A spatial model to predict water attenuation for the bathymetric correction of remotely sensed images

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ABSTRACT

Objective measurement of habitat change using remote sensing requires processing of the images to enhance the bottom reflectance signal. This process typically uses correction techniques to remove the influence of the water column on bottom reflectance, and to enable the accurate correction of the imagery for varying bathymetry. Such correction measures depend on reliable estimates of water column light attenuation.

An investigation into the spatial variation in attenuation in a typical tropical region was undertaken. Measurements of gross spatial variations in downwelling attenuation around San Andres and Providence islands in the Caribbean were made using a PAR sensor. Measurements of specific attenuation were also made for blue, green and red light using filters fitted to the sensor. Results showed a four-fold variation in light attenuation in shallow littoral regions alone.

These findings suggest that the results of studies where single measurements of 'average' attenuation have been used to depth-correct remotely sensed imagery should be interpreted with a high degree of caution. The paper goes on to show that simple models can be empirically obtained where attenuation can be spatially predicted with confidence, based on the variables of water depth, distance to and size of mangrove beds, and distance to and size of towns. The models obtained showed high statistical significance, with 89% and 80% of the spatial variation in attenuation explained for San Andres and Providence, respectively. It is postulated that the use of such approaches for the estimation of attenuation will lead to more accurate depth-correction and hence improved interpretation of remotely sensed imagery for littoral regions.

Keywords and phrases: spatial variation, Caribbean littoral zone, depth-correction measures , downwelling attenuation, remote sensed images, spatial modelling.

1.0 INTRODUCTION

Optical remote sensing offers a non-invasive technique with which to rapidly monitor changes in the cover and health of submerged habitats. However its full potential is still to be exploited in littoral environments, where the strong attenuating influence of the water column has been a limiting factor. A combination of optical properties in the water column (absorption, scattering) result in a significantly reduced and spectrally altered bottom reflectance. This impact gets greater with increasing depths and with waters of greater turbidity (Spitzer and Dirks 1987, Gould and Arnone 1998). To extend the potential of optical remote sensing in littoral applications such as for monitoring coral reef health and for qualitative and quantitative monitoring of seagrass habitats, the influence of the water column must be removed from the remotely sensed image. Such a process also significantly improves the accuracy of classification of such habitats (Mumby *et al*. 1998).

Despite the existence for some time of a number of algorithms for correcting for water column depth and turbidity effects (e.g. Lyzenga 1978, 1981, Moussa et al. 1989, Bierwirth et al. 1993) few studies of tropical marine habitats attempt such correction techniques before classification. Mumby et al. (1998) reported only four studies out of forty five (9%) that attempted such pre-processing methods and concluded that authors were either unaware of these methods or believed that the clear waters of the tropics have constant and negligible attenuation properties.

In order to address the confounding influence of the water column in images of the littoral zone, a knowledge of the local attenuation (K_d) is necessary. Few studies have used independently acquired estimates of attenuation, with most extracting K_d values for relevant bands directly from their imagery in areas of uniform bottom type (e.g. sand) and known depth (e.g. Lyzenga, 1981, Bierwirth et al. 1993). Nearly all of these studies assume that K_d values extracted for one area can be applied to other regions. However, it is likely that attenuation in the tropical littoral zone spatially may be highly variable. This paper reports the first attempt to investigate the nature of the spatial variation in water column attenuation for a tropical littoral region, and infers its potential influence on calculated bottom reflectance.

2.0 STUDY SITE DESCRIPTION

This study focuses on the littoral habitats of the Archipelago of San Andres and Providencia, Colombia, an expanse of 250,000 km^2 isolated within the western waters of the Caribbean Sea (Figure 1). Its two main islands are: San Andres (12° 34’N; 81° 43’W), and Old Providence (13° 22’N; 81° 23’W).

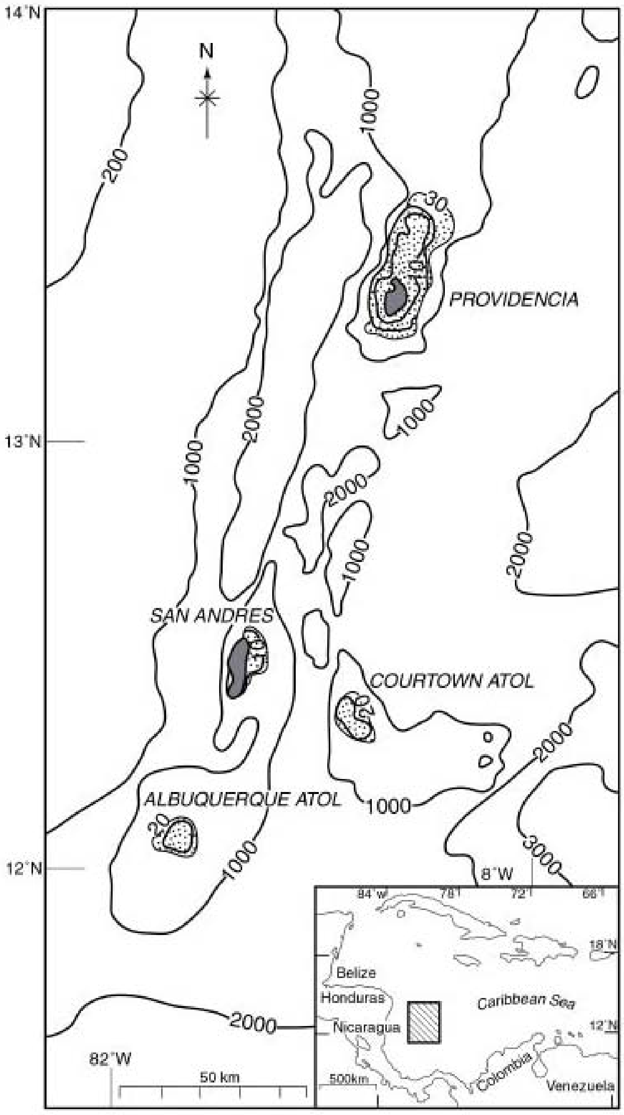

Figure 1: Map showing location of the islands of San Andres and Providence in the south western Caribbean Sea.

Significant increases in the human population migrating to San Andres from the 1950's through to the 1980's saw a dramatic rise in population from 5,675 inhabitants in 1952 to around 80,000 by 1992 (Vollmer 1997). Still today San Andres is by far the most developed island of the archipelago and a major tourist destination.

San Andres has a smooth topography and an area of almost 26 km^2. The main extent of its platform is to the east and north east of the island bordered by a barrier reef with depths ranging between 1 to 20 m before dropping rapidly to over 1000m at the edge of the platform. The lagoonal area behind the reef receives some inputs of diffuse organic pollution since most urban development is concentrated in the north east in the town of San Andres, along with the main harbour, the airport and a number of hotel resorts. Census data from 1990 indicates that over 70% of the population lives in the north eastern sector of the island (Diaz et al. 1995). The enclosed lagoon has a limited influence from the open sea and relatively calm waters. Sewage is diverted to the west coast where the platform is much narrower and steeply plunges to deep waters.

In contrast to San Andres, the population Old Providence (Providencia) still today does not exceed 5,500 inhabitants. The platform surrounding Old Providence is more extensive at between 5-10 m depth. To the north, it extends for 60 km with the second longest barrier reef in the Caribbean bordering its eastern side. The substrate is finer darker silty sand comparing with the white coarse sediment of coraline origin of the platform around San Andres.

The typical submerged habitats found around both islands are seagrass (mainly *Thalassia* and *Syringodium* genera) and algal beds in different proportions, soft and hard coral habitats, as well as sandy and rocky substrates. A number of mangrove habitats of different sizes are also scattered around the coastlines of both islands, which represent an extra source of natural eutrophic waters. The effects of increased tourism to both islands in recent years but mostly to San Andres have had a significant effect on the clarity of the surrounding waters as they have been receiving increasing inputs of organic pollution and increased boat traffic.

3.0 METHODS

3.1 Broad-band Irradiance Measurements

Measurements of gross spatial variations in downwelling PAR attenuation at stations around both San Andres and Old Providence islands were made using a submersible PAR cosine quantum irradiance meter (Macam model Q203 PAR, sensor 5638). In addition to broad-band PAR measurements, profiles of specific attenuation were also made for red, green, and blue light using filters fitted to the sensor closely matching the three visible band widths of the Landsat TM sensor. The sensor was fixed facing upwards on a weighted lowering frame and lowered below the water surface. Measurements were made at 1 m, 0.5 m or 0.25 m intervals to a maximum of 10 m depending on the depth and degree of attenuation of the water column. In that way a vertical profile comprising typically 10 measurements was produced for each station. Measurements were referenced to above surface incident irradiance using an identical continuously logging PAR cosine sensor on deck to correct for fluctuations in surface incident flux due to drifting clouds. An electronic damping circuit, part of the submersible meter, was also used to temporally average the readings, to smooth out rapid fluctuations in irradiance intensity produced by wave action

The measurements were made at selected sites chosen around San Andres, and Old Providence after dividing up the coastal zone into arbitrary "optical zones" and assuring that at least one sampling site was contained in each. Measuring site positions were located to an accuracy of less than 4 m using Differential GPS. All measurements were made between 10:00 and 15:00 hours local time each day, to minimise solar angle effects.

The first set of PAR measurements (AS1-AS25 and AP1-AP18, Figures 2 and 3) took place over a one month period (first collection period, A) from 16-4-99 to 14-5-99. A second set of PAR measurements were carried out in San Andres a few weeks later (BS1-BS24, Figure 2) during the period 6-6-99 to 23-6-99 (second collection period-B). The second set of PAR measurements around San Andres (B) included a number of sites that were also sampled during the first collection period (A) which allowed for comparisons of temporal changes in attenuation. Pairs of stations within 300 m distance from each other were considered to be the same site, and subsequently 11 pairs of measurements were compared. These stations, in close proximity, were used to test the hypothesis that temporal factors did not influence the K_d (PAR) measurements, at least within the time frame that this study took place. To test this a paired-sample t-test was carried out for the 11 paired stations around San Andres.

For all downwelling measurements, the diffuse vertical attenuation coefficients (K_d) were calculated as the linear slope coefficient of the logarithm of downwelling PAR irradiance with respect to depth (Kirk 1994). The majority of regressions between ln-irradiance and depth gave r^2 values of 0.95 or above. Poor linear relationships were omitted.

4.0 RESULTS

4.1 Downwelling PAR Measurements – Temporal Variations

During the first collection period (A) 25 profiles (AS1-AS25) of downwelling PAR irradiance were measured around San Andres and 18 around Providence (AP1-AP18). During the data collection period (B) a second set of 21 PAR measurements (BS1-BS24) were obtained for San Andres. As Figure 2 shows a number of sites in San Andres were re-sampled during the two data collection periods, or on another date during the same data collection period. Attenuation coefficients for these stations that were in close proximity (not more than 300 m apart) are summarised in Table 2.

Table 2 *Comparison of K_d (PAR) values for revisited stations around San Andres island corresponding to those shown in Figure 2.*

Date	**Station**	**K_d (m^{-1})**	**Station**	**K_d (m^{-1})**
13/5/99	AS2	0.139	BS4	0.110
16/4/99	AS23	0.081	BS22	0.130
16/4/99	AS22	0.193	BS21	0.139
16/4/99	AS21	0.161	BS19	0.108
22/4/99	AS19	0.088	BS18	0.113
22/4/99	AS19	0.088	AS20	0.045
14/5/99	AS17	0.299	BS12	0.287
15/6/99	BS13	0.249	BS12	0.287
14/5/99	AS14	0.262	BS9	0.304
7/6/99	BS3	0.157	BS2	0.153
14/5/99	AS9	0.272	AS8	0.292

No consistent pattern in variation in attenuation is evident, although differences do exist at some stations. The results of a paired-sample t-test on the data indicated no significance consistent differences due to sampling period (n = 11, t=0.511, P>0.05). Thus, differences between stations were considered to be more due to spatial as opposed to temporal variation in light attenuation. Subsequent analysis of the dataset treated all the data combined, irrespective of sampling period.

4.3 Downwelling PAR Measurements – Spatial Variations

Spatial variation in K_d around the islands is also shown in diagrammatic form in Figures 2 and 3. Detailed measurement tables for each station are reported in Karpouzli *et. al.* (in press).

Attenuation around San Andres ranged from 0.05 to 0.57 m^{-1} corresponding to a range of depth in the euphotic zone of 102 m down to 8.1 m. The highest attenuation was measured at locations closest to the port, the mangrove areas and nearest to the developed coastline by the major towns. The lowest attenuation values were found off the north west coast and at the southern most point of the island. These patterns follow general variations in water quality (chlorophyl and dissolved colour) observed in samples taken coincident with optical measuremnts (Karpouzli *et. al.* In press).

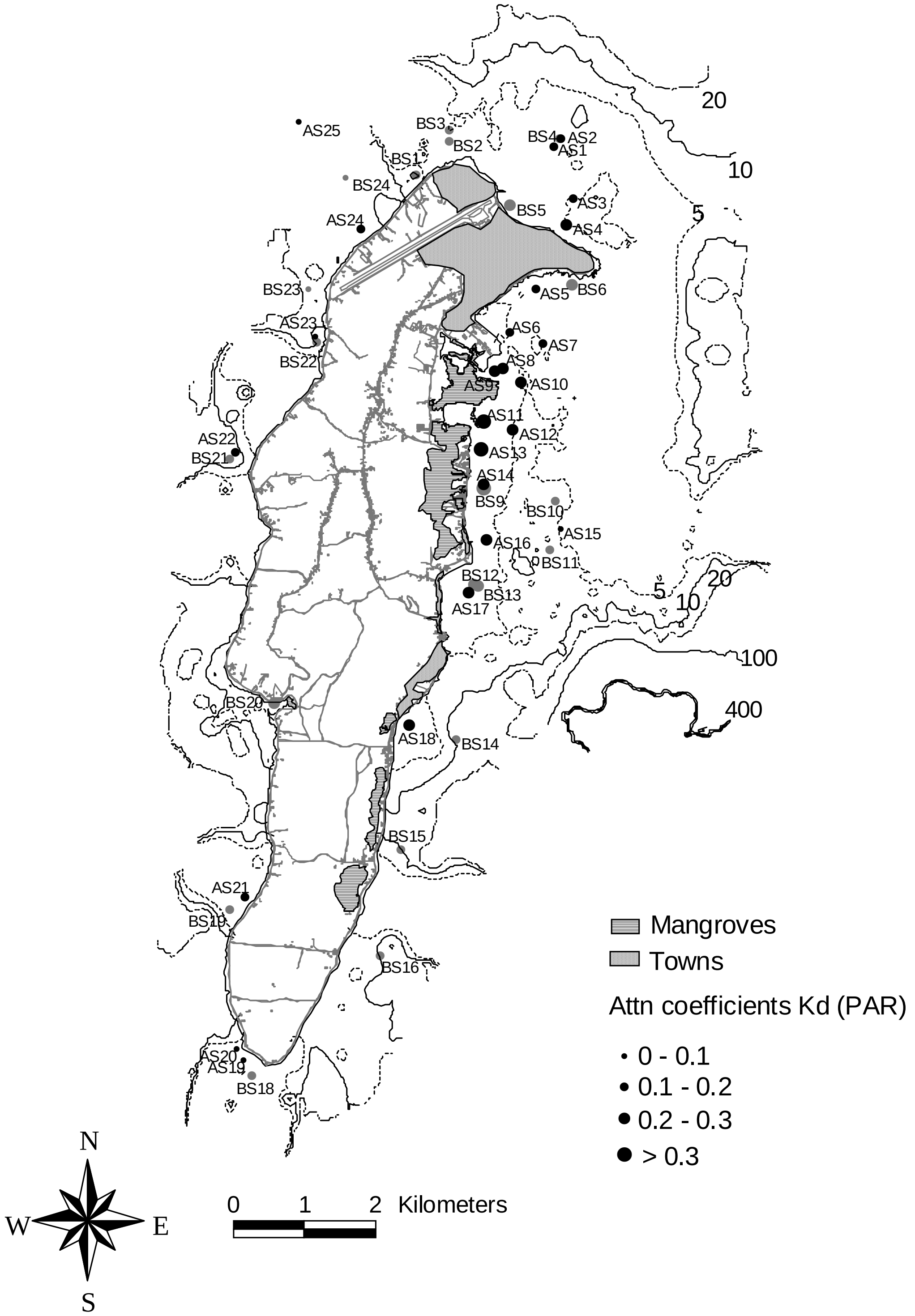

Figure 2: *Variation in measured PAR attenuation (K_d) in coastal waters around the island of San Andres. Sampling stations marked A denote first sampling period, B second sampling period.*

Similarly, for Providence attenuation ranged from 0.06 to 0.38 m^{-1} corresponding to variation in euphotic zone depths of 74.2 m down to 12.1 m. The greatest attenuation was measured near the harbour by the town of Old Providence and along the west coast of the island where most of the tourist resorts are found (Figure 3).

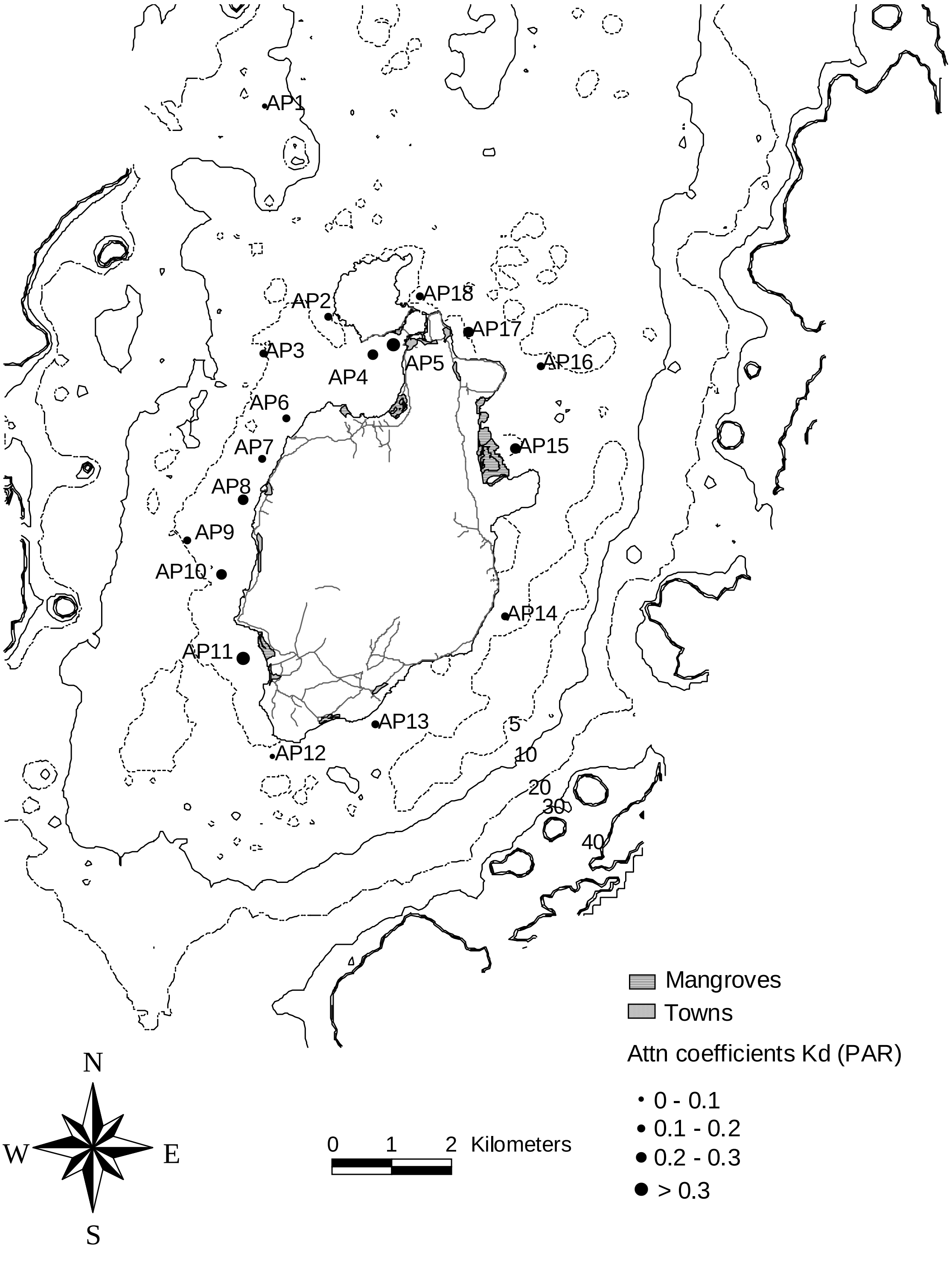

Figure 3: Variation in measured PAR attenuation (K_d) in coastal waters around the island of Providence during the first sampling period.

The spatial variation of attenuation in individual red, green and blue bands closely followed the pattern of the PAR measurements, being highest at the same stations that PAR attenuation was highest. Lowest attenuation was almost always observed at the blue region, suggesting that blue light is the most penetrative. Red light was most attenuated, attributed to the influence of the greater absorption of the light in this region by water itself. In the few cases that green band attenuation approached or was less than that for blue light, these were generally in the most turbid areas or where it might be expected localized eutrophication effects were operating (e.g. near ports and mangroves).

4.4 Predictive Models for Spatial Estimation of Attenuation

To process a remotely sensed image to bottom reflectance in order to investigate underwater habitats and to enable the accurate correction of the imagery for varying bathymetry, an accurate measure of the water column attenuation at each pixel is required. However, the results of the spatial survey indicate a high degree of variation in light attenuation in the waters around both islands under study. Thus, if a single measure of 'average' attenuation is used for water column correction of imagery, the accuracy of the result is likely to be questionable.

However, it is possible to generalise some factors about the behaviour of light attenuation around the islands. Firstly, K_d values generally decrease with greater distance from the shore of each island. Secondly, K_d values are generally lower over deeper waters than shallower ones. These trends would suggest that it may be possible to develop simple relationships which may be used to explain and map the distribution in attenuation in such waters. Thus, in an attempt to better understand the sources of variation in water attenuation around the coastal zones of San Andres and Providence, multiple regression analysis was employed to develop simple models to estimate PAR attenuation. A predictive model to estimate K_d in areas where such measurements were not made would also give rise to better estimation of attenuation as opposed to direct interpolation between the measured K_d points.

The construction of a simple model was attempted separately for San Andres and Providence islands. For San Andres the measurements of PAR attenuation for both the first and second collection periods were used. Deep water sites were not included in the analysis since the precise water depths for these sites was not known.

A number of predictor terms were considered and their significance to K_d tested using stepwise multiple regression, performed using the Systat™ software package. Terms were validated by being added and removed from the analysis to lead to an optimal subset of variables that gave the best possible regression equation. The predictor terms that were considered were:

- *Distance from shore* (L_M) - the minimum straight line Euclidean distance of the sampling station from the respective island shore, calculated from relevant data layers using ARC/Info™ GIS.
- *Water depth* (D or $1/D$) - the depth of the water column at each sampling station, measured during sampling using a hand-held echosounder.
- *Influence of Mangroves* (M_A/L_M or M_A/L_M^2) - a cumulative predictor hypothesised to influence K_d as a factor of mangrove bed surface area (M_A) and their distance from the sampling stations (L_M). In the absence of detailed information on current directions around the islands it was assumed that all mangroves on the coast facing the particular station would have some influence on it. Thus, sampling stations were divided into east or west groups and only the east coast mangroves were considered to have an effect on the east lying stations and the contrary for the west lying stations.
- *Influence of major towns* (T_A/L_T or T_A/L_T^2) - In the absence of detailed population estimates for the different towns or of waste water volumes from different sources, the area of the settlements (T_A) and their distance from the sampling stations (L_T) was used to form this cumulative predictor. As for the mangroves, only those coastal towns on the east or west coasts were considered depending on the particular location of the sampling station.
- *Influence of river and sewage outlets* ($1/L_R$ or $1/L_R^2$) - a cumulative predictor estimated assuming that their influence on K_d is inversely related to their distance (L_R) from a particular sampling station. The predictor was then the sum of the inverse distances from the outlets to the given sampling point or the sum of the distances squared. Again, only east or west outlets were considered depending on sampling station location.

Regression Results - For San Andres the strongest correlation between attenuation and a single variable was with water depth:

$$K_d = 0.061 + 0.673\ 1/D, \quad n = 44,\ r^2 = 0.752,\ p < 0.001,$$

indicating the major influence of depth in determining relative water clarity around the island. With the addition of further variables, it was found that the regression was improved to

$$K_d = 0.0778 + 0.4781\ 1/D + 0.0074\ M_A/L_M^2 + 0.0028\ T_A/L_T^2,\quad n = 44,\ r^2 = 0.890,\ p < 0.001,$$

With the elimination of Station 11 (Southwest Bay) from the dataset for Providence island, which was indicated as an outlier, depth was also a strongly correlating variable with K_d:

$$K_d = 0.069 + 0.646\ 1/D,\quad n = 16,\ r^2 = 0.633,\ p < 0.001,$$

The relationship between K_d and depth for Providence is very similar to that obtained for San Andres above. With the addition of more variables into stepwise regression analysis the model was improved to:

$$K_d = 0.226 - 0.0136\ D + 0.0007\ T_A/L_T,\quad n = 16,\ r^2 = 0.80,\ p < 0.001,$$

The addition of further variables did not improve the model.

5.0 DISCUSSION

This investigation has shown that there was a three to four-fold spatial variation in the attenuation of tropical “clear” littoral waters around the islands of San Andres and Providence in the south western Caribbean Sea, corresponding to extremely wide variations in the depth of light penetration around both islands. Coincident water quality measurements suggest that this variation was largely the result of attenuation due to scattering by particulate matter in the water column, rather than varying concentrations of dissolved yellow substances. Broad-band spectral measurements indicate that blue light was the most penetrating. However although there is some evidence for slightly increasing chlorophyll concentrations around San Andres, light is still of sufficient quality to support a wide variety of plant and coral habitats.

The limited sampling over time in this study (April to June) indicated that there was little influence of a temporal component to variation in K_d (Table 2). However, this would need greater investigation in order to ascertain the degree of variation over the different seasons.

These results therefore suggest that it may be highly inappropriate to use a single or few measures of ‘typical’ attenuation obtained in deep water or shallow areas for water column correction of remotely sensed images acquired over tropical regions where reflectances are influenced by both variations in water depth and bottom type. It further suggests that the results of such corrections should be interpreted with a high degree of caution. Deepwater attenuation values tend to be much lower than those over related littoral zones and, as a result of scattering by varying concentrations of particulate matter, attenuation values in shallower waters are highly variable. Clearly, field data from deep water sites, as well as in the proximity of more turbid or organic-rich water sources, are required to objectively correct remotely sensed images for water column attenuation.

In this study, shallower waters generally showed greater attenuation compared to more open and deeper sites. However, there was considerable variation in attenuation in shallow regions alone, with up to three-fold variations encountered. It is thought this variation was a function of

- proximity of the sampling stations to the coastline
- proximity to centres of population or mangrove and lagoon environments
- local currents

That attenuation was lowest further away from shore tends to indicate the decreased influence of land processes and deeper waters which both encourages settlement of sediments and discourages their resuspension.

From the empirical modelling studies, water depth had the largest influence on K_d. Deeper water would be expected to be both further away from the shoreline and clearer, due to the larger volume of water over which turbid particles may diffuse, and also due to lessened influence of sandy substrates where sediment may become resuspended. The results from the multivariate regression analysis gave very similar models for both islands for the prediction of attenuation from water depth alone, suggesting that a general model for both islands would be obtainable.

For both islands, predictions of K_d were significantly improved by including terms for the proximity and hence influence of, mangrove beds (known to be significant sources of suspended sediments) and towns. The overall strength of the equations developed for San Andres was high, with nearly 90% of the variation in K_d explained by variations in depth, distance to and size of mangroves and distance to and size of towns. Relationships for Providence were less strong, with only 80% of the variation in K_d explained by depth and distance to and size of towns. This may be partially the result of the lower number of sampling stations measured around this island but may also suggest that other factors that were not included in the analysis may have been responsible in part for the variation encountered in K_d. One such variable not included is the influence of current strengths and directions. These may have had more influence around Providence island where the platform is more exposed to the predominantly north-eastern wind-induced currents as the barrier reef is less continuous around where stations were located around this island than for San Andres (Diaz et al. 1996, 1997). Current hydrologies around both islands may thus be markedly different.

The results of this study suggest that, using the equations developed, K_d may be predicted spatially with a high degree of confidence for all locations on the platforms around both these tropical islands. This would then enable remotely sensed images to be more accurately corrected for water column effects than if based on 'average' attenuation values alone. It further suggests that similar relationships with driving variables may be obtained for other littoral areas. The models reported here were developed for broad PAR attenuation. For the correction of multispectral remotely sensed images over littoral regions, estimates of band-specific Kd would be required. However, the similarities in behaviour between the broad-band blue, green and red attenuation measurements made during this study and the broader PAR attenuation values suggests that models specific for individual sensor bands should be easily obtainable.

More accurate measurements of distance to sources of turbid water may lead to improvements in the accuracy of the models. For example, populations of towns may be a better variable to describe the influence of towns as opposed to their size as was used in this study. The influence of river flows and sewage outfalls may also be more quantitatively related to their discharge volumes rather than simple distance from their locations. Furthermore, more detailed information on hydrology may allow greater understanding of the diffusion of pollutants in the water column and hence lead to better estimates of K_d. Nevertheless, the results from this study are particularly encouraging, given the limited information available for the study region.

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