area, but are also affected by river discharge from the Maya Mountains.

SITE	EASTING	NORTHING
L1	391328	1952034
L2	392184	1951947
L3	396549	1957595
L4	394753	1963660
L5	394219	1967877
L6	393430	1968717
L7	391577	1969573
L8	389394	1969680
L9	386553	1969691
L10	384560	1969641
L11	382514	1969641
L12	379624	1966649
L13	379345	1969711
L14	376484	1969723
L15	373462	1969609
L16	373598	1962714
L17	376514	1962674
L18	379610	1962616
L19	382609	1962604
L20	385601	1962581
L21	386465	1959760
L22	387231	1956955
L23	383588	1953702
L24	387723	1953147
L25	389455	1959655

SITE	EASTING	NORTHING
C1	355393	1827654
C2	356606	1828732
C3	358506	1828729
C4	360072	1828276
C38	361519	1828239
C5	362509	1828813
C6	363974	1829224
C7	365455	1828739
C28	367059	1827234
C8	367514	1828624
C9	369441	1827799
C36	369722	1829084
C10	370362	1826673
C22	371241	1826641
C11	371478	1825804
C33	372187	1825744
C12	374525	1826649
C14	380011	1826451
C15	381484	1826734
C16	383246	1827076
C17	385593	1826631
C19	390496	1827733
C20	392491	1827495

Table 2.1_1. Survey station locations (NAD27 Central America datum).
L=Long Cay (northern area) C=Cary Cay (southern area)

At each site sample stations were arranged along shore-normal transect(s), in order to maximise variation in terrestrial/oceanic influences. In the north the stations were arranged in two transects, in the south (where the coastal zone is much wider) a single transect was defined.

The sampling positions are identified in Table 2.1_1. Maps showing the position of these sites relative to water body properties and seabed conditions are presented in the Results sections (3.1 and 3.2 respectively).

Using fast boats (capable of speeds up to 20+ knots) it was planned to visit each site weekly for water column observations, and to undertake a SCUBA seabed survey of each of the 40 station per expedition.

2.2 Seabed mapping

2.2.1 Seabed Sampling Strategy

The SeaWiFS ocean colour satellite data used in the project has a pixel size of 1km^2 (Section 2.6). To measure the optical properties of the whole seabed of such a large area and for a large number of sites is clearly impractical. A structured sampling strategy was therefore devised.

In terms of its light-reflective properties, the seabed in the study area can be considered to be composed of four basic substrate categories:

SEDIMENT (including coral rock) (s)
LIVE CORAL (c)
EPI-BENTHIC SESSILE FAUNA (e1)
EPI-BENTHIC FLORA – SEA GRASS and ALGAE (e2)

The most practical method of mapping the presence and relative contribution of each to the total substrate is by SCUBA quadrat transects. Within the timing/manpower constraints of the project, these could be up to 100m in length at each station (with 1m^2 quadrats, giving a mapped area of 100m^2).

The application of 100m^2 of SCUBA data to represent 1,000,000m^2 of a satellite image pixel cannot be undertaken with statistical confidence. A means was therefore sought of making a basic measure of habitat characteristics at a sampling density of 10,000m^2 per pixel, to bridge the scale-gap problem.

Acoustic mapping presented an ideal solution to this requirement. A RoxAnn system was used by WRIScS during the Phase 1 project, and donated to the Coastal Zone Management Institute. This was kindly made available for the Phase 2 project, and at most sites a 'cross' was surveyed covering the 1km^2 pixel area, providing information on bathymetry and sediment type (bed hardness and roughness) for 5,000 – 10,000m^2 of seabed per pixel (Figure 2.2_1). In the absence of the RoxAnn system, an ordinary digital recording echo-sounder might be similarly employed.

2.2.2 SCUBA Quadrat Surveys

Raleigh 'Venturer' teams, under the guidance of graduate Science Officers, were used for SCUBA seabed surveys.

The first task at each station was to conduct a simple survey in order to identify whether the substrate was uniform or complex (degree of substrate variability). This information was used to prioritise subsequent transect/quadrat mapping in order to optimise resource and time limitations.

On arriving on site (determined by stand-alone GPS to an accuracy of ±10m) a marker buoy was dropped. A dive pair then descended and made a reconnaissance of the site. A 10m transect was

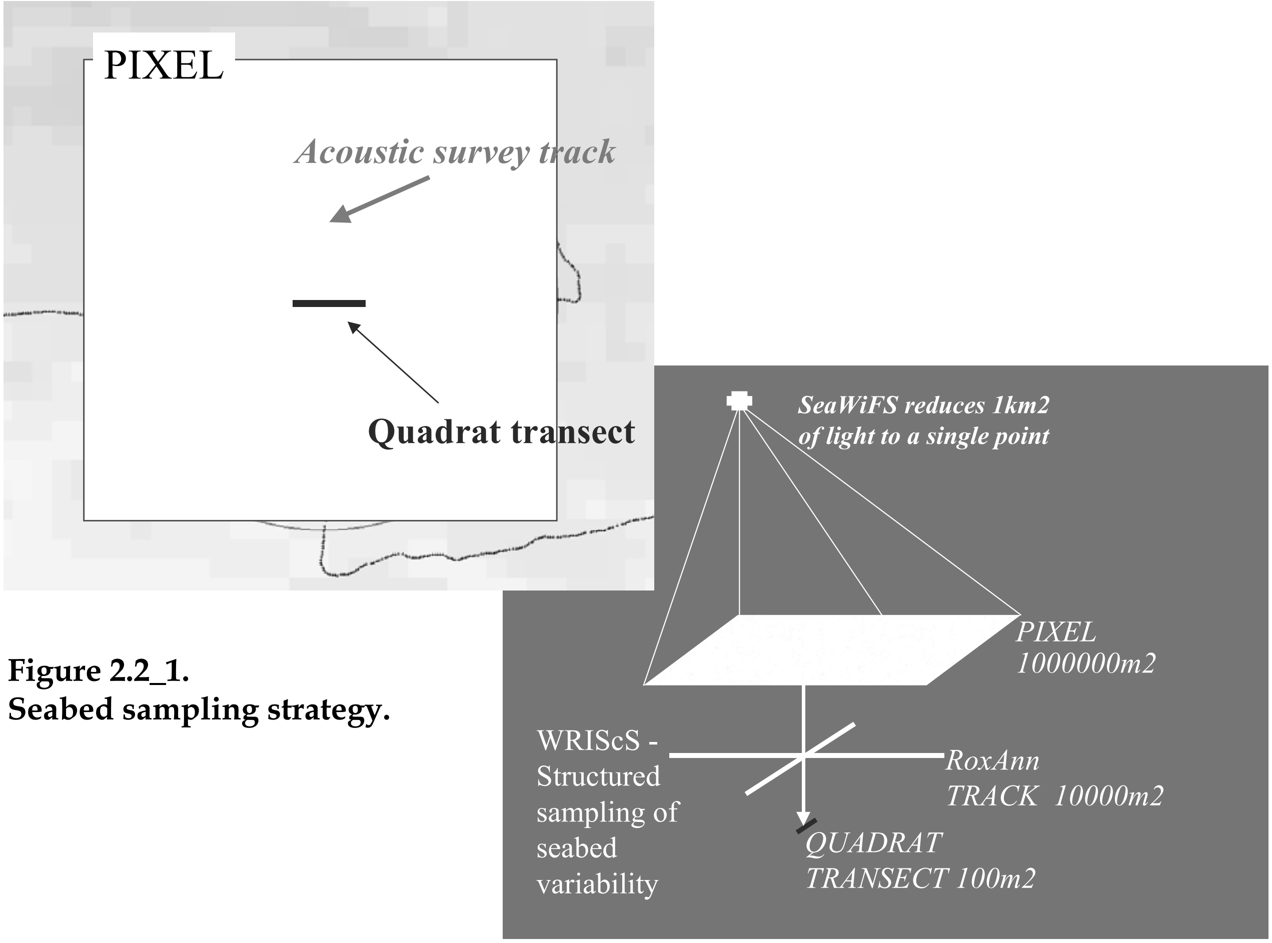


Figure 2.2_1.
Seabed sampling strategy.

laid (aligned roughly N-S or W-E) to cover the most complex substrate observed in the vicinity. The transect was then mapped at $1m^2$ resolution, using the techniques described below.

For uniform seabed types, this was the only survey undertaken. Complex bed areas were revisited at a later date, and a 50-100m transect survey completed. The transect extremes were positioned using a surface marker buoy and GPS.

QUADRAT MAPPING

The plastic $1m^2$ quadrats were just negatively buoyant, and were moved along a leaded-line transect marked off at 5m intervals.

Within each quadrat the surveyors had to determine:

1) The nature of the physical substrate -if it is dominated by live rock-building coral, or dead coral rock, or one of six sediment types. (s)
2) The dominant coral life-form, if any is present (note: recording of data here can be possible even when there is no 'live coral' entry under 1), as coral may not be the dominant component of the square). (c)
3) The dominant sessile epi-fauna (soft corals, sponges) growing on the sediment/rock. (e1)
4) The dominant flora (sea-grass, alga) growing on the sediment/rock. (e2)

5) Which of the above four categories was dominant in terms of the colour of the quadrat area.
6) The colour of the dominant category (using Munsell cards, see Section 2.4.3)
7) The depth and a relief index of each m^2 .

‘DOMINANT’ was interpreted in terms of the total volume of the organism, not just the holdfast area. The mapping categories are identified in Table 2.2_1 A.

Underwater keys and a simple coding slate were provided for the divers. Data was transcribed to a paper form after each dive, then regularly entered into a field computer. A typical entry is shown in Table 2.2_1 B.

SEABED PHOTOGRAPHS

A digital camera was used to photograph selected quadrats, as described in Section 2.4.2.

A.

SEDIMENT

Live coral
Dead coral rock
Coarse coral rubble
Fine coral rubble
Coarse sand
fine sand
muddy sand
muddy sand

RELIEF

Flat	1
1-10cm	2
10-50cm	3
50-100cm	4
>100cm	5

CORALS

Branching	**Staghorn** **Elkhorn**
Finger	**Finger coral** **Tube coral** **Ivory Tree coral**
Encrusting / massive	**Starlet corals** **Star corals** **Mustard Hill**
Meandroid	**Pillar coral** **Brain coral** **Rose coral** **Rough/elliptical star coral** **Cactus coral**
Leafy	**Lettuce coral**
Hydroids	**Fire coral**

SESSILE EPI-FAUNA

Rods/whips/plumes
Sea fans
Sponges

FLORA

Sea Grass

Halimeda
Pine cone algae
Filamentous algae
Fan algae
Bristle-brush algae
Fuzzy finger algae

B.

Quad	depth	relief	category	dominant	optically dominant	colour	Photo ID
4	12.1	2	s	7	x	GLEY1 6/10GY	
			c	LI			
			e1	W			
			e2	Z			
5	11.6	1	s	7	x	GLEY1 6/10GY	C09Q5W-E.JPG
			c	Et			
			e1	W			
			e2	Z			
6	11.2	1	s	7	x	GLEY1 6/10GY	
			c	LI			
			e1	W			
			e2	Z			

Table 2.2_1. Quadrat Mapping

A. Categories
B. Example of transect coded data form

2.2.3 Acoustic Surveys

RoxAnn is an echo-sounder signal processing system. With the Groundmaster system used, a standard Furuno LS6000 sounder provides the acoustic source for the system, operating at 200khz, thus being sensitive to conditions at the sediment-water interface of the seabed. The sounder is custom-mounted in a waterproof box together with the RoxAnn circuitry. This box, together with the transducer, a laptop computer, power supply and hand-held GPS comprise the hardware system. The software used is SEARANO, a DOS-based programme. The system records (every 1-2s) digital data on position, time, water depth, a seabed hardness index and a roughness index.

For each station two 1km transect lines were surveyed at ~10km hr-1, the lines being N-S and W-E oriented and crossing close to the SCUBA transect site (Figure 2.2_1).

A description of data analysis methodology can be found in WRIScS (2000 B), and on the CD-ROM RoxAnn Training Course prepared for and provided to Belize Institutions during 2001.

2.3 Water Body Properties

2.3.1 Secchi Disc Observations

Secchi-depth measurements were planned for all survey sites at approximately weekly intervals (although weather and logistical problems frequently made this impossible) throughout the Raleigh expeditions (March-May, July-September). The methodology is ideal in that it was simple and directly related to optical aspects of water quality.

200mm secchi discs, weighted with a small lead block and fitted with ~30m of line marked at 1m intervals were provided, together with a glass-bottomed box so that viewing took place from just below the surface. The use of the viewing box, careful boat control (so that the disc hangs vertically) and restriction of data collection to the hours between 8am and 4pm were critical aspects of the secchi observations.

A major problem in the northern area was optical shallowness – at many sites the seabed was always visible and therefore the secchi disc could not be used in a conventional manner. To overcome this problem the secchi was also used in a horizontal mode (Figure 2.3_1) and a correlation established between vertical and horizontal measurements.

In the horizontal mode, the disc is fastened at 45° to a pole which placed vertically over the side of the boat to a depth of about 1m. A snorkler then swims out with the secchi line until the disk is not visible while viewing from 1m below the surface. Whenever possible, both vertical and horizontal secchi measurements were made to enable a relationship to be established between the two types of measurement (Figure 2.3_2).

All repeated water column observations (eg secchi disc) have been analysed using the date in Julian Day format (day of the year, 1-365). A table relating Julian Day to normal date is provided in Appendix 1.

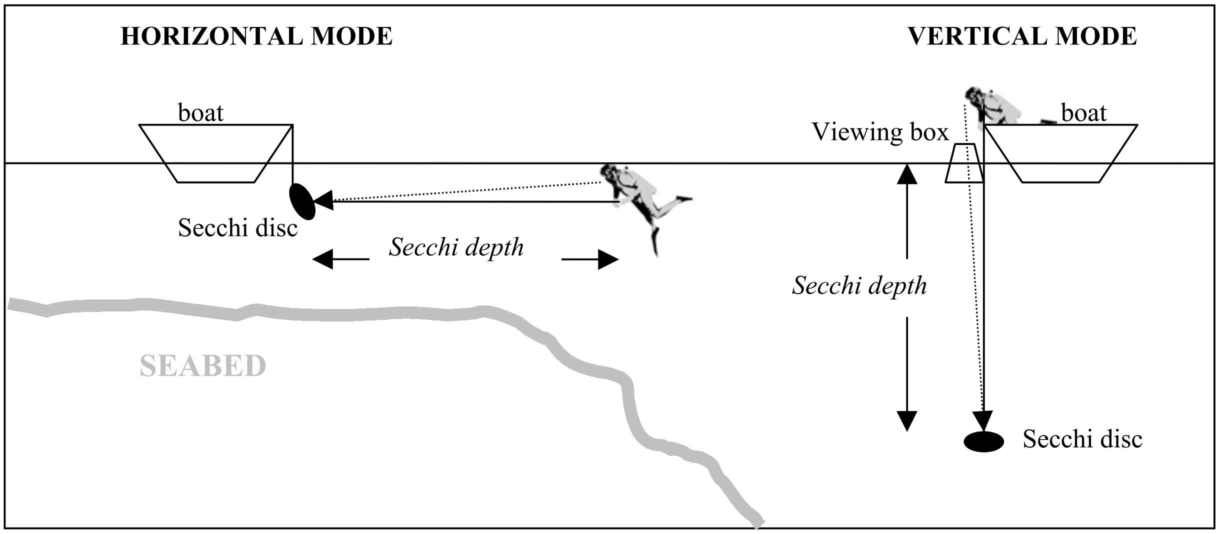


Figure 2.3_1. Secchi Disc observation methods

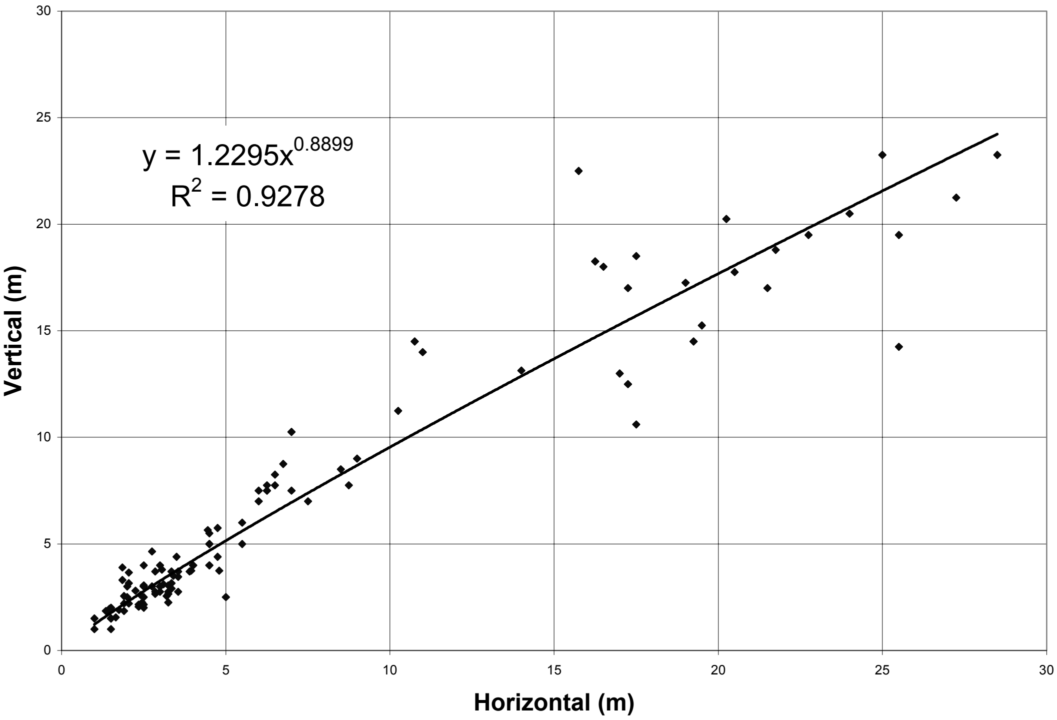


Figure 2.3_2. Calibration of Horizontal Secchi Disc data. Based on 117 observations.

2.3.2 Salinity, Temperature and Turbidity Profiles

A WS Ocean Systems Marine Monitor CTTD (measuring conductivity, temperature, turbidity, depth and GPS position) was used once at all stations in June 2001 (between expeditions). The equipment was used to profile the water column at all the survey stations, to provide an indication of typical salinity, temperature and turbidity conditions at the onset of the rainy season.

This equipment was loaned by the Belize Fisheries Department for the survey. Full details of the instrument and the mode of operation used can be found in WRIScS (2000 C)

2.4 Optical Measurements

2.4.1 Profiling Reflectance Radiometer Profiles

A Biospherical PRR Instrument (Figure 2.4_1) was loaned to the project by Plymouth University for the duration of the Belize expeditions. The instrument was used to profile the water column for downwelling irradiance and upwelling radiance. From these data a measure of the attenuation of light with depth was derived (attenuation coefficient, K_D).

FIELD OPERATION

The equipment was used under the supervision of the Science officers, who had received specific training in its use. Observations were made at all stations in one survey area over a period of a day or two, then the instrument was transferred when possible to the other campsites for a round of observations there. This cycle was repeated as frequently as possible throughout the study period.
Measurements were only taken after 8am and before 4pm, using the following routine:

1) Sensor covers were removed and the upwelling radiance window (bottom sensor) was carefully cleaned.
2) The instrument was immersed over the side of the boat for a while to allow its temperature to equilibrate to that of the seawater.
3) When instrument had reached temperature equilibrium, it was returned to the surface and the cover sensors fitted so that no light could enter. Dark values were logged for one minute (to effectively set zero).
4) The boat was placed on station and the depth measured (using the secchi line). The PRR was slowly lowered over the side into the water on the sunny side of the boat. Logging was initiated.
5) The PRR was slowly and steadily lowered to 1-2m above the bed (determined from the graph displayed on the computer), then steadily back up to the surface again.
6) Logging was stopped as the unit reached the surface.

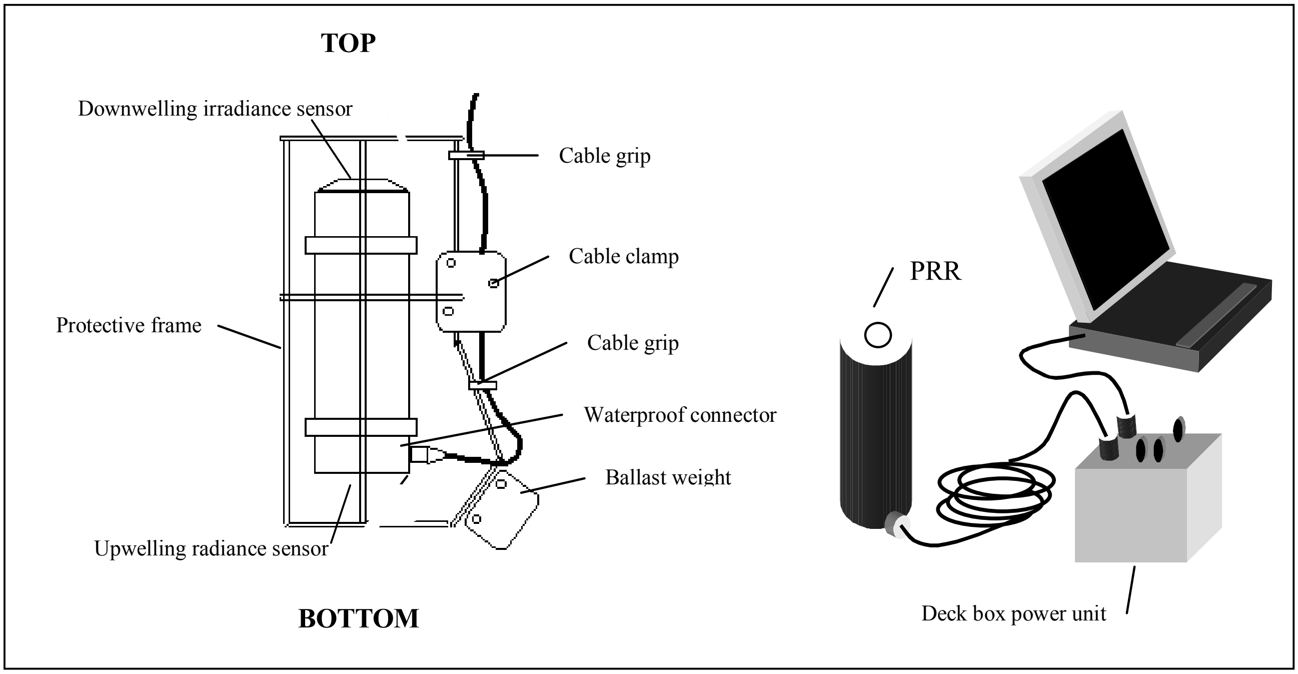


Figure 2.4_1 The Biospherical Profiling Reflectance Radiometer (PRR)

DATA ANALYSIS

Determination of in-water spectral ***downwelling irradiance*** and ***upwelling radiance*** (see Figure 2.1.1) are required for the calculation of the ***remote sensing reflectance*** (ocean colour from satellite images) and ***diffuse attenuation coefficient*** Kd(describing the rate of light attenuation with depth, - see Figure 2.1.1). Symbols used are:

Downwelling irradiance	$Ed(z, ,\lambda)$
Upwelling radiance	$Lu(z, ,\lambda)$
Remote sensing reflectance	$Rrs(\lambda)$
Diffuse attenuation coefficient	$Kd(z, ,\lambda)$

(z = depth, λ = wavelength; the annotations by each symbol indicate that each parameter varies with water depth and/or light wavelength)

Remote Sensing Reflectance $Rrs(\lambda)$

$Rrs(\lambda)$, is defined as a ratio of the ***water leaving radiance*** $Lw(\lambda)$ to ***the downwelling solar irradiance*** $Ed(0^+,\lambda)$ above the sea surface (Figure 2.1_1). Symbols used are:

water leaving radianc*e*	$Lw(\lambda)$
downwelling solar irradiance	$Ed(0^+,\lambda)$

(Note: 0^+ signifies just above the water surface, 0^- signifies just below the water surface – this annotation is used in the following paragraphs).

The equation is: $Rrs(\lambda)=Lw(\lambda)/Ed(0^+,\lambda)$

The most reliable *in-situ* method of determining water leaving radiance $Lw(\lambda)$ is to extrapolate from PRR data an in-water profile measurement of $Lu(0^-,\lambda)$. Extrapolation should be made from profile values which came from at least the top three measurements (ie just below the water surface) to calculate a reliable subsurface measurement (at 0^- or $z = 0$).

Extrapolation of $Lu(z,\lambda)$ to the subsurface can be done using the following relationship:

$$Lu(z,\lambda) = Lu(0^-,\lambda) \exp [-Ku(Zmn, \lambda) * (Zm - Zn)]$$

Where $Lu(z,\lambda)$ is the upwelling radiance at the depth Z and wavelength λ, $K(Zmn,\lambda)$ is the average upwelling diffuse attenuation coefficient between depths Zm and Zn. A statistical approach, involving an exponential curve fit, was used to best-fit the Lu light profile and hence obtain $Lu(0^-,\lambda)$.

$Ed(0^+,\lambda)$ is a spectral irradiance measurement that ideally should be made synchronous to the in-water measurements. This equipment was not available during the WRIScS study. The parameter can also be generated using the in-water irradiance profile as follows. On deriving the $Ed(0^-,\lambda)$ values, using the same approach described above as for Lu, $Ed(0^+,\lambda)$ can be calculated. The above-water surface downwelling solar irradiance can then be calculated following the assumption that approximately 96% of the total downwelling irradiance will be transmitted through the air-sea interface. Therefore:

$$Ed(0^-,\lambda) = 0.96 * Ed(0^+,\lambda)$$

Diffuse Attenuation Coefficient $Kd(z, ,\lambda)$

The attenuation of downwelling irradiance in an aquatic medium is a consequence of absorption and scattering processes proceeding in tandem as the photons encounter organic and inorganic matter in their subsurface propagation (Figure 2.1_1). Irradiance attenuation generally is described in terms of the irradiance attenuation coefficient, K, which is an apparent optical property i.e. a property dependent upon the spatial (vertical) distribution of the radiation. The irradiance attenuation coefficient, $K(z, \lambda)$ is defined as the logarithmic depth derivative of the spectral irradiance at the subsurface depth (z). Since irradiance is conveniently divided into its downwelling and upwelling components, Kd may be used to refer to the attenuation of the downwelling irradiance at depth z as:

$$Kd(z, \lambda) = -\log(Ed(z, \lambda)-Ed(0, \lambda))/z \qquad m^{-1}$$

[Note: It is not practical to use Ed(0), but instead a depth 2-5 metres below the surface (depending on turbidity), to avoid surface effects such as wave focusing and defocusing.]

The vertical profile of attenuation coefficients $Kd(z, \lambda)$, together with the respective value of downwelling irradiance just below the surface $Ed(0^-, \lambda)$, provide the best description of the optical environment of the water column under investigation.

2.4.2 Digital Photography

FIELD OPERATION

Olympus C-860L digital cameras were mounted in inexpensive underwater housings that could be used to 20-25m depth. These were used during quadrat surveys to take oblique (10-50º from zenith) photos of the seabed composed within the white quadrat at close range (1-2m). Examples of images collected are given in Figure 2.4_2. Images were generally collected at the beginning and end of each quadrat transect, and at intervals along it where the nature of the substrate changed. Care was taken that the photographer did not cast a shadow on the photographed area.

DATA ANALYSIS

The expectation was that the camera could record in a consistent fashion the light reflected from the seabed. It was recognised however that these measurements could be degraded in one of two ways:

1) By environmental factors. For example, high levels of water turbidity could both impair visibility and also significantly alter reflectance characteristics of the light reflected from the seabed before it entered the camera.
2) By the behaviour of the camera. The simple cameras used could not be used in a totally controlled fashion. The two most important 'uncontrolled' aspects of the camera operation were a) the auto-exposure and b) the white balance, which was used in a 'preset' rather than auto mode, in an attempt to impose a constant change in values.

Data analysis combined with a simple series of tank experiments (Appendix 2) showed that the auto-exposure had indeed varied in an indeterminable fashion, and that also the blue-band values had all been modified by an equal but unknown amount as part of a white-balance algorithm. Thus the images of the seabed can only be used for optical purposes as follows:

1) Using relative values within one colour band i.e. comparing seabed reflections to the white (quadrat) reflections within (but not between) the red, green and blue bands.
2) Comparing the red to the green values i.e the R/G ratio may be valid.

The images logged during the field survey were archived in a catalogue by transect. For each transect, each photo was inspected. Note that photos were not collected at all sites due to survey error. A selection of the photographs to be used for analysis was copied into a new working folder (as .TIF files), selection being based upon;

1) Provision of a representative series of images of the variation in bed-type found (based on quadrat survey records and RoxAnn survey acoustic data of seabed variability within 500m of each survey site).
2) Focussed images free of excessive turbidity (ie where seabed features could be discerned).
3) Images taken from between 10 and 50º from the vertical (or free of diver shadow).
4) Images containing a quadrat.

On selection, image files were re-named using the following notation (for effective sorting).

C1_Sxx_Qyy

where C (or L) is for Cary Cay or Long Cay, 1 (or 2) is for the Expedition number, xx is fore Site number and yy for Quadrat number.

Images were analysed using IDRISI software. The sequence for each image was as follows:

1) Import the .tiff photo image using the BIPIDRIS routine. This produces three files (Band1 = green, Band 2 = blue, Band 3 = red).
2) Create a 'collection' of the three images (this enables simultaneous interrogation of pixel values in the three images.
3) Display the three files.
4) Using the 'Feature Properties' tool make five ' structured random' measurements of RGB individual pixel values for each media (sediment, live coral, flora and fauna). The 'structured' element related taking most pixel readings on upward-facing (brightest) areas, but also including one or two measurements in more shady areas.
5) A single reading was taken from the white quadrat, with an effort being made to find the brightest spot on the quadrat.
6) A sub-composition was made of the view to eliminate the quadrat and any zones of reflection from the camera housing (sometimes present). The new composition was saved as a new Idrisi file and the three band files opened.
7) For each band in turn the histogram of reflection intensity was displayed and the minimum, maximum and mean values noted.

2.4.3 Munsell Chart Observations

Standard Munsell colour cards were waterproofed (encapsulated in plastic) and carried by divers to the seabed. The cards were matched to the 'dominant seabed colour' in quadrat surveys.

The colour seen by the diver at depth is not the colour of the card seen at the surface, due to light attenuation effects. However, attenuation will be affecting the cards and the substrate equally, so a match is still possible. The assumption has to be made that there is sufficient width of light spectra available at survey depths (up to 20m) to enable effective matching of colour. Analyses undertaken within this survey (Appendix 2.) indicate that the assumption is valid.

A further check on the reliability of the Munsell charts in determining potential reflectance of sediment was completed by collecting a series of sediment samples from observation quadrats on the seabed, and undertaking a Munsell-match with the sediments (wet) on the surface. The agreement was consistently good.

Some difficulty was experienced in educating the volunteer divers to recognise 'dominant' seabed colour. In most instances the dominant element of the seabed was the sediment, and in many instances the divers continued to record the sediment colour even when flora or fauna dominated the seabed. In the case of sea grass, it was in fact impossible to use the Munsell cards as the right colour card was not available. To overcome this ambiguity in the data, all Munsell observations used in analyses have been assumed to be sediment values, and in the relatively few observations where sediment was not recorded as dominant, the values have been checked individually and assigned as 'sediment' or 'non-sediment' on the basis of their match with adjacent sediment-dominated quadrats. Algal mats are included in the sediment colour category, unless specific differentiation was identified in the field notes.

Munsell colour coding was converted to light values using standard software supplied by the Munsell Card manufacturers, and the Japanese Electrotechnical Society
(at http://www.aist.go.jp/RIODB/ssrdoc/soba_e.html).

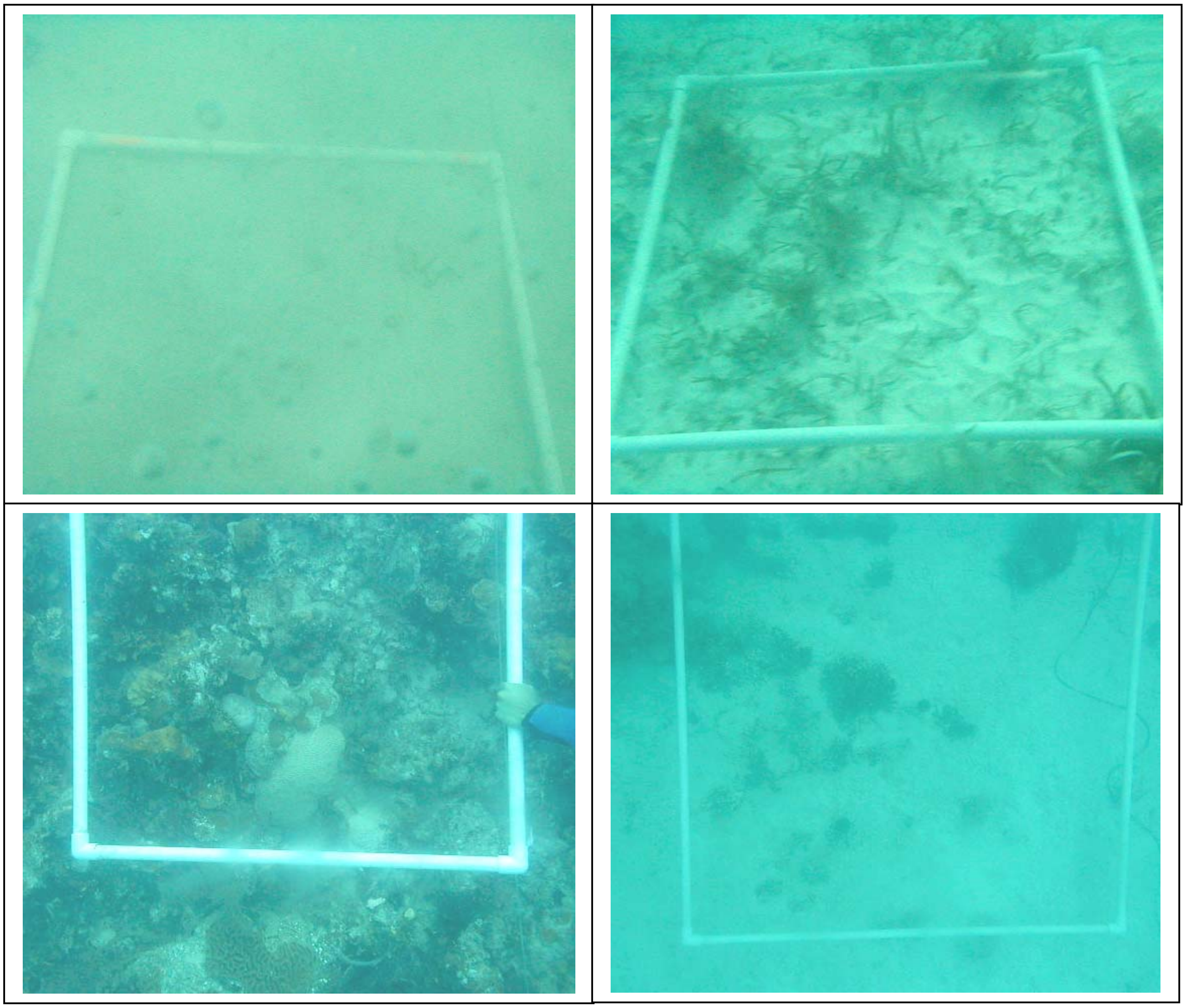


Figure 2.4_2. Examples of seabed digital camera images.

(Top left to bottom right: L2_S21_Q01 L2_S01_Q05 C2_S16_Q05 C2_S15_Q05)

2.5 *Laboratory Analyses*

2.5.1 *Sample Collection Protocols*

Water samples were collected for a basic range of water quality parameters, viz.

Suspended Particulate Matter (SPM)
Organic Matter (% of SPM)
Chlorophyll-a
Coloured Dissolved Organic Matter (CDOM)
Plankton Count

Only sample pre-treatment and some filtration could be undertaken in Belize, most analyses were conducted in UK at the Plymouth Marine Laboratories.

Samples were collected from sixteen selected sites every three weeks. The site numbers and the sample types collected at each are shown in Table 2.5_1. Samples were shipped to UK (Southampton), refrigerated, courtesy of Fyffes Ltd, on their banana boats. The samples were then couriered to Plymouth and stored frozen until analysis.

Volumes of seawater (ml) processed are shown

STATION	BOTTLE	PLANKTON	CHLOROPHYLL	GF/F FILTER	MEMBRANE FILTER	CDOM
C2	1	200	1500			
	2					
	3					
	4			1500		
	5					
	6					
C5	1				1500	100
	2					
	3					
	4			1500		
	5					
	6					
C8	1				1500	
	2					
	3					
	4			1500		
	5					
	6					
C10	1	200	1500			
	2					
	3					
	4			1500		
	5					
	6					
C12	1				1500	100
	2					
	3					
	4			1500		
	5					
	6					
C14	1				1500	
	2					
	3					
	4			1500		
	5					
	6					
C17	1				1500	100
	2					
	3					
	4			1500		
	5					
	6					
C20	1	200	1500			
	2					
	3					
	4			1500		
	5					
	6					

STATION	BOTTLE	PLANKTON	CHLOROPHYLL	GF/F FILTER	MEMBRANE FILTER	CDOM
L4	1	200	1500			
	2					
	3					
	4			1500		
	5					
	6					
L6	1				1500	100
	2					
	3					
	4			1500		
	5					
	6					
L10	1	200	1500			
	2					
	3					
	4			1500		
	5					
	6					
L13	1				1500	100
	2					
	3					
	4			1500		
	5					
	6					
L15	1	200	1500			
	2					
	3					
	4			1500		
	5					
	6					
L17	1				1500	
	2					
	3					
	4			1500		
	5					
	6					
L19	1				1500	100
	2					
	3					
	4			1500		
	5					
	6					
L24	1				1500	
	2					
	3					
	4			1500		
	5					
	6					

Table 2.5_1. Water Quality sampling sites, showing determinands at each site and volumes of water processed.

For every sampling run, a fresh set of water bottles and bucket sampler was supplied to each camp-site. Water samples were collected by dipping a clean (freshly rinsed in local seawater) bucket over the LEE side of the drifting boat at each station, being careful not to contaminate samples with such things as boat fuel etc. Two litres of water were collected at each site and stored in four 0.5l plastic containers provided. Lugols solution (0.5ml) was added to one of the bottles (for plankton preservation). The samples were despatched to arrive in Belize City within 24 hours of collection. They were then stored in the dark and cool while filtration/pre-treatment was completed, then despatched to the Fyffes ship at Big Creek, which departed weekly for UK.

2.5.2 Filtration

The Suspended Particulate Matter (SPM) concentrations were determined using two methodologies, based on filtering a known volume of water through a membrane (0.2 µm) or Glass Fibre (GF/F) filter (0.7 µm). The filter papers were pre-weighed, and re-weighed after the water sample has passed through them, after drying at 105°C to constant weight. The weight of SPM is equal to the difference between the weights and this is divided by the known volume to give a concentration in milligrams per litre (mg l^{-1}).

The membrane filters provide the most accurate weight, but the GF/F's can be used to determine the organic/inorganic fraction of the SPM. This is achieved by incineration in a muffle furnace at 500° C for 4 hours, until the volatile fraction is burnt off. The papers ar then re-weighed and the loss of weight is calculated as a percentage loss, approximately equivalent to the organic component.

Filtration was undertaken in Belize to minimise sample transport logistics and water sample degradation. Filter papers were pre-weighed in the Plymouth Marine Laboratory and stored in petri-dishes until required. The papers were dried and weighed in Belize, then stored in individual petri-dishes and sent to Plymouth to be re-dried, check weighed and combusted.

2.5.3 Chlorophyll-a

Particulate Chlorophyll was extracted from water samples in Belize by filtering 1.5 litres of seawater through a GF/F filter paper. The filter paper was then placed coloured-side-up on thick tissue to drain/dry, and then sealed in a flat-bottomed glass container with 20ml of methanol. The samples were then kept refrigerated (or as cool as possible during road transport periods) during their transport to PML where they were deep frozen until undergoing spectrophotometric analysis. This was not an ideal situation as the filter papers should have ideally been stored frozen in liquid nitrogen immediately after generation.

The spectrophotometer measured the spectral absorption from 380 to 800 nm at 2nm intervals. The spectra then show the absorption by all pigments (Figure 2.5_2).

The chlorophyll-a concentration was calculated using the following equations (Strickland & Parsons, 1968):

$$\text{Chl-a} = (R+PS+RU)/3$$

$$\text{Where [P], [RS] and [RU]} = (a*((E(665)-E(750))*P) - (b*(E(645)-E(750))*P + (c*(E(630)-E(750))*P)$$

The parameters in the latter equation are:

P= spectophotometer path length used
E = spectrophotometer reading at the indicated wavelengths
a=15.6, b=2 and c=-0.8 for R
a=11.6, b=1.31 and c=-0.14 for PS
a=11.64, b=2.16 and c=+0.1 for RU

An average of the three values was then taken as the chlorophyll-a concentration in mg/m^3.

A qualitative check was made to ensure that degradation had not converted all chlorophyll-a to accessory pigments, due to the non-ideal storage conditions. Figure 2.5_3 shows the results of adding 1 drop of Hydrochloric Acid (HCl) , which converts chlorophyll-a to accessory pigments. T1 and T2 show the effects of a time delay, to showing the progressive action of the acid, and demonstrates that the original peak represented degradable chlorophyll-a.

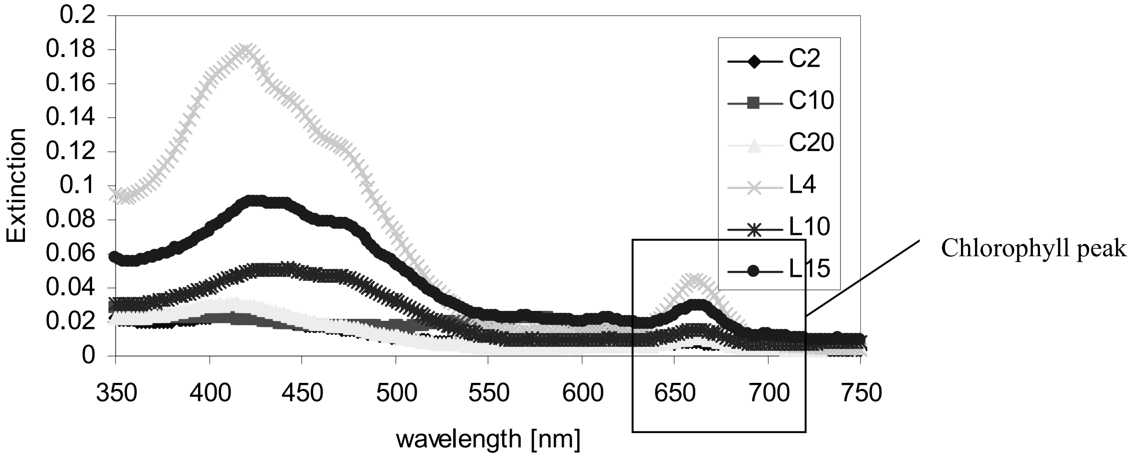


Figure 2.5_2. Spectral extinction of the 13/14 September 2001 pigment samples.

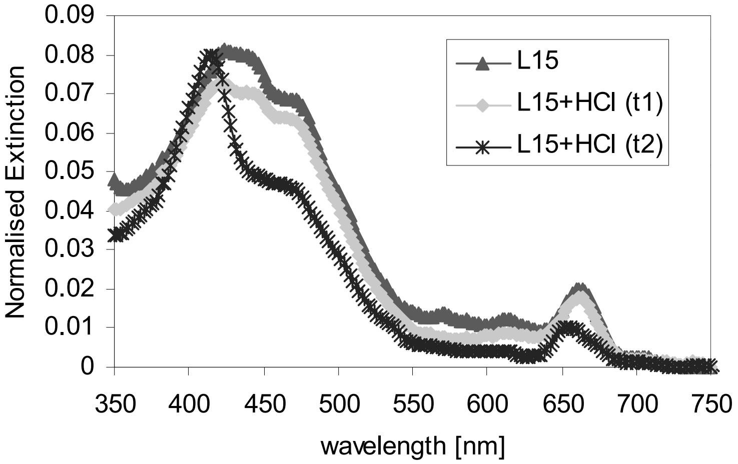


Figure 2.5_3. Spectral extinction after HCl was added to a sample.

2.5.4 Coloured Dissolved Organic Matter (CDOM)

The Coloured Dissolved Organic Matter was measured using the filtrate from the chlorophyll membrane filtration (Section 2.5.2). Sodium azide (0.5ml of 1% solution) was added to fix the CDOM as the samples were not stored under ideal conditions. They were kept refrigerated (or as cold as possible during road transport), but should have ideally been frozen in liquid nitrogen.

The samples were spectrophotometrically analysed as described in Section 2.5.3. A typical output is shown in Figure 2.5_4.

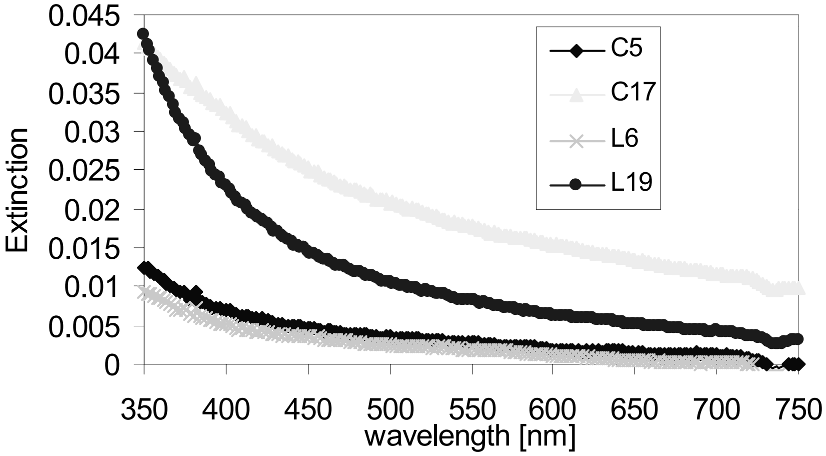


Figure 2.5_3 Spectral extinction of the 13/14 September 2001 CDOM samples.

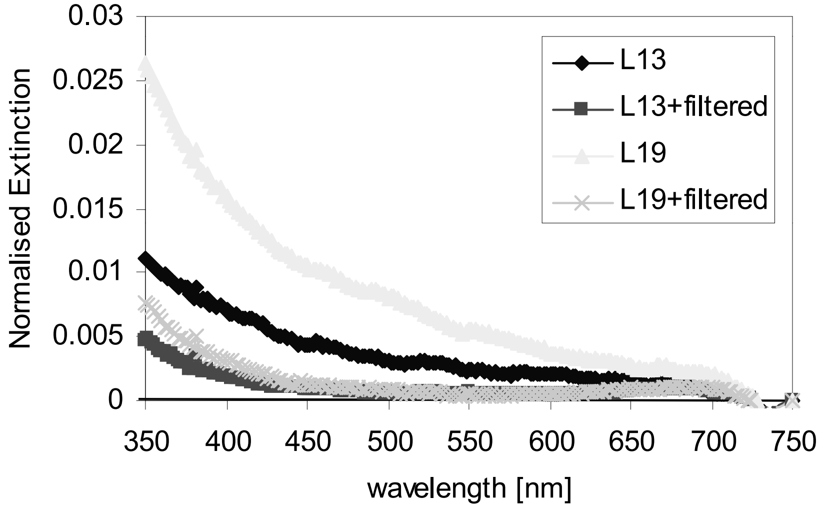


Figure 2.5_4. Spectral extinction after the samples were re-filtered through a 0.2 μm membrane .

Some of the samples had high levels of scattering (possibly caused by very small calcium carbonate particles in suspension) and so these samples were re-filtered through a 0.2 µm membrane.

The absorption due to CDOM (at 440 nm) was then calculated according to the following equation:

$$a_{CDOM}(440) = (E(440)-E(750))*\text{pathlength}$$

This value has been used as an index, and not converted to CDOM concentration. The index has not been corrected for a_{WATER} content.

2.5.5 *Plankton Counts*

Plankton counts were undertaken by an expert (D. Harbour). As the objective was to provide a synoptic understanding of the nature of the material suspended in the water samples, a semi-quantitative approach was adopted.

Approximately 100ml. of the shaken Lugol- fixed sample was settled overnight and the supernatant water pipetted off until 10ml. remained. This was settled in a 10 ml. Utermohl chamber. The whole of the base plate was examined at x 187 magnification and species were allocated a frequency score (present in every field, present in most fields, present in every microscope transect, approximately 10-100, <10) . Species names used are those in Hasle *et al* (1996).

2.6 *Satellite Image Processing*

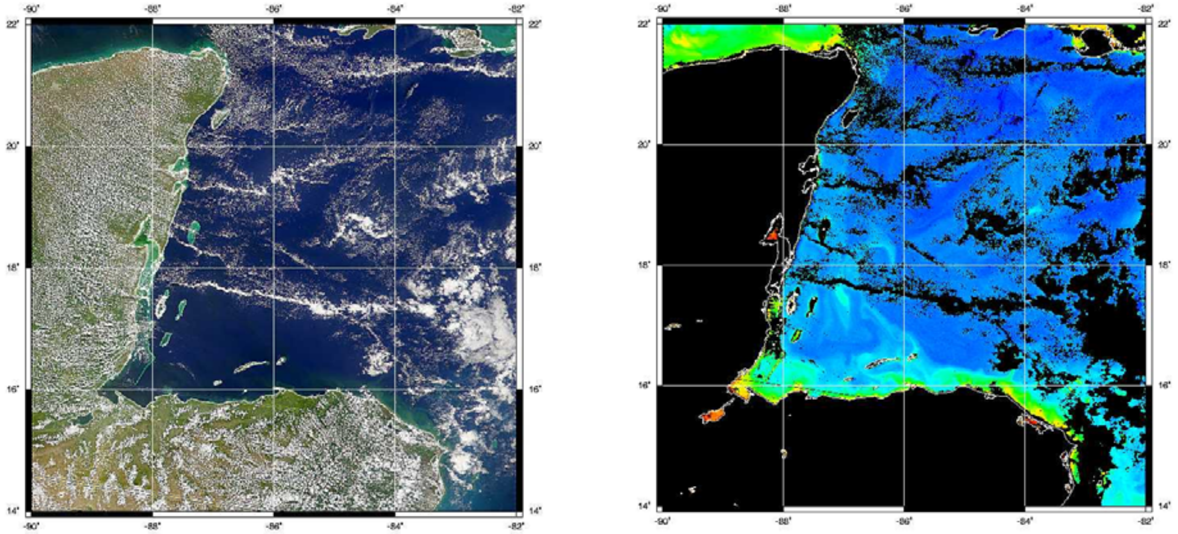
The WRIScS project is registered with NASA for the research use of SeaWiFS (Sea-viewing Wide Field-of-view Sensor) satellite imagery. Images are available daily and at a resolution of 1km^2 for the Belize study area.

Through the project, thirty seven SeaWiFS satellite images (Figure 2.6_1) were acquired from NASA. For the initial analysis, the (relatively) cloud free SeaWiFS imagery corresponding to field data collection times was downloaded and processed to level 2 (optical / biogeochemical products) using the NASA SeaWiFS Data Analysis System (SeaDAS). This was initially undertaken with SeaDAS version 4, but with the released of SeaDAS v4.1 in November 2001 the data was reprocessed with latest calibration file (released 18 December 2001).

A result of the standard level 2 processing is that shallow areas are often lost due to an inaccurate land mask and/or overactive cloud mask. The code was therefore been changed so that a non-water mask rather than the standard SeaDAS cloud and land masks was used. The mask is based on the near infra-red (NIR) single scattering aerosol corrected reflectance, R:

$$R(\lambda) = \left[\frac{L_s(\lambda)\pi}{F0(\lambda)\cos(\theta)} \right] - R_r$$

Where L_s is the sensor radiance, F0 is the extraterrestrial solar irradiance, θ is the solar zenith angle and R_r is the Rayleigh corrected reflectance. It uses both a comparison of two NIR wavebands and threshold on a single band, see Figure 2.4_2, and resulted from the research of Moore *et. al.* (1999).



a) b)

Figure 2.6_1. SeaWiFS a) Level 1 and b) Level 2 (chlorophyll) quicklooks of Belize.

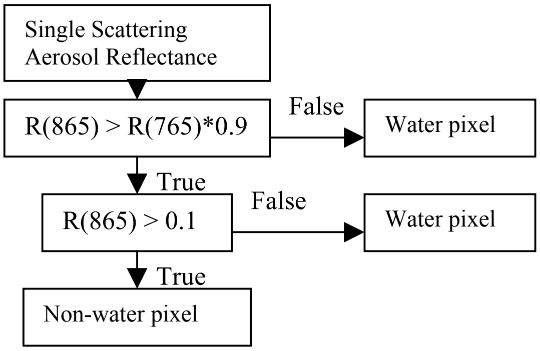


Figure 2.6_2. Decision tree for masking a non-water pixel.

A template with the survey stations (Table 2.1_1) was been developed, and individual pixels (corresponding to the stations) were extracted from each image. A time-series of reflectance

(Remote Sensing Reflectance, Rrs(λ) – see Section 2.4.1) and derived water quality properties could then be created for each station (pixel) .

The SeaWiFS products (spectral bands) are shown in Table 6.1_1.

Band	SeaWiFS wavelengths Band range & centre λ (nm)	Colour
1	402-422 (412)	Violet
2	433-453 (443)	Blue
3	480-500 (490)	Blue/Green
4	500-520 (510)	Green
5	545-565 (555)	Green/yellow
6	660-680 (670)	Red

Table 2.6_1. SeaWiFS Bands and corresponding colours.