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Beach Erosion along the West Coast of Aruba, Netherlands Antilles

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ABSTRACT

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Beach erosion along the west coast of Aruba was studied in order to design adequate protection measures for the resort beaches. Along the west coast of Aruba two different wave-induced longshore current systems can be distinguished. The first pattern refers to the normal east trade wind waves, refracted around the north and south capes and meeting at the utmost west point of the island. The second group of wave patterns is related to two different types of refracted swell waves, generated by hurricanes or storms tracking outside and inside the Caribbean Island Arch. As a result of these patterns there is a longshore sand transport in the breaker zone towards the west during the wind wave conditions and towards the east during the occasional swell wave events. In the long run there is a net sand movement towards the west. However, in the short run considerable eastward sand movement and severe beach erosion occur during the swell events. After such events the beach recovery by the wind wave system normally takes more time. Thus there is a delicate balance between both opposing phenomena. Based on the sand transport patterns and budgets several possible engineering measures to protect the beaches are briefly discussed.

ADDITIONAL INDEX WORDS: *Beach erosion, breaker zone, longshore current, sand transport, shore protection, swell wave regime, trade wind waves.*

INTRODUCTION

Since the nineteen-sixties many hotels have been built along the west coast of Aruba. In recent years alarming erosion of the resort beaches necessitated a careful study of the beach dynamics of this coast. This study focused on the evaluation and explanation of the erosion phenomena on the long and short term. Insight into the mechanisms of erosion is essential in the selection and design of prevention measures. There are three main categories of attitudes which may be taken, listed here in an increasing measure of distrubance of the natural coastal regime: (1) wait and see; erosion problem is only of limited or transient nature; (2) artificial beach nourishment (a "soft structure"), and (3) groynes or other hard structures. These options may be combined sequentially or simultaneously. A comprehensive study of the behaviour of the Aruban beaches has not been performed previously. Only two months were available for the execution of measurements. Furthermore, the financial and therefore the technical means were restricted (low budget study). Under these limitations we have chosen to apply several simple methods of investigation. These methods supplement and check each other as far as the possibilities for interpretation are concerned. The research strategy was as follows: (1) identify the major systems (tides, currents, wind, waves, available sediment, beach configuration) relevant for the coastal morphodynamics; (2) determine the actual causal relationships between the active forces (mainly the

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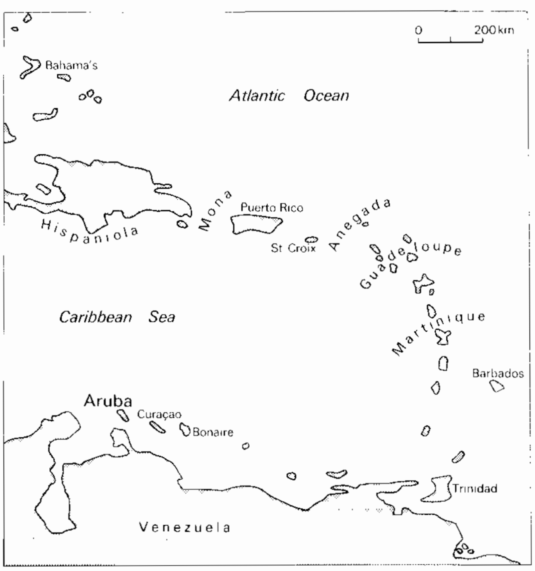


Figure 1. Location map of the eastern part of the Caribbean.

water movement in the breaker and surf zone), the transitory processes (sand movement parallel and perpendicular to the shore), and the resulting form of the coast; and (3) analyse the historic changes of the coast line.

AREA OF INVESTIGATION

The island of Aruba is a part of the Caribbean Island Arch (Figure 1). The coastline along the north and east coast of the island consists of Pleistocene barrier reef complexes which are now eroding. The south coast consists of inactive barrier reef and back reef zones, while the west coast is mainly built up of coral sand. Locally along the west coast some small coral reefs are present.

Aruba is situated in the trade wind belt. The prevailing easterly wind has a mean speed of 7.7 ms^{-1}. These trade winds generate wind waves ($H_0 \sim 2$ m; $T_0 \leq 7$ s) which refract around the north and south capes of the island. These refracted waves meet each other at the west point of the island near Manshebu (Figure 2). Occasionally, hurricanes or severe storms, tracking over the Atlantic, may produce swell waves, which may reach Aruba ($H_0 \sim$ 0.5-3 m; $T_0 > 7$ s) and may have a considerable effect on the beaches. These beaches are situated along the west side of the island between Malmok and Oranjestad (Figure 2). The resort beaches, the subject of this study, lie between Pos Chikitu and Manshebu (Eagle Beach) and between Manshebu and Oranjestad (Pelican Beach). The tide is diurnal and has a range of 0.13 m at neap and 0.43 at spring. Outside the breaker zone relatively low current velocities were measured, having a mean of 0.15 ms^{-1}.

Relevant Sand Transport Systems

In almost tideless systems such as the Aruban coastal zone, the wave-generated longshore current is the most prominent means of alongshore sand transport. Along the west coast of Aruba two different longshore current systems may be distinguished, induced by the following wave patterns. The first pattern (Figure 2) stems from the normal (trade) winds waves, which refract around the north and south capes and meet near Manshebu (H_{br} = 0.2-0.5 m; $T \leq 7$ s). The location of the meeting area depends on the slight variation in direction of the trade winds. The second group of wave patterns is related to two different types of swell waves (H_{br} = 0.2-3 m; $T > 7$ s). One swell pattern is generated by hurricanes or storms tracking east or north of the Caribbean Island Arch.

On the west side of these storm depressions there are southward pointing wind fields. The generated waves may have such a height and travel direction that they may enter the Caribbean Sea via the passages Mona, Anegada, Guadeloupe and may reach Aruba. WILSON (1968, 1969) and WILSON *et al.* (1973) demonstrated that swell waves passing the Mona Passage may hit the west coast of Aruba, with periods between 13-15 sec. Conformative construction of refraction patterns by Wilson were performed only for periods of 13, 14 and 15 sec and did not reach farther south than Manshebu. However, during our measurements it appeared that refracted swell waves may also influence the beach between Manshebu and Oranjestad. Furthermore, we found that shorter period swell waves (8 s) may also affect the studied Aruban beaches. The other swell pattern is attributed to hurricanes tracking within the Caribbean Island Arch. We will treat the hurricane David (1979) as an example of this type.

THE NORMAL WIND WAVE SYSTEM

The wave-induced longshore current velocity was measured by means of painted leaves of the

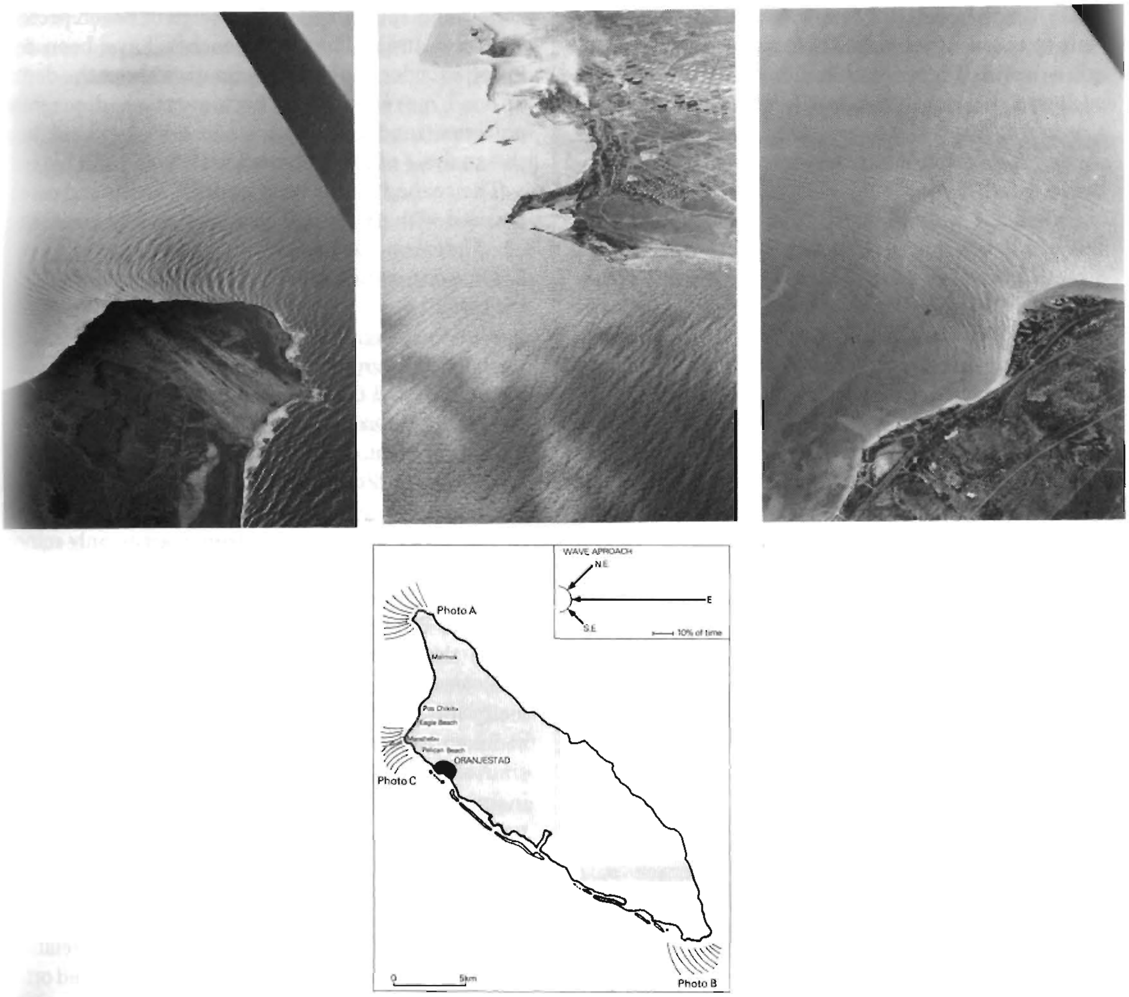


Figure 2. Sandy beaches are located between Malmok and Oranjestad. Dominant wave approach from the east; wave refraction around the north and south capes of the island; meeting area of refracted wind waves near Manshebu.

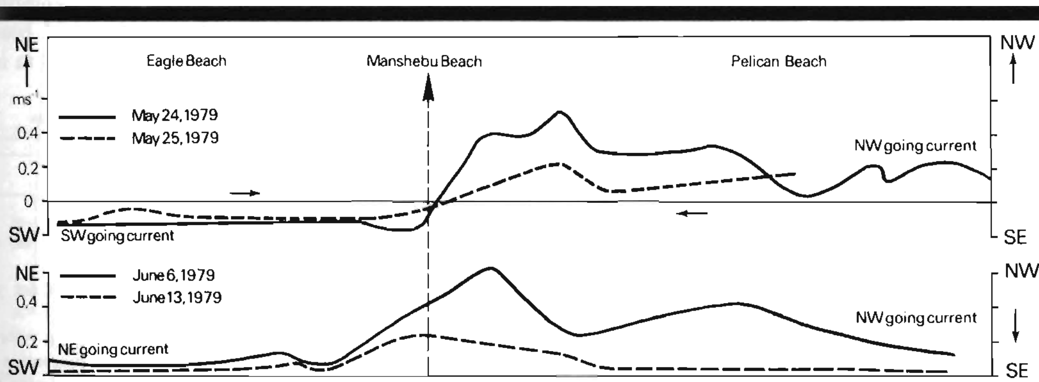


Figure 3. Measured direction and magnitude of longshore currents during the normal wind wave system.

shrubby horse tail *(Coccoloba unifera (L))* used as floats. In the relatively narrow, well-defined surf zone (approx. 10 m wide) this method proved to be quite useful. The excursion alongshore of this (low budget) float was determined over a time interval of 1 minute. Every measurement was repeated 4 times; the variation in the outcomes ranged between 10-40%.

Under the normal wind wave system the longshore current along Pelican Beach was always directed towards Manshebu. The longshore currents along Eagle Beach are weak and quite variable. They are sometimes directed towards Manshebu, sometimes from Manshebu (Figure 3). However, there is an overall systematic trend, *viz.* from June until October the trade winds shift a little towards the southeast. In this period there is a vast increase in northgoing longshore currents along Eagle Beach, in accordance with a slight shift in the wave refraction pattern.

The effect of the longshore current pattern on the sedimentation and erosion along Eagle and Pelican Beaches was established by repeated levelling of fixed sections. This resulted in the following general qualitiative trends: Pelican Beach, erosion; Manshebu, sedimentation; Eagle Beach, alternating low erosion and sedimentation, depending on wind direction (Figure 4).

These findings apply to the beach and not to the nearshore area below MSL. However, general knowledge of the rate of sand movement in the nearshore zone is indispensible for the design of beach protection measures. Three approaches have been followed in order to obtain information about the depth of sand movement, *viz.* bottom-attached seagrass patterns, sand mobility tests in a wave tunnel, and the analysis of grain characteristics.

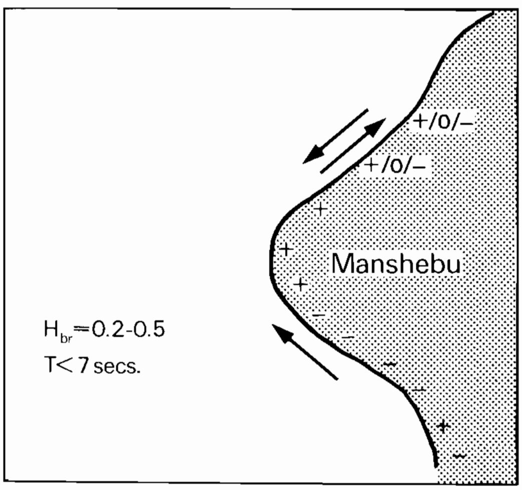


Figure 4. Observed erosion (−) and sedimentation (+) along the west point of Aruba during the normal wind wave system.

The seabed on the west coast of Aruba is densely covered with patches of seagrass, mainly consisting of *Thalassia testudinum* ("turtle grass") and *Cytingodinium filiforme.* From aerial photographs of the last 20 years it appears that the spatial distribution of the seagrasses does not change very much, and that the upper boundary of the vegetation lies between 2 and 6 m below MSL. These seagrasses can only grow in places with limited water and sediment movement. The absence of seagrasses in shallow water thus indicates that the water and sediment movement is appreciable in water depths less than 2 to 6 m, whereas in deeper areas only minor sand mobility is indicated. The density of these grasses in this deeper area is more than 20%.

In the wave tunnel (HULSBERGEN and BOSMAN, 1980) the original coral beach sand (D_{50} = 0.260 mm) was tested, in order to assess the critical velocity for incipient motion as well as the near-bed sediment concentration for increasing values of the sinusoidally oscillating velocity. The test results on incipient motion and ripple formation for wave periods ranging from 4 to 16 secs are presented in Table 1.

From these laboratory results it is concluded that near-bed orbital peak velocities below 0.25 ms^{-1} will cause virtually no sediment transport. The relation between this threshhold value and the near-bed orbital peak velocities (applying linear wave theory) of the Aruban wave climate follows from Figure 5. For a wave height of 0.5 m and a wave period between 4 and 6 secs—a condition which is representative for the refracted wind waves near the west coast of Aruba—it appears that a depth of 4 to 6 m is the

Table 1. *Results from wave tunnel experiments.*

u_o(ms^{-1})	Description
<0.10	no grain movement
0.10-0.20	grain movement in contact with bed; no ripple formation
0.20-0.25	start of ripple formation, but grains not yet in suspension
0.25-0.30	further ripple development, increasing vortex formation, and sediment thrown into suspension
>0.30	increasing ripple formation, and increasing height and concentration of suspended sand

lower limit of sand movement under normal conditions (swell waves are still effective at much greater depths, as will be discussed later). The above result is also corroborated by near-bed sediment concentration measurements in the wave tunnel, for conditions which represent the above mentioned normal wind waves, *viz.* a wave height of 0.5 m and wave periods of 4 and 6 secs (Figure 6): below a water depth of 5 to 6 m there is hardly any sediment brought in suspension, but for shallower depths a rapid increase in sediment suspension occurs.

The third approach to obtain information of the long-term near-shore sand transport pattern was to analyse the grain characteristics such as size and shape. A microscopic study of the analysed material shows that 95% is of a biogenic origin. Most of the grains were recognized as coral debris. Only 5% is quartzose. Four areas may be distinguished with respect to the median grain size (D_{50}) values (Figure 7).

Area A

Area A is the beach landward of the step in the beach profile which is present at the seaward margin of the breaker zone. Area A consists of relatively coarse sand: D_{50} between 0.14 and 0.85 mm, mean 0.36 mm. There are no systematic changes in D_{50} normal to the coast. Along Eagle Beach and Pelican Beach there is a coarsening towards Manshebu. This coincides with the observed increase in breaker height and longshore current velocities towards Manshebu (Figure 3). The grain

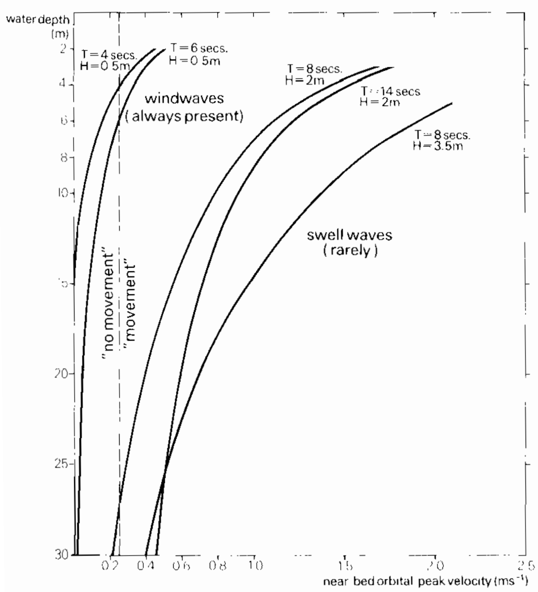


Figure 5. Peak orbital velocities near the bed ($\hat{u}_0$) according to the linear wave theory for several combinations of wave height and period.

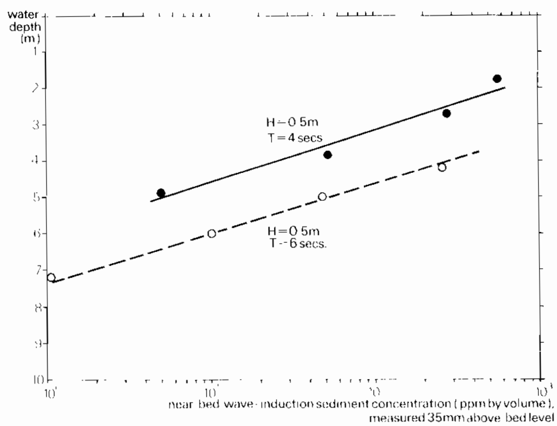


Figure 6. Suspended sediment concentration at 3.5 cm above the bed as a function of water depth. Results from flume experiments.

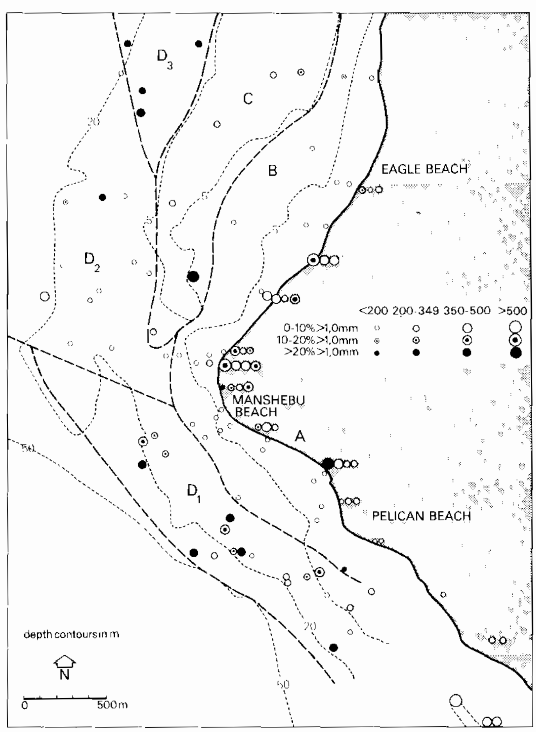


Figure 7. Grain size of bed material. For characteristics of areas A-D, see text.

size findings point to an intensive shore normal and shore parallel selection process. The finer fractions finally disappear outside the breaker zone and must be transported offshore. Alongshore the finer fractions are increasingly washed out with the rise in intensity of the water movement towards Manshebu.

Area B

There is a remarkably sharp boundary between the grain diameters of Areas A and B. Area B runs from the step to depths up to 6-7 m and is characterized by fine to very fine material (D_{50} between 0.09 and 0.44 mm, mean 0.13 mm). There is no shore-parallel trend in D_{50} values, but shore normal the material becomes finer with increasing water depth. Apparently material, washed out from the beach sand, is transported offshore and deposited (more and more) in deeper water.

Area C

Eagle Beach sandbank. This offshore bank contains medium sand (D_{50}: 0.24-0.73 mm, mean 0.28 mm). Wave attack on this shallow bank may result in the washing out of finer material. The latter is added to Areas B and D. The material becomes coarser northward where the bank shallows and the wave attack is stronger.

Area D

Seabed between 7-20 m below MSL. There are two populations, *viz.* D1/D3 and D2. D1/D3 is charactertized by coarse sand (D_{50} about 0.35 mm). The sand layer is very thin here. Often pieces of cemented sand and coral debris were found during sampling. In area D2 the sand is much finer (D_{50} about 0.175 mm). The grain size distributions show two maxima, *viz.* at 0.300 mm and 0.090 mm. This may be explained by mixing of coarse sand derived from greater depth or from D1 or D3, and sand which comes from Areas B and C.

From the grain size data we may anticipate that the lower boundary of the on/offshore transport under normal wave conditions may be situated in the area where the finest material, washed away from the shore, may settle down and apparently is not resuspended and reintroduced into the nearshore system. This lower boundary then coincides with that of Areas B and D, which lies at a depth of 6-7 m. This is in accordance with the wave-tunnel findings for 4-6 sec waves.

The grain size sorting shows the following picture. The beach sediments have a good sorting, the shallow nearshore area has a medium sorting, and the deeper parts (below 6-7 m) a medium to poor sorting. Areas subject to severe wave attack (beaches, sandbank in front of Eagle Beach) show the best sorting as the selection process has worked very well. The deeper parts have a poor sorting due to mixing of coarse and finer material.

Besides grain size observations, grain shape was also used as an indicator of transport patterns of sand. This is based on the fact that not only the weight and diameter of the sand grains but also the grain shape influences the mobility of the grains, all other factors being constant (current velocity, pressures, etc.). Flume experiments by WINKELMOLEN (1969, 1971) revealed that over a rough bed angular grains are more susceptible to the water movement over them. In addition, settling velocities of angular grains are lower. Thus, angular grains are more easily picked up from the bed and remain longer in suspension: angularity incrases transportability.

In the direction of transport the more easily transportable grains will run ahead of the less

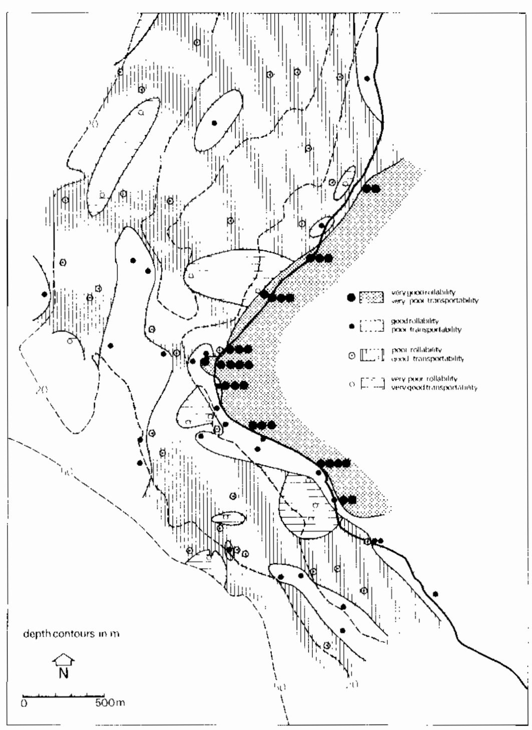


Figure 8. Rollability of bed material for the fraction which contains the median diameter of the sample.

transportable grains. Thus, the angular grains run out faster from a source area in the direction of net long term transport while the rounder grains lag behind.

Figure 8 gives the spatial variation in rollability for the fraction in which the D_{50} of the sample is present. From this figure the following may be deduced:

(1) The beach samples show a good rollability and therefore a low transportability. This is in line with the grain size pattern, indicating that the beach is a lag sediment, the product of a washing-out process.

(2) The shallow areas have a substantial variation in rollability. There is no longshore trend, but offshore a decrease in rollability is observed. Here the more angular grains, derived from the beach are found. This also supports the findings based on the grain size data.

(3) In deeper water (below 7 m) as well as on the sandbank at Eagle Beach, the rollability values indicate a good transportability. This means that the most easily transportable grains are found here. They may be the forerunners of the grains washed out from the beach or they are derived from deeper water moving shoreward.

It may be concluded that the rollability data are complementary and support the grain size data. The following general transport pattern emerges from the wave and the grain size and shape data, applying to the normal wind wave conditions. There is a longshore transport along Pelican as well as Eagle Beach converging towards Manshebu in the breaker zone above MSL (Area A, Figure 7). The rapid grain size drop at the step around MSL represents an important change in transport pattern. Below MSL up to 6-7 m depth the transport is mostly shore normal. The great drop in grain size around MSL indicates a rather sharp boundary between both transport systems. The finer material and the addition of fines in offshore direction point to a rather small transport intensity (Area B, Figure 7). Further offshore at depths between 7-20 m, on the one hand there is a further fining of the material, which may be regarded as a continuation of the shore normal transport pattern of Area B but on the other hand, there is another shore-normal pattern, bringing coarse sands from greater depth in a shoreward direction. This produces a mixing of sediment (Area D, Figure 7). The introduction of this coarse material cannot be explained by the normal wind wave conditions because at these depths the wind waves hardly affect the bed. Therefore the transport of this coarse material should be due to another process, *viz.* occasional swell wave activity. We will return to this point later in this paper.

Swell events may of course disturb the transport pattern sketched above and the grain size and shape pattern on which it is based. In fact we do not know how the grain-pattern is changed during a swell event. However, the last swell event occurred more than two months before the sampling presented in Figures 7 and 8. This time-span was long enough to generate a full beach recovery (TERWINDT, HULSBERGEN and KOHSIEK, 1984). Thus, we anticipate that during this recovery the selection process by the wind waves was operative long enough to be indicative of the transport pattern.

QUANTITATIVE EVALUATION OF LONGSHORE SAND TRANSPORT UNDER THE NORMAL WIND WAVE CONDITIONS

The results of the grain size and shape data and the wave tunnel tests indicate that sand transport relevant to the behaviour of the beaches may occur in water depths shallower than MSL–6 m.

The most intensive sand transport takes place in the breaker zone, landward of the step. Here longshore transport predominates. The longshore sand transport S (m^3s^{-1}) is by definition:

$$S = V F C \qquad (1)$$

where:

S = mean longshore sand transport (m^3s^{-1})
V = mean longshore current velocity (ms^{-1})
F = cross sectional area of the longshore current (m^2)
C = mean sand concentration by settled volume (−)

As stated before the longshore current velocity was determined from the excursion of floats during 1 minute. Each measurement was repeated 4 times and the mean value was calculated. The mean longshore current velocity appeared to be related to H_{br} and $\sin 2\varphi_{br}$ according to:

$$V = 2.4\, H_{br} \sin 2\varphi_{br} \qquad (2)$$

where φ_{br} is the angle of wave incidence of the breakers, was determined by direct visual observation and checked by aerial photographs taken from a light aircraft. H_{br} is defined as the mean value of the three highest breakers occurring in 2 minutes.

From our measurements the following empirical relationship could be established between the cross-sectional area of the longshore current F and H_{br}:

$$F = 6.25\ H^2_{br} \quad (3)$$

F was determined at the same sections where H_{br} was measured.

The sand concentration C was derived from one hundred samples taken at mid-water depth in the breaker zone. C turned out to be independent from H_{br}, and has an overall mean value:

$$C = 0.010 \quad (4)$$

Substituting (2), (3) and (4) in (1) gives:

$$S = 0.15\ H^3_{br} \sin 2\varphi_{br} \quad (5)$$

This formula resembles the well-known CERC formula (VITALE, 1980).

Applying the averaged wave data into (5), sand transports were calculated as indicated in Table 2 (Figure 9). Keeping in mind that the trade wind driven waves are fairly constant over the year (except for the occasional swell conditions), the yearly transport rates may be derived, which are presented in Table 2.

From Table 2 it may be deduced that a net yearly sand transport along Pelican Beach of about 75,000 m^3yr^{-1} towards Manshebu may occur, due to wind wave conditions alone. Deviations from this mean value may occur due to variations in wave characteristics from one year to another. The range is estimated between 25,000-100,000 m^3yr^{-1}. The net sand transport along Eagle Beach towards Manshebu is very limited: 3,000 m^3yr^{-1}. It should be noted that these conclusions refer to a condition of continuous wind waves without disturbances of swell waves. The effects of the swell waves are treated in the following paragraph.

THE SWELL WAVE SYSTEMS

During swell wave events the sand transport is orders of magnitude higher than during the normal

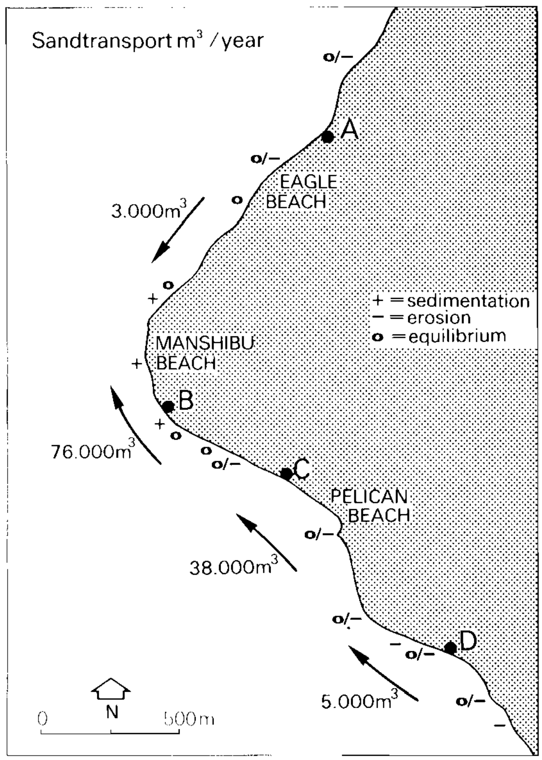


Figure 9. Calculated sand transports in m^3yr^{-1} under normal wind wave conditions.

Table 2. *Calculated sand transports under wind wave conditions.*

Location*	$\bar{H}_{br}$	$\bar{\varphi}$	Sand Transport			
	m	degr.	$10^{-3}m^3s^{-1}$	m^3day^{-1}	m^3yr^{-1}	direction
A	0.27	1.0	0.10	90	3,000	220°
B	0.37	9.3	2.42	2,090	76,000	325°
C	0.32	7.0	1.19	1,030	38,000	295°
D	0.20	3.75	0.16	140	5,000	295°

*see Figure 9

wind wave conditions but also the direction of the sand transport may deviate considerably. These events occur only a few times a year and measurements of the waves and the behaviour of the beaches were almost absent. As our field campaign was only of short duration we tried to analyse the effect of the swell wave events by analysing the grain size data, beach profiling and refraction computations. Fortunately during our campaign Hurricane David (1979) passed by and we were able to measure the effects on the beach.

The depth-limitation of grain movement under swell waves may be evaluated as follows. Swell waves approaching the west coast of Aruba may have an H_0 up to 3 m and T_0 of 8-12 sec.

Referring to Table 1 and Figure 5, it may be anticipated that occasionally swell waves may be able to set sediment in motion up to water depths of 30 m. We ascribe the admixture of coarse material to the sediment in area D1/D3 to these occasional swell events.

Certainly swell waves will mobilize the sediment in Area B and also in Area A, due to shoaling. This means that under swell waves all the nearshore sediments up to depths below 10 m are mobilized.

The direction of sand movement along the Aruban beaches may be evaluated by considering the refraction patterns. Two distinct patterns may be distinguished depending on the origin of the swell, *viz.* outside the Caribbean Island Arch and within the Arch: the "outside" and "inside" system, respectively. The wave approach from the outside system to the island of Aruba is almost unidirectional (φ_0 = 20). This unidirectionality is caused by the fact that only waves travelling in the direction of the Passage (Mona, Anegada, Guadeloupe: Figure 1) can enter the Caribbean Sea. The wave period of these long-distance waves varies between 8-15 sec. The inside system is characterized by multi-directional wave approach, from 20-300°, changing with the course of the track. The period is almost constantly 8 sec during swell. The computation of the refraction pattern used here for quantitative interpretation goes in two steps, *viz.*:

Step 1: large area, large grid which serves as boundary condition for

Step 2: small area, small grid.

THE "OUTSIDE" SYSTEM

In this system two refraction computations have been performed:

(1) H_0 = 2 m; T_0 = 14 s; φ_0 = 20°.
(2) H_0 = 2 m; T_0 = 8 s; φ_0 = 20°.

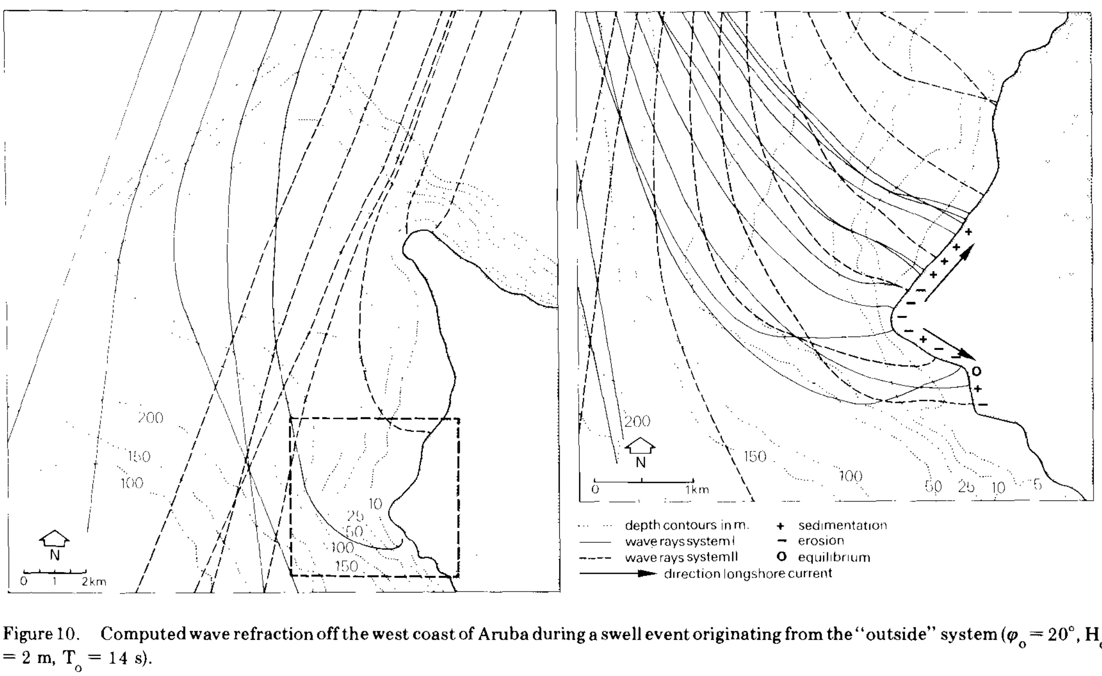


Figure 10. Computed wave refraction off the west coast of Aruba during a swell event originating from the "outside" system (φ_0 = 20°, H_0 = 2 m, T_0 = 14 s).

The first case has the same boundary conditions as WILSON's (1968, 1969) computations. However, the latter ones only apply to Eagle Beach up to Manshebu. We extended the computation also to Pelican Beach. Due to the plateau at water depth of 25-50 m to the northwest of the island the two sets of wave rays show convergence towards the Manshebu area (Figure 10). Interference of the two sets of wave rays produce a rather complicated cross pattern west of Manshebu.

This cross pattern is demonstrated in further detail in the small grid results (Figure 10). If we assume that the angle of the wave incidence is indicative for the longshore transport direction, then we may conclude from Figure 10 that there is a diverging net drift starting from Manshebu along Eagle Beach as well as Pelican Beach. The inferred qualitative picture of the resulting erosion and sedimentation is shown in Figure 10 too. In the second case the above-mentioned pattern of the large grid is absent (Figure 11). The small grid indicates a continuous southwest-southeast transport along Eagle and Pelican Beaches. This is in line with the measured longshore currents, which

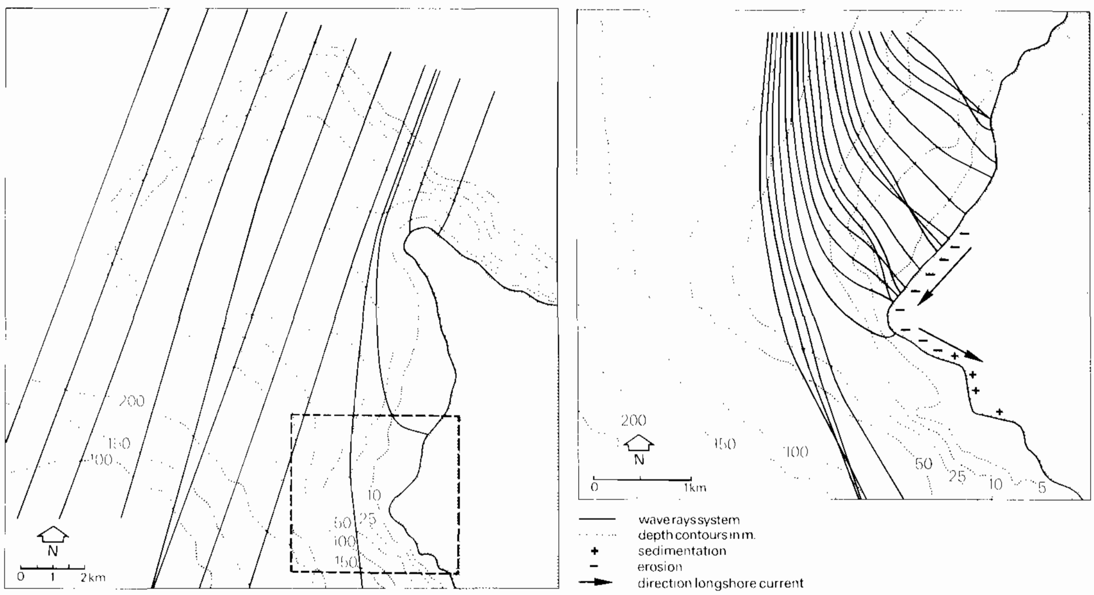


Figure 11. Computed wave refraction off the west coast of Aruba during a swell event originating from the "outside system" ($\varphi_o = 20°$, H_o = 2 m, T_o = 8 s.

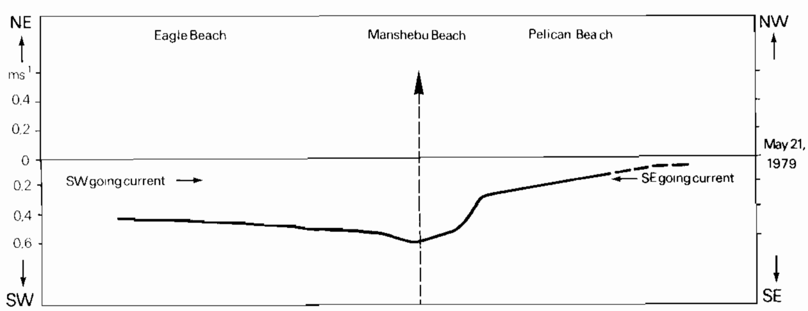
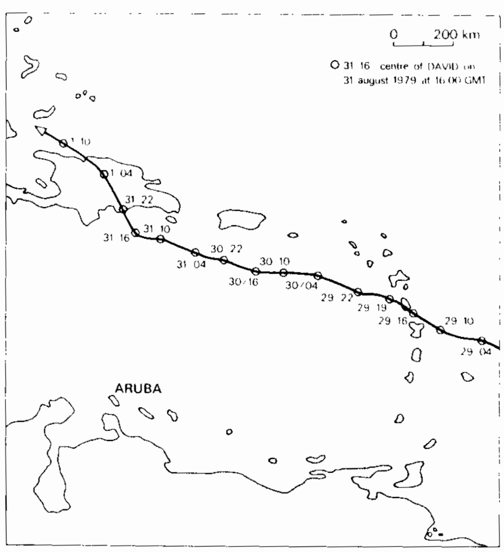


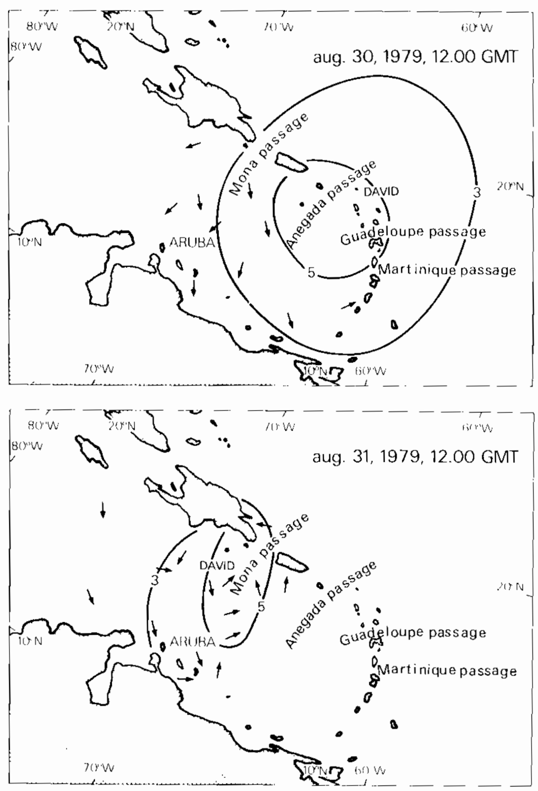
Figure 12. Measured direction and magnitude of longshore currents during a swell event of the "outside system".

were observed during a swell event (21 May 1979), having almost the same conditions as in case 2 (Figure 12). It may be noticed that the refraction pattern can also be interpreted in an absolute sense: areas with greatest convergence of wave rays also show the highest measured longshore currents. Under the conditions of case 2 there is substantial erosion along Eagle Beach and Manshebu and to a lower extent along Pelican beach as well. Only at the easternmost part of Pelican Beach does sedimentation occur. These tendencies were well-established in the measured beach profiles.

THE "INSIDE" SYSTEM

As stated above, the direction of the swell waves change with the course of the track of the hurricane. We will analyse the conditions, occurring during the passage of Hurricane David (30 August—2 September 1979) as an illustrative example. At our request the Royal Dutch Meteorological Institute reconstructed the track of David and predicted the accompanying wave fields for several different time steps (Figure 13). On August 30th, 12:00 GMT, the direction of the wave travel coincides with that of the Mona Passage (Figure 13). Given the predicted period of 8 sec a similar condition consists as was treated before in the "outside" system, observed on May 21, 1979 (case 2), resulting in similar southgoing longshore transport.





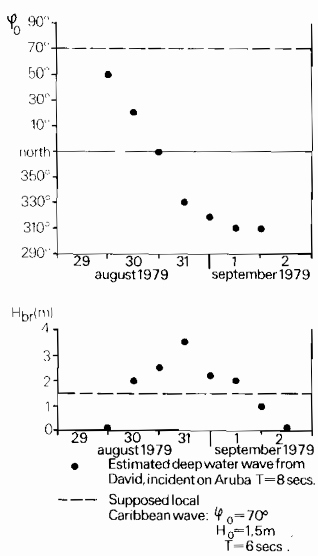


Figure 13. Track of Hurricane David (Aug. 29—Sept. 1, 1979) and the calculated wave fields based on meteorological data (courtesy Royal Dutch Meteorological Institute). Direction and breaker height of swell waves on Aruba during David.

On August 31, 12:00 GMT, the swell wave came from the northwest (Figure 13). A refraction computation was performed for this situation (Figure 14) because at this moment the maximum wave height occurred (Figure 13). It appears that the refraction pattern at the beaches is very similar to that of case 1 on the outside system (Figure 10) indicating a diverging northeast and southeast transport from Manshebu along Eagle and Pelican Beaches respectively. This is in line with the measured longshore drift directions (Figure 15). The erosion and sedimentation pattern was substantiated by the results of the beach profiling.

On September 1st the waves came from the west. Then the above picture of sand movement along the beach is even stronger (Figure 16).

It may be concluded that the inside system always results in a consistent pattern of longshore sand transport, *viz.* erosion at Manshebu and northeast-going transport along Eagle Beach and southeast-going transport along Pelican Beach.

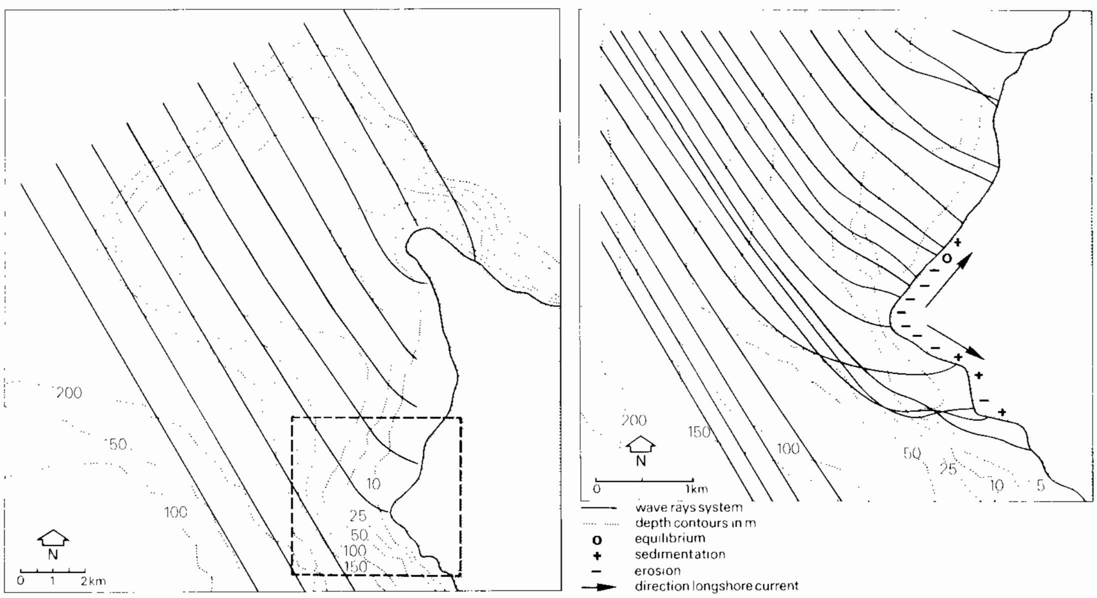


Figure 14. Computed wave refraction off the west coast of Aruba during the passage of Hurricane David (Aug. 31, 12:00 GMT)($\varphi_o = 330°$, $H_o = 3.5$ m, $T_o = 8$ s).

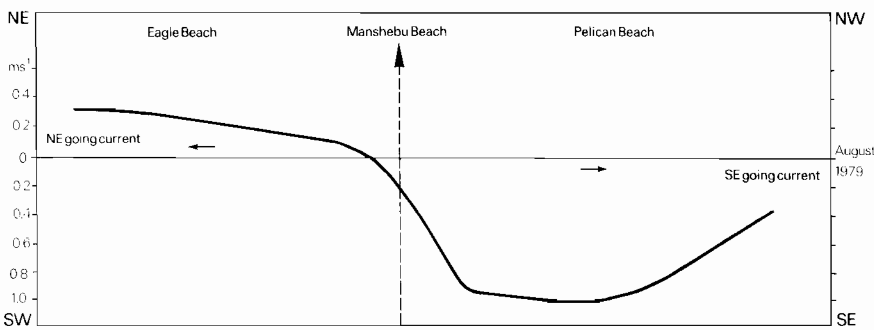


Figure 15. Measured direction and magnitude of longshore currents during the passage of Hurricane David (Aug. 31, 1979).

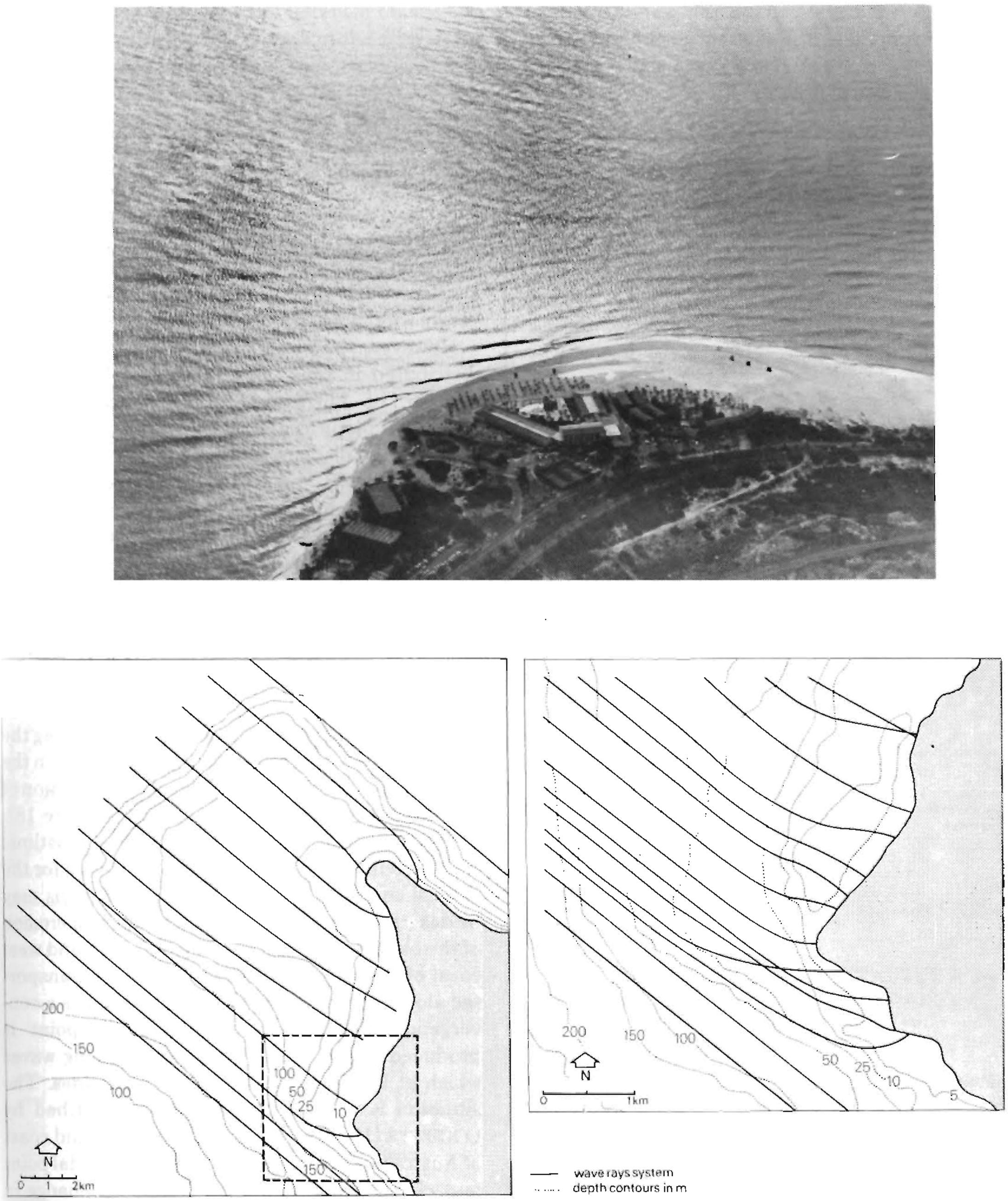


Figure 16. Swell on the west coast of Aruba during the passage of Hurricane David (Sept. 1, 1979) and the computed wave refraction pattern $\varphi_o = 310°$, $H_o = 2$ m, $T_o = 8$ s.

Table 3. *Beach volume changes and calculated sand transport during the passage of Hurricane David.*

Location*	Measured H_{br} (m)	Measured V (ms^{-1})	Sand Transport with (2) sin $2\varphi_{br}$	with (5) (m^3s^{-1})	($m^3 day^{-1}$)†	(m^3/1-2 days)
A	0.4	0.5	0.52	5.10^{-3}	430	2,000
B	1.3	0.9	0.29	96.10^{-3}	8,260	11,000
C	0.7	0.8	0.48	25.10^{-3}	2,130	6,000
D	1.9	0.3	0.066	68.10^{-3}	5,870	11,000

*Figure 17 † From beach volume

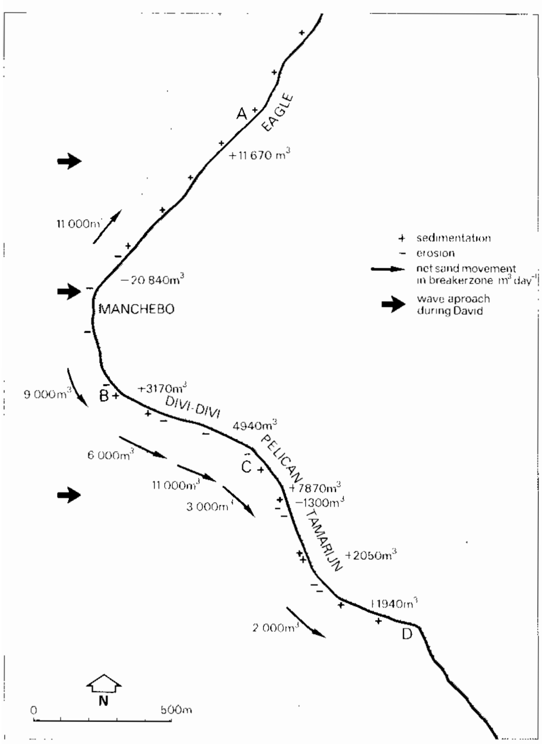


Figure 17. Calculated sand transport (in $m^3 day^{-1}$) during the passage of Hurricane David.

QUANTITATIVE EVALUATION OF THE SAND TRANSPORT OF THE INSIDE SYSTEM

Beach profiling during David produced quantitative data on volume changes. These data are compared with calculated sand transport by (5), based on the measured wave and current data during David. Table 3 shows the results.

Taking into account that the beach profiling mostly took 2 days it may be concluded from Table 3 that the order of magnitude of the calculated and observed sand transports match very well. This indicates that during an inside swell event some 5000 $m^3 day^{-1}$ of sediment is exported from Manshebu (Figure 17). We calculated earlier a yearly sediment import towards Manshebu of 25,000-100,000 m^3 during normal wind wave conditions. This means that 5-20 swell wave events per year can compensate the total yearly wind wave transport.

However, the swell wave events are unevenly distributed in time. Deviations from the normal number of hurricanes influence considerably the above picture of sand budgets at Manshebu. As a result, displacements of beach contours of 20-30 $m^3 year^{-1}$ should be considered as normal fluctuations on the long term trend. Nevertheless swell wave events, either originating from the outside or inside system, are an essential part of the overall transport pattern along Aruban beaches.

LONG TERM TRENDS IN BEACH BEHAVIOUR

The long term behaviour of the beaches along the west coast of Aruba may be analysed, based on the results of the present study. We take the position of the MSL of 1948 as a starting point (Figure 18). This is the earliest known position of the coastline, without human interference, thus indicative for the natural conditions. These natural conditions may be described as follows. Sand derived from erosion of the coral reefs, present along the south and west coast of Aruba finely wash ashore and is transported alongshore towards Manshebu, which is a convergence point. Such a convergence point is produced by the intersection of conveying waves which at this point approach from all sides. The situation is comparable with that, described by O'KEEFFE (1979) for a cay at the Queensland coast of Australia. O'Keeffe found that such a nodal point may change position when a systematic change in the direction of wave approach is generated by the deviating direction of the swell waves.

Thus the natural equilibrium system along the west coast of Aruba is made up of *wind* and *swell* wave transport directions which oppose each other. The area of Manshebu functions alternately as a starting and a collecting place for 25,000-100,000 m^3 of sand a year. In the long run both opposing sand movements are not completely in balance, as witnessed by the gradual growth of the converging point at Manshebu indicating that there is a slight net transport towards this point. This natural equilibrium system was disturbed between 1948 and 1952 when 150,000 m^3 of sand, derived from dredging a new harbour, was dumped in the nearshore area, just south of Pelican Beach. This sand, much finer than the original beach sand, moved as a migrating beach wave in the course of 30 years towards Manshebu with a mean rate of 35 $m^3 day^{-1}$ (Figure 18), illustrating the net westward sandflow along this beach.

Superimposed on this process, another consequence of the deepening of the harbour entrance in the early 1950's was that sediments derived from the coral reefs were trapped in the channel and could no longer reach the Aruban beaches. The natural source of the sands, supplying the Aruban beaches, was cut off. Unaware of these processes several resort hotels have been built in 1968-1975 near the shore, partly on the passing beach wave. Although these hotels were originally situated far enough from the waterline to be unaffected by the normal fluctuations of the beach, they are facing considerable beach retreat in recent years after the passing of the beach wave.

COASTAL ENGINEERING MEASURES

The present study was made in order to advise engineering measures to protect the beaches in front of the resort hotels along Pelican Beach. The study resulted in the following relevant boundary conditions related to this problem. During normal trade wind conditions there exists a longshore sand transport in the breaker zone towards the west in the direction of Manshebu. Occasionally swell waves may cause a strong erosion of the beach, resulting in considerable landward displacement of the waterline. The eroded sediments are mainly transported towards the east, thus in an opposite direction as during wind wave conditions. In the long run the frequency of occurrence of the swell

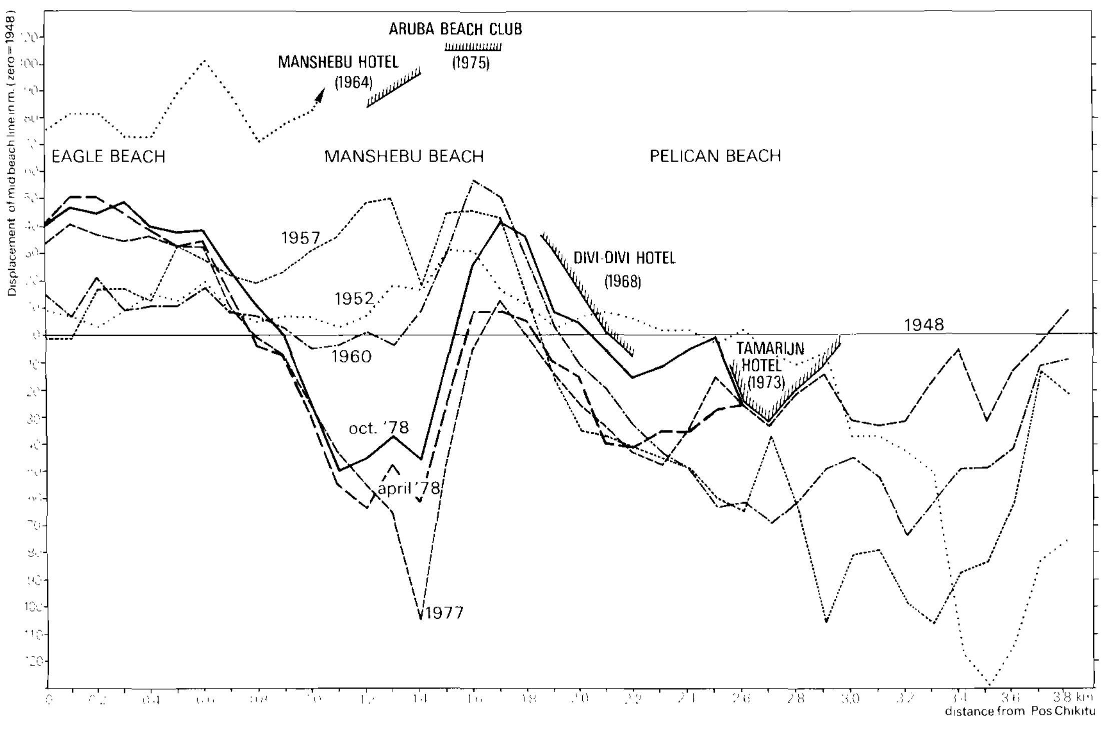


Figure 18. Location of the waterline related to the position of 1948 from aerial photographs, coastal maps and measurements.

wave events is such that the total eastward transport almost compensates the westward movement by the wind waves, so that a small net west movement exists. However, from year to year these swell wave events show quite a variation, so that the net transport may vary considerably.

The hotels had been built partly on the migrating beach wave, at a beach already deprived of its natural sand source. This means that the hotels have been built too far seawards and that a continuous threat of erosion of the beaches in front of the hotels must be anticipated. This obviously excludes the passive "wait and see" option, mentioned in the Introduction. Active measures that protect not only the hotels themselves but also the recreational values of the beaches should be taken. These measures may be divided into soft structures, like beach nourishment, and hard constructions like revetments, groynes and breakwaters.

Beach nourishment has some advantages in the situation of the Aruban beaches. The appearance of the beach remains very natural which is a recreational selling point. Furthermore, the construction is very flexible, which means that unfavourable developments may be restored easily by simple additional sand replenishment. However, due to the exposed positions of some resort hotels beach nourishment will not suffice and complementary structures in front of the hotels should be incorporated in the overall plan.

Taking into consideration the specific physical characteristics of the studied coastal area as well as technical aspects and financial limitations, the following "low-profile" measures were advised in their order of priority:

(1) protect the threatened hotels with hard structures according to strict guidelines, *viz.*: define the alignment of the revetment-like structures as far shoreward as possible, *i.e.* merely surrounding the proper hotel areas instead of incorporating a part of the adjacent beach; keep the height of the revetments as low as possible, so that the structures are completely covered with sand except during occasional erosion events,

(2) provide favourable conditions in order to stimulate natural beach formation next to and on top of the above-mentioned revetments, by constructing a row of low, short, closely spaced groups of suitable stable elements, and

(3) consider the application of small scale beach nourishment schemes on an as-needed basis.

CONCLUSIONS

On the basis on fieldwork, flume experiments and refraction computations a clear picture of the longshore sediment movement and the response of the beaches was obtained. It appears that occasional swell waves have an important effect on the longshore sediment budget. Further, it turned out that the width of the zone of important longshore sediment movement is rather restricted. These findings appeared to be important for a proper design of beach protection measures.

ACKNOWLEDGEMENTS

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□ RESUMEN □

Se ha estudio la erosión de las playas a lo de la costa oeste de Aruba para poder diseñar las medidas adecuadas de protección de sus playas. A lo largo de la costa oeste de Aruba se pueden distinguir dos sistemas de corrientes longitudinales inducidas por el oleaje. El primer sistema está relacionado con el oleaje debido a los alisios del este, refractado alrededor de los cabos norte y sur y que se encuentra en el punto más oeste de la isla. El segundo sistema de oleaje está relacionado con dos diferentes tipos de swell refractado, generados por los huracanes o por borrascas que circulan por el exterior o interior del arco de islas del Caribe. Como resultado de estos sistemas, existe un transporte de arena en la zona de rotura hacia el oeste durante la época de los alicios y hacia el este durante las situaciones ocasionales de swell. A largo plazo, existe un transporte neto de arena hacia el oeste. Sin embargo, en los cortos periodos de swell se proucen considerables movimientos de arena hacia el este que se traducen en fuertes erosiones de las playas. Después de estos periodos, la recuperación de las playas mediante el oleaje debido a los alisios requiere basante tiempo. Por lo tanta, existe un delicado balance entre los dos sistemas opuestos. Se exponen brevemente varias medidas ingenieriles para la protección de las playas, basadas en los modelos de transporte de arenas y previsión de oleaje.

□ ZUSAMMENFASSUNG □

Die Strandauswaschung der Westküste Arubas ist studiert geworden, um Massnahmen für die Ferienstrandschutzen zu formulieren. Langs dem Westküste Arubas sind zwei verschiedene, von Wellen verursachten Strömungsysteme zu finden. Das erste System bezieht der normalen Ostpassatwindwellen, der um die Nord- und Sudkapen gebrochen sind, und beim extremen Westpunkt des Insels treffen. Der zweite System ist an zwei verschiedene Typen gebrochenen Wellen verwandte, wodurch Hurrikane oder Stürme drinnen und draussen der karibeanische Inselkreis erschöpft sind. Diese Systeme verursachen eine in der Schwellenzone gefundene Sandbewegung langs der Strand, die am Westens während der Windwellenumstände und am Ostens während der Schwellenumstände ist. Über die lange Strecke gibt es eine Sandbewegung am Westens. Über die kurze Strecke gibt es jedoch eine merkwurdige Sandbewegung am Ostens, und während der Schwellenumstände gibt es strenge Strandauswaschung. Nach solchen Umstände ist der Strandheilungzeit durch die Windwellensystem normalerweise länger. Es gibt also ein delikate Balanz zwischen die gegeneinandere Phenomen. Viele verschiedene, auf dem Sandbewegungsmustern und Budgets gegrundete Baumöglichkeiten sind hier beschrieben.