The use of optical satellite observations to optimize ship-based sans inventories in coastal areas

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1. INTRODUCTION

For small islands states like the islands in the Caribbean sea the economic development depends heavily on the tourist industry. The growth of the tourist industry and therefore of the economic development mainly depends on the availability of an up-to-date infrastructure.

For the development and construction of the islands infrastructure -like houses, hotels, roads, coastal defences- sand is needed. However, due to the nature of these islands, sand on the islands themselves cannot be used. As a consequence sand is a scarce commodity and, therefore, studies are needed to assess the available submarine sand supplies in the immediate vicinity of these islands.

One of such studies has been performed by DELFT HYDRAULICS for the Ministry of Economic Affairs of the Caribbean island Aruba (Hoozemans and Hulsbergen, 1991). Within the framework of this study a sand inventory was performed in the coastal waters of Aruba up to a depth of 30 meters. The aim of this study was both to find suitable areas for mining sand and to assess the size of these sand resources, its quality and the consequences of sand mining for the ecological system.

In order to assess the bottom composition of the coastal zone of Aruba an extensive ship based survey was executed. Of each sample the sand concentration and sand quality was assessed. In addition the thickness of the sand layer was determined. The cost and the success of such a traditional survey are determined by the number of samples taken. In order to cover the whole area a considerable number of samples should be taken, making the survey rather expensive and time-consuming.

At DELFT HYDRAULICS techniques have been developed to map the sea bottom topography of shallow coastal waters by optical remote sensing. In relatively clear coastal waters it has been demonstrated (Hesselmans 1990) that bottom features can be discerned up to a depth of 40 m. As part of this technique the composition of the top layer of the sea bottom can be assessed. Therefore, it can also be used to optimize ship-based sand inventories in coastal areas. The aim of this study is to investigate the technical and commercial feasibility of the technique for sand inventory studies.

2. PROBLEM

The availability of sand is important for the development of Aruba in the Caribbean Sea. The availability of sand offshore at depths less than 30 m has extensively been investigated by ship based methods. Systematic sampling of the sea bottom using traditional ship based methods requires a substantial effort.

The problem addressed is how optical remote sensing data can be used to optimize a sand inventory in two ways:

1. *planning:* by optimizing the deployment of the vessels used to sample the sea bed and to assess the thickness of the sand layer. Sampling efforts should be concentrated on the sandy areas.
2. *spatial interpolation and extrapolation:* using optical remote sensing data for interpolation between ship based measurements to make an optimal guess of the sand concentration and sand quality at locations not covered by the survey vessel. The sand volume can be determined by combining the sand layer thickness measurements and the sand surface assessment derived from the (calibrated) remote sensing data.

3. DATA

The sand inventory discussed in this report was executed in the coastal waters of Aruba, an island in the southern part of the Caribbean (10° 30'N 70°W). A map of the island is shown in **Fig. 1**. In this project Landsat Thematic Mapper imagery is used. The imagery was recorded September 8, 1988. An intensity image based on bands 1,2, and 3 is shown in **Fig. 2**. The bright spots in the image are clouds. Landsat TM data consist of 7 bands of which 3 are located in the visible part of the electromagnetic spectrum. Light in these three bands can penetrate the water and reveal properties of the sea bed. The pixel size is 28.5 x 28.5 m^2. An Admiralty Chart of Aruba is also available. The chart is based on soundings in the period 1970 - 1972.

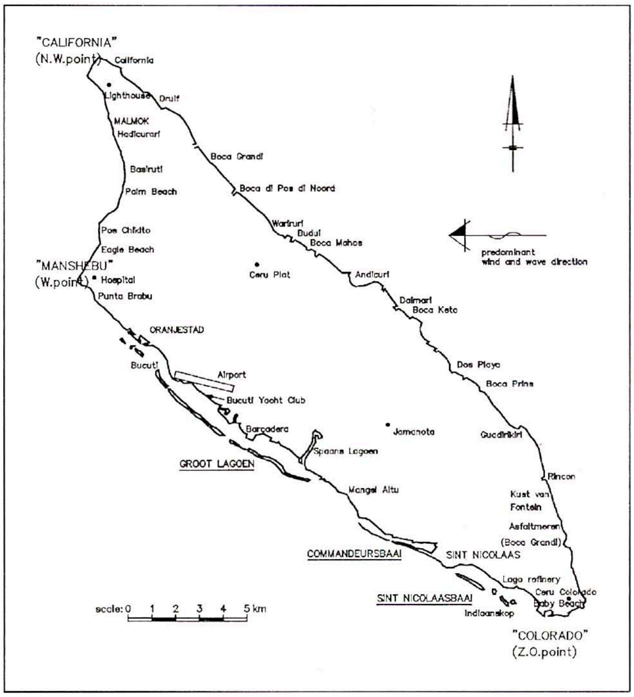

Figure 1 - Map of Aruba

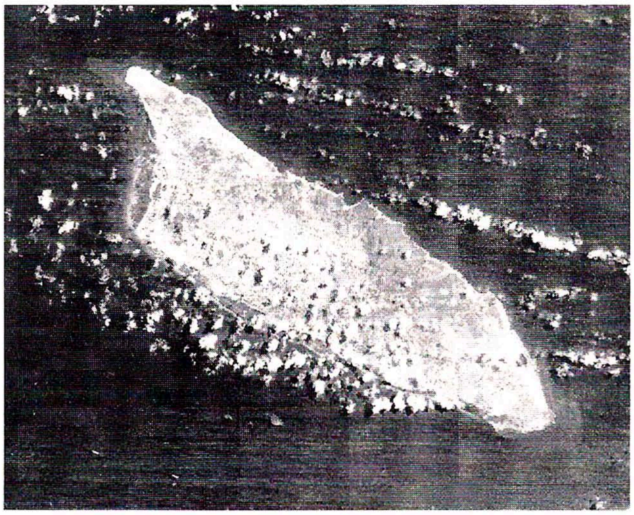

Figure 2 - Landsat TM image of Aruba: intensity of the optical bands 1, 2 and 3

In situ data on the occurrence of sand in the top soil layer of the sea bed have been compiled by Hoozemans and Hulsbergen (1991). These data extend up to the 30 m depth line. **Fig. 5** shows the 927 sample sites and the amounts of sand in the top layer. At 59 sites two samples were taken. These samples have a correlation coefficient of 0.71. The average difference between two samples at the same site is 15 per cent and the maximum difference is 75 per cent. In three areas a homogeneous top layer was found with a sand concentration of more than 50 per cent. In these areas 115 extra locations were sampled to assess the position of the sand layer in more detail. This reduced the sampling distance to effectively 125 m.

Bottom samples were taken using a two litre Van Veen grab sampler. The penetration depth of the Van Veen grab sampler is about 15 cm. The contents of the sampler was passed through a sieve. Particles smaller than 7 mm were classified as sand. Larger particles were classified as coral. The size of both fractions was estimated visually. The sand fraction in all samples taken, consists of crumbled coral and shells ($CaCO_3$).

Three sites in deep water have been studied in more detail. These areas are located in the North-West (California), in the West (Manshebu) and in the South-East (Colorado). The sand properties of the top layer of these areas were assessed. In addition the thickness of the sand layer in these three areas has been determined. Results are given in **Tab. 1**. At each location two or three measurements of the thickness of the sand layer are made.

4. METHOD

Planning

Planning of a sand inventory can be improved by using optical (multi spectral) remote sensing. The remote sensing observations in the blue and green spectral bands can be processed using a model describing the relation between depth, bottom composition and irradiance levels. The processed observations of areas with the same bottom type will show up as points on a straight line in the two dimensional histogram. The position along the line is determined by the local depth. Data taken of areas with a different bottom composition will show up as points on a parallel line. The distance between these lines is a measure of the difference in bottom composition. A map of the differences can be interpreted as a bottom composition map. For a more detailed description of the relation between

Table 1 - Thickness, extend and content of the sand layer in three areas in the coastal zone of Aruba

area	number of sampled locations	thickness of sand layer [m] minimum	average	maximum	surface [km²]	sand content [10^6 m³] minimum	average	maximum	Average percentage of sand
California	9	1.4	1.70	2.0	2.3	3.2	3.9	4.8	87
Manshebu	9	1.2	1.45	1.7	1.6	1.9	2.3	2.7	80
Colorado	7	0.8	1.35	1.9	1.8	1.4	2.4	3.4	70
Total					5.7	6.5	8.6	10.7	

depth, bottom composition and irradiance levels the reader is referred to Hesselmans 1990.

The Admiralty Chart is used to confirm the depth dependence along each line in the two dimensional histogram. Using the bottom composition map locations with a high sand concentration can be identified and a ranking of the most promising areas can be made. This ranking can be based on the amount of sand, the distance to the area where it is needed, and the local depth. Based on this list a survey can be executed at the location(s) at the top of the list. This survey can be limited to a few samples needed to verify the predictions and to assess the actual thickness of sand layer.

Spatial interpolation and extrapolation

The limited ship based survey proposed above can be used for calibration of the model applied in the planning phase. The resulting calibrated sand map is used to determine the boundary of the sand layers by setting for instance a threshold of 50 per cent.

To assess the total sand volume measurements of the thickness of the sand layer are needed. Assuming, a smooth behaviour of the layer thickness between sample points and the boundary of the area an optimal estimate of the sand content can be made. This should provide sufficient data to determine whether or not it is economically feasible to use this sand.

5. THEORY

Light coming from below the surface of the sea yields information about substances in the water, bottom composition and height of the water column. Since each bottom type has its own spectral signature it is possible to determine the influence of the bottom composition on the upwelling light intensity. The same holds for the water composition and the height of the water column.

Wavelength bands suitable for a sand inventory should have a sufficient penetration depth. Such wavelength bands are found in the visible part of the electromagnetic spectrum. Especially green and blue are suitable. Other wavelength bands cannot be used, because the penetration depth is too small. Sand on the beaches is also visible in more wavelength bands. The technique to assess places where sand can be found on the sea bed from radiance measurements uses the two-flow transfer model by Spitzer and Dirks (1987).

Two-flow transfer model

The two-flow transfer model describes the amount of upwelling I_u and downwelling I_d radiation. Both radiation intensities change due to absorption and backscatter. Absorption reduces both whereas backscatter causes a transfer from down to upwelling radiation and vice versa. This is described by a Ricatti differential equation. Assuming depth independent absorption and backscatter coefficients this differential equation can be solved for a given depth and bottom reflectance.

Bottom types

The two-flow transfer model relates the irradiance values, the height h of the water column, the reflectance r at the bottom and the water composition. Therefore, four variables have to be determined, which requires measurements in four wavelength bands or additional information. Here, we will consider the case of one or two available bands. The additional information used is the presence of clear water. In clear water, the backscatter coefficient is negligible. In addition, the absorption coefficient is constant over the area of interest and can be determined *a priori*.

If the depth h is known the bottom reflectance r can be determined straight forward from <u>one band</u>: $\ln(r)=X+ah$, where X is the logarithm of the ratio of upwelling and downwelling radiation. If the bottom topography is not known, two wavelength bands (indices 1 and 2) are needed. Elimination of h yields:

$$X_2 = \frac{a_2}{a_1}X_1 + \frac{a_1\ln(r_2) - a_2\ln(r_1)}{a_1}$$

The X_i values are linear related. The offset of this relation is determined by the bottom reflection coefficient.

6. RESULTS

Based on the near infra red band land and water were discriminated. A co-occurrence histogram of band 1 and band 2 of the water area is shown in **Fig. 3**. The histogram shows three peaks. The offset of a sandy bottom is smaller than the offset for a vegetated or mud bottom. Therefore, the peak in the right bottom part of **Fig. 3** can be related to the occurrence of sand. The central peak is related to the main sea area where the sea bed is covered by vegetation or mud. It turns out that the peak in the upper left part of the figure can be related to edges of clouds and hazy areas. The data in the lower and central peaks are grouped along almost straight lines. **Fig. 4** shows the distance to the central peak for each pixel in the lower peak (after the logarithmic transformation). It is expected that larger distances in colour space correspond to increased amounts of (white) sand. Therefore **Fig. 4** can be interpreted as a map showing relative concentrations of sand. The absolute

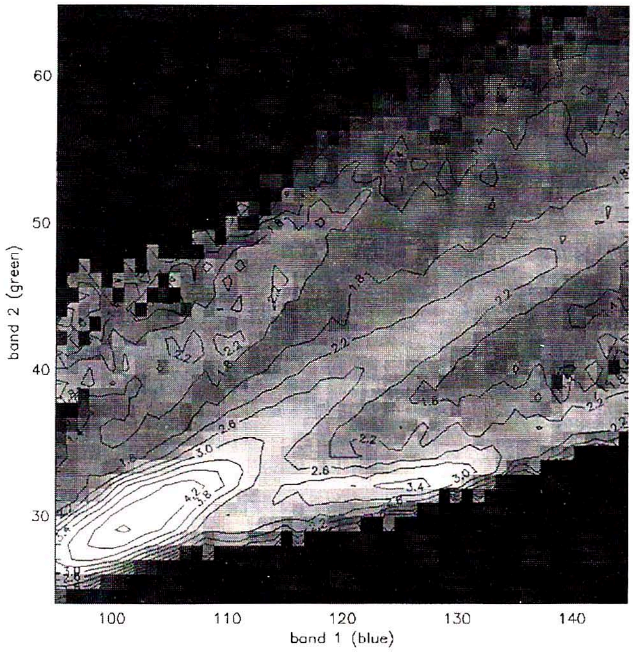

Figure 3 - Co-occurence histogram of irradiance values in band 1 and band 2. The number of occurences is displayed on a logarithmic scale

scale has still to be determined from in-situ measurements. In addition white places in the imagery are shown as white spots in **Fig. 4**. These white spots correspond to the sandy beaches, but also to clouds. Based on **Fig. 4** three areas can be identified which show high levels of sand: North-West, West, and South-East. Based on this finding a survey can be limited to these three areas.

The Admiralty Chart indicates that the depth in all three areas is similar. If one is only interested in mining sand and not in a complete inventory, the survey can be limited to the nearest site.

The results compiled by Hoozemans and Hulsbergen (1991) serve as data obtained from an actual survey. **Fig. 5** shows the measured sand concentration of the top soil of

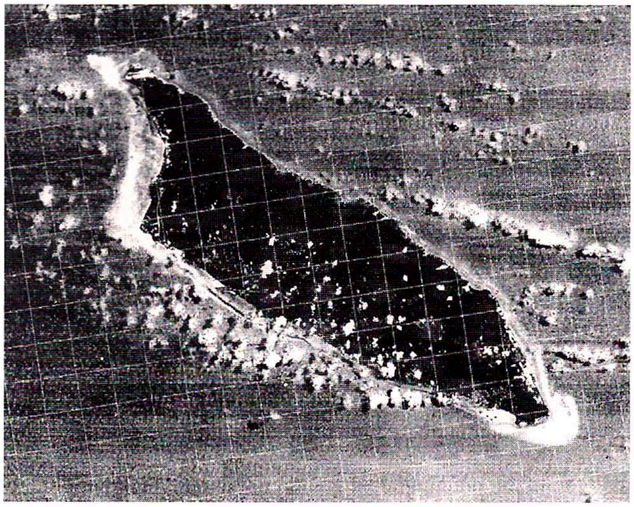

Figure 4 - Relative concentration of sand in the top layer of the sea bed as predicted from the Landsat TM imagery

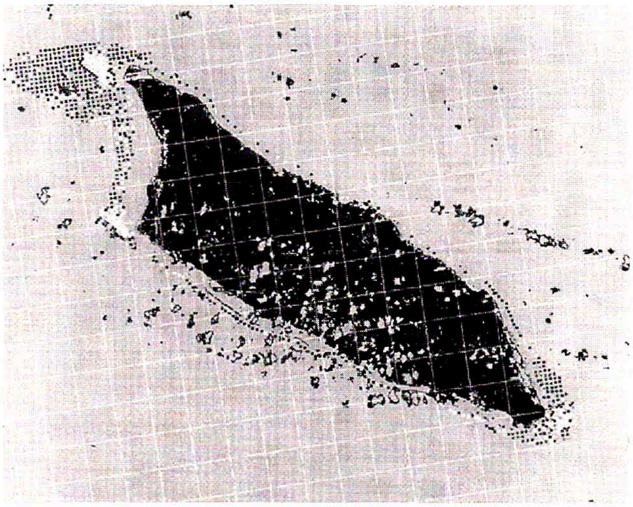

Figure 5 - Position of the 927 sample sites. Sand concentrations (grain size less than 7 mm) are presented on a linear grey scale

the sea bed. It shows three sandy locations at the same places as in **Fig. 4**. The shapes of the North-West area and the South-East area match almost perfect. Whether or not the shapes in the West area match can not be determined from **Fig. 5** because the measurements only partially cover the sandy area indicated by the optical remote sensing data. Data in **Fig. 5** are limited to the depth range between 10 and 30 m. Earlier measurements by Hoozemans and Hulsbergen (1987) in the Manshebu area show that parts of the sea bed above the 10 m line are covered by sand as well. These areas correspond well to those predicted from the optical remote sensing imagery.

The sand concentration measurements have been used to calibrate the sand map. The result is shown in **Fig. 6**. Setting a threshold of 50 per cent the surface of the three sandy areas has been estimated (see **Tab. 2**).

Table 2 - Surface of the sandy areas. Sandy areas are characterized by a sand concentration of more than 50 percent

area	sand surface [km²] optical remote sensing	Hoozemans and Hulsbergen (1991)
California	2.23	2.3
Manshebu	1.95	1.6
Colorado	2.90	1.8

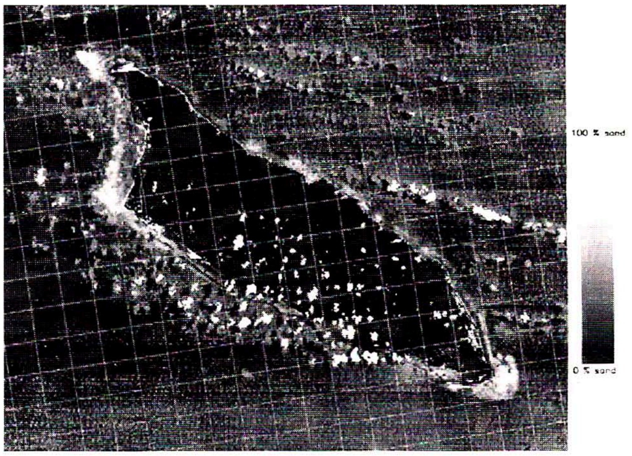

Figure 6 - Sand concentrations in the top layer of the sea bed as predicted using the Landsat TM image and calibrated using in-situ data

7. DISCUSSION AND CONCLUSIONS

A comparison of **Fig. 3** and field data (see **Fig. 4**) collected in 1991 (Hoozemans and Hulsbergen) shows a remarkable correspondence. The shape of the sandy areas in the South-East area (Colorado) and North-West area (California beach) is almost exact. The shape of the West area (Manshebu) is somewhat different. It has been suggested that the bottom in the area is white but that it may not be covered with sand. In addition the data presented in **Fig. 4** are limited to a depth between 10 and 30 m, whereas the remote sensing data include data of areas shallower than 10 m as well. This may explain why the algorithm overestimates the amount of sand. **Fig. 3** shows that all three areas having the highest sand concentration as measured by Hoozemans and Hulsbergen (1991) are detected by means of the remote sensing images. In addition the remote sensing data show no "false positive" areas.

An analysis on a pixel by pixel basis yields a correlation coefficient of 0.35 (927 samples), which indicates that the remote sensing data are not suited to predict sand occurrences at specific points. Remote sensing data are better suited to provide estimates over larger areas. The rather low correlation at specific points is at least partly due to the natural variability in sand concentration which turned out to be 15 per cent on average. In addition the colour of the sand may vary and parts of the surface may be covered by vegetation. Other factors resulting in a lower correlation are the clouds and haze present in the imagery.

Estimates of the size of the surface of the sand layers at Manshebu and Colorado are larger than the values given by Hoozemans and Hulsbergen (1991). This difference may be caused by:

- an incorrect classification of coral as sand,
- differences in sand colour and grain size (see **Tab. 1**),
- incomplete coverage of the sandy areas by Hoozemans and Hulsbergen (1991). A considerable number of samples taken at the borders of both areas contain more than 50 per cent sand. This implies that the sandy areas may be larger.
- the fact that the boundaries of the sandy areas are ill-defined. Changing the threshold slightly changes the surface considerably. For example a threshold of 55 per cent yields a surface of 2.4 km² instead of 2.9 km² for the Colorado area.
- the bottom composition map based on optical remote sensing includes areas shallower than 10 m as well.

The survey reported by Hoozemans and Hulsbergen (1991) consists of two steps.

- In the first phase 927 samples were collected at 812 locations on a course grid (250 m interval). This survey covered the whole area in the depth range between 10 m and 30. Based on this survey three sandy areas were identified.

- In the second phase a survey was conducted at another 115 sites in the three sandy areas, which reduced the effective grid size to 125 m. Furthermore, the thickness of the sand layers was assessed at 25 locations.

Based on the results presented in this report it can be concluded that:

- The first phase can be replaced by an analysis of optical remote sensing data. This will result in a considerable cost reduction. Costs of the first phase of the Aruba survey were about US$ 60.000 (excluding mobilization costs). The acquisition of the Landsat TM imagery and the subsequent analysis required just US$ 15.000.
- In the second phase the remote sensing data are calibrated using a limited number of samples of the sea bed. The calibrated sand map can provide a more accurate assessment of the size and the volume of the sand layer. The spatial resolution of Landsat TM imagery is 28.5 m x 28.5 m, which is considerably better than the 125 m attained in the Aruba sand survey. The cost reduction due to the use of remote sensing is in the order of US$ 25000.

In addition, based on the improved contours of the sandy area the sites where the thickness is to be measured can be optimized, resulting in a lower statistical uncertainty of the total sand content of the layer.

REFERENCES

Hesselmans G.H.F.M., Bathymetry in Indonesian coastal waters: a first pilot project, DELFT HYDRAULICS report H964, November 1990.

Hoozemans F.M.J. and Hulsbergen C.H., Sand inventory Aruba (in Dutch), DELFT HYDRAULICS report H553, part I, December 1987.

Hoozemans F.M.J. and Hulsbergen C.H., Sand inventory Aruba, phase 2 (in Dutch), DELFT HYDRAULICS report H553, part IV, February 1991.

Prieur L. and Sathyendranath S., An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials, *Limnol. Oceanogr.*, 26(4), 1981, 671-689.

Spitzer D. and Dirks D.W.J., R.W.J. Bottom influence on the reflectance of the sea, *International journal of remote sensing*, 1987, vol. 8, no. 3, 279-290.