COASTLINE EVOLUTION IN RESPONSE TO A MAJOR MINE SEDIMENT DISCHARGE ON THE NAMIBIAN COASTLINE

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Abstract

The measurement, monitoring and modelling of the impacts of a major sedimentary discharge to the highly dynamic coastline of southern Namibia is described. Some 27 million m³ of sediment will be discharged over a 5 year period as a result of a novel diamond mining technique employing an inland dredger. The study demonstrates that mathematical modelling, supported by comprehensive monitoring information, constitutes an important tool for mining optimization and impact prediction and management.

Introduction

A major diamond mining operation at Oranjemund in Namibia (Figure 1) which commenced in April 1997 involves the dredging and processing of overburden material (CSIR, 1996; Smith *et al*, 1996). This overburden sediment overlays rich diamond deposits located primarily in gravel layers on thc bedrock. Typical overburden thicknesses are from 5 to 20 m. As an alternative to historical "dry" mining techniques, calling for massive dewatering operations, the present mining uses a dredger floating in excavated ponds. Water-levels in the ponds are controlled by a balance between seepage from the sea, a wellfield on the beach, and extraction pumping.

The sediment resulting from the dredging process is then discharged onto the beach (Figure 2 and Figure 3) on a highly dynamic coastline (median wave height ≈ 1.9 m). A total of some 27 million m³ is to be discharged onto the beach over a period of about 5 years. This massive amount of sediment is comparable with the total quantities supplied for beach nourishment in some European countries (Hamm *et al*, 1998). The shoreline accretion which results from the discharge will have a significant effect on the **safety** of mining operations and in the protection of beach wellfield installations from wave action. In addition, the shoreline behaviour affects the rate of **water seepage** to the inland dredge pond, and accordingly affects pumping requirements to maintain the required water-level.

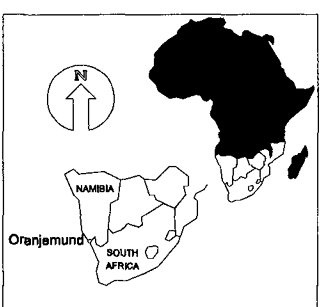

Figure 1: Location map

Furthermore, accretion of the shoreline will facilitate **land reclamation** and consequent additional

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exploitation of mining terrain. Thus, accurate predictions of the shoreline evolution, both in the short-term and long-term, are essential for the mine to plan these aspects.

Figure 2: Dredger tailings discharge

A delicate balance exists, with regard to water seepage, as is schematically illustrated in Figure 4. In Figure 4 (top) the situation at the start of dredging is shown. At this stage the dredger was situated on an existing pond created from a previously mined-out area. By means of pumping from a wellfield close to the shoreline, the water-level was maintained just above mean sea level (MSL). As dredging progresses, the pond water-level is progressively lowered, as indicated in Figure 4 (bottom). The advantage of this is that the bedrock, which is inclined towards the sea, will be accordingly exposed, thus allowing mining to continue. As the water-level drops, seepage will tend to increase. However, by optimising the beach accretion the seepage during the later stages of dredging can be minimised. This optimisation of accretion was evaluated at the feasibility stage of the project by adapting the sediment discharge locations.

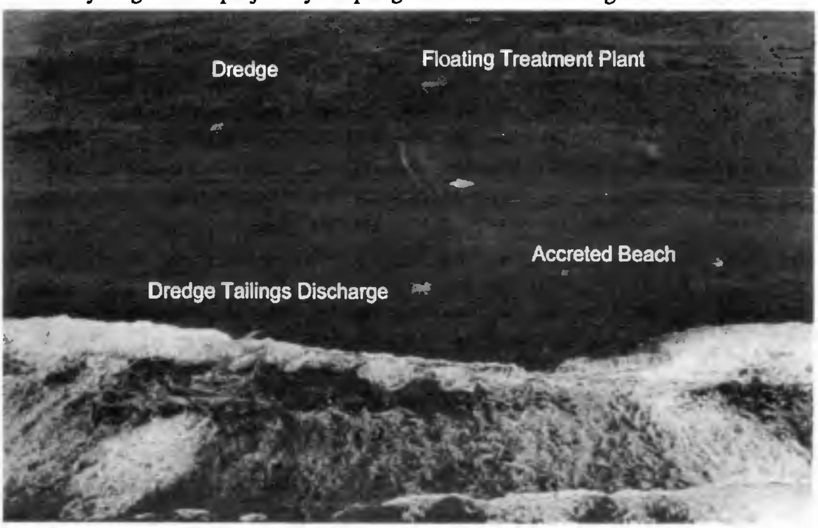

Figure 3: Aerial oblique view of the study site

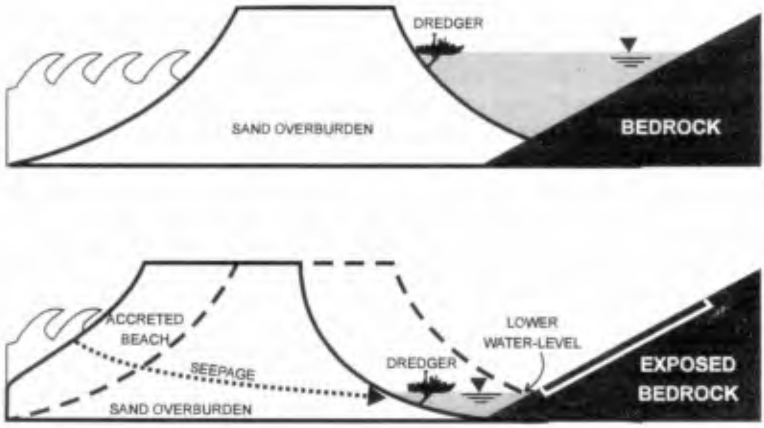

Figure 4: Water-levels and seepage at the commencement (top) and during dredging operations (bottom)

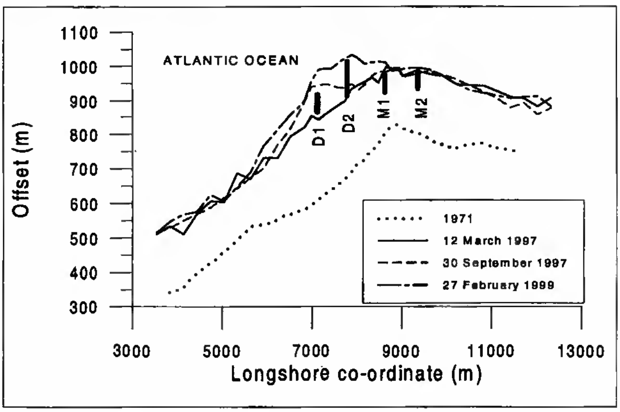

Figure 5: Shorelines at the study site

An interesting aspect is that the coast in the project region is already in an extremely accreted condition. This is due to the discharge in the region of some 80 million m^3 of sand onto the beach between 1971 and 1997. About 60% of this quantity was in the form of hydraulically discharged mine tailings, while 40% was in the form of direct nourishment of overburden sand to massive sand seawalls used for protection from wave action and in some cases for land reclamation (Smith *et al*, 1996). This sand input to the shoreline caused accretion of up to about 250 m in places (Figure 5). With the use of survey data in regions relatively unaffected by sand input, the assumed beach profile of 1971 was reconstructed, and is plotted together with the pre-dredging profile of 1996 in Figure 6. It may be noted that the recently measured profile is steeper on average. Utilising profile information together with shoreline data, the total volume of accretion between 1971 and 1997 could be estimated. Taking into account losses of sediment as a result of longshore transport, it was estimated that some 6% of material comprised fines lost offshore.

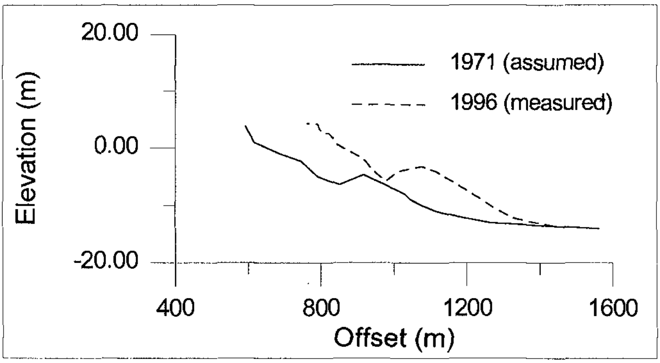

Figure 6: *Nearshore profiles prior to mine discharges (1971) and subsequently (1996)*

In sum, both the massive quantity of sediment to be discharged on a high-energy coastline during the dredging project and the extremely accreted condition of the beach result in a unique shoreline evolution study. In order to attain quality shoreline predictions, the long-term (months/years) shoreline behaviour is assessed by means of monitoring data analyses in combination with employment of a one-dimensional shoreline model. Superimposed on these results, short-term (hours/days) shoreline fluctuations are investigated by means of data analyses and cross-shore profile modelling.

Monitoring Data Analysis

The comprehensive monitoring programme at the study site incorporates wave measurements, sediment measurements, measurement of beach topography and nearshore bathymetry, photography and debris-line recordings.

Waves

Directional wave measurements were conducted offshore of the project site in 16 m to 20 m water depth. In the first few months of measurement, two SEAPAC current meters, utilising an electromagnetic current meter and a pressure sensor to resolve directional waves, were situated 4 km offshore. A directional wave buoy operating on a dual-frequency differential GPS system (CSIR, 1997) was situated 2 km offshore. The measurement by three instruments allows some comparison and data quality checks. In Figure 7(a) it may be noted that the time series of significant wave height for SEAPACs and the GPS buoy are remarkably similar, despite being some 2 km apart. Directions are also reasonably similar (Figure 7(b)) considering instrument accuracy and the separation between the instruments. More recently, only a single instrument has been deployed. A total of 14 months of measurements has been recorded since October 1996. It is intended to obtain a further 10 months of measurements.

An energetic wave climate is reflected in the exceedance plot (Figure 8) which indicates a median significant wave height of 1.9 m and significant wave heights of up to 6 m. The nearshore waves (in 20 m depth) approach the project site from a fairly narrow band of directions, with waves approaching from the south-westerly and south-south-westerly sectors 89% of the time (Figure 9). Since the coastline extends from south-east to north-west, this results in a net northerly-directed longshore sediment transport, varying from

0.4 to 1.6 million m^3/year. Wave periods are relatively long, with 80% of these being between 8 and 14 seconds.

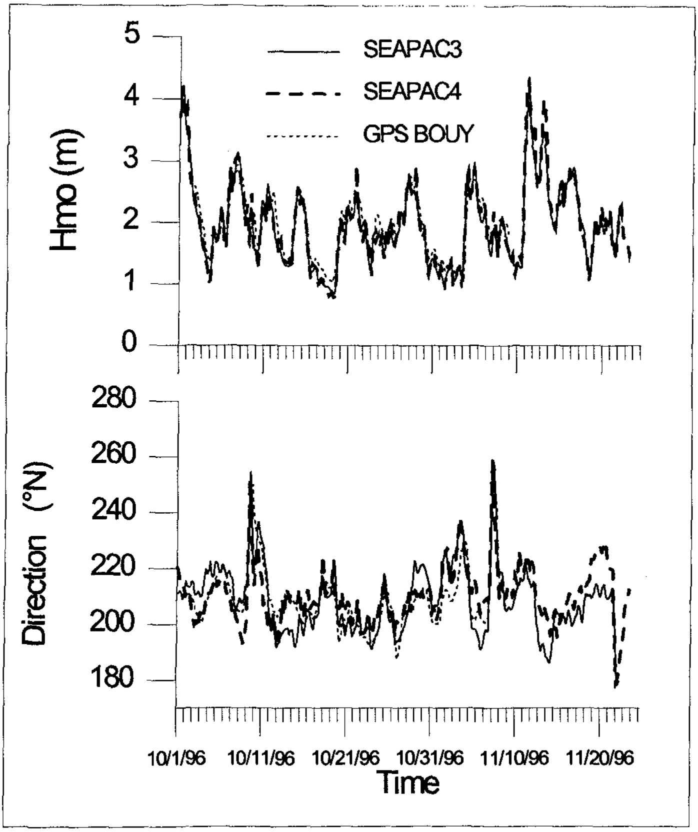

Figure 7: *A comparison of wave heights (top) and wave direction recordings by 3 different instruments*

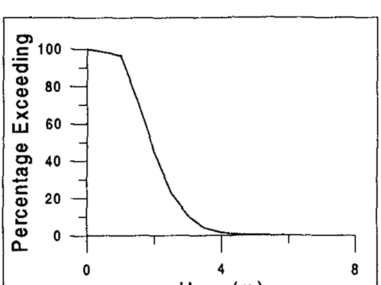

Figure 8: *Wave height exceedence graph*

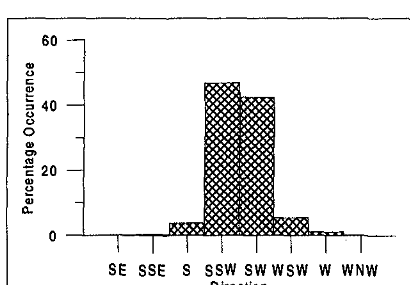

Figure 9: *Histogram of wave directions (measured in 20 m depth)*

Sediment

The beach sediment at the project site is fairly coarse, a composite median grain size of 611 μm being recorded prior to the commencement of dredging in April 1997. Extensive sampling of the beach 4 months after dredging had commenced indicated a somewhat finer composite median grain size of 447 μm, seemingly in response to the discharge of material of median grain size 495 μm. This occurred despite the winnowing effect of winter waves on a steep beach. It is recognized, however, that as the sampling is limited to the intertidal beach (spring tidal range $\approx$ 1.6 m) the sediment sizes are not representative of the entire cross-shore profile.

Morphology

An analysis of surveyed beach topography and nearshore bathymetry reveal a dynamic hydro-sedimentary regime at the study site. Vertical variations in the profile of up to 4 m over a period of a few months are also not uncommon, with a profile closure depth of up to 18 m.

Figure 5 illustrates the shoreline evolution since commencement of the dredging project in April 97. The details of quantities discharged are as indicated in Table 1. A total of 3.766 million m^3 of dredger tailings was discharged in a period of 16 months. During this period, a quantity of 0.832 million m^3 (in the form of a finer tailings discharge from a mine processing plant) was discharged via positions M1 and M2. This slightly finer sediment seems to have a limited impact on shoreline evolution (Figure 5). However, the effect of the dredge discharge, which shifts (for the most part) from position D1 to D2 to D3, on the shoreline evolution is clearly evident. By July 1998, the maximum measured seaward shoreline excursion (as represented by the MSL+2m contour) relative to the pre-dredging shoreline of 12 March 1997 is about 130 m.

Table 1: Dredge Discharge Volumes

Discharge Position (as per Figure 5)	**Start date**	**End date**	**Vol. of sediment pumped onto the beach (m^3)**
D1	4 April 1997	28 Nov 1997	1 814 000
D2	28 Nov 1997	14 Jan 1998	488 000
D1	14 Jan 1998	13 Feb 1998	174 000
D2	13 Feb 1998	19 Feb 1998	43 000
Dredger testing	19 Feb 1998	10 Mar 1998	
D2	10 Mar 1998	29 April 1998	479 000
D3	29 April 1998	31 July 1998	768 000
TOTAL			3 766 000

A survey of the beach topography and nearshore bathymetry was conducted in September 1997, after 1.107 million m^3 had been discharged onto the beach from discharge point D1. With the use of GIS overlay techniques whereby the September 1997 survey is superimposed on a pre-dredging survey, the fate of this material could be assessed. At that stage material was evenly distributed, with 0.57 million m^3 calculated to have accumulated to the north-west of D1, while 0.55 million m^3 was deposited to the south-east. The slightly higher accretion to the north-west is likely due to the discharge of finer mine tailings at positions M1 and M2, although the morphology suggested that most of this material is transported north-westwards away from the dredge discharge region.

The surveys also revealed that at that stage about half of the accreted material was situated above MSL, while some 45% of the material accumulated between the MSL-6m and MSL.

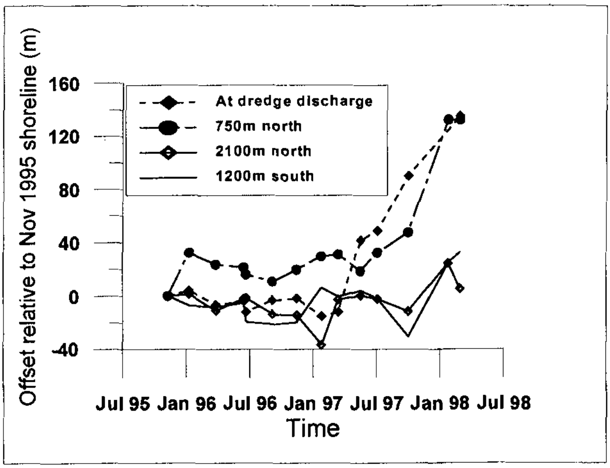

Figure 10: Contour excursions relative to November 1995

The above information provides valuable insights for shoreline modelling to estimate the long-term shoreline evolution. Superimposed on this, an understanding of the short-term variability of the shoreline is also required. Figure 10 shows the on/offshore excursions of the MSL+2m contour, relative to the situation as measured in November 1995. In some cases a classical summer/winter variability occurs, such as 1200 m south of the discharge location, where a shoreward shift is seen around and after July, while a seaward shift is seen around January. This trend does not always occur, however. For example, the data from 2100 m north (Figure 10) indicate a retreat of the MSL+2m contour in January 1997. Such deviations from seasonal trends are likely due to the formation of localised giant cusps, as observed frequently on the study coastline. Also evident in Figure 10 is the accretion as a result of dredge discharge. A steady build-out of the shoreline is evident from about April 1997 at the dredge discharge position (D1), while 750 m to the north, the response of the shoreline is delayed but extremely rapid. This is likely the result of relatively rapid distribution of sand by longshore transport.

Also evident in Figure 10 is a rapid retreat of the shoreline just prior to July 1996 (except for the 2100 m north case, since data was not available). This retreat occurred as a result of a major storm (of estimated recurrence interval of 2 years) during which significant wave heights of up to 5.9 m were recorded, while high waves (mostly over 4 m) persisted for four days. The result of this storm was an average retreat along the 9 km study coastline of 5 m, while a maximum retreat of 20 m was recorded.

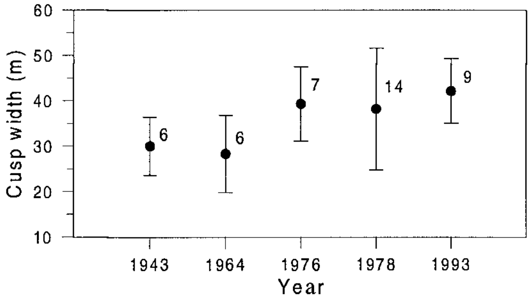

Figure 11: *Average widths of cusp embayment. The number of samples are shown as well as the standard deviation (error bars)*

A detailed analysis of the variability of the shoreline was conducted, utilizing 9 surveys of 38 beach profiles along some 9 km along the study site. These indicated a maximum shoreline (MSL+2m) accretion (relative to the average of the shorelines) of 29 m, while a maximum shoreline retreat of 35 m was measured. Since the major variations of the shoreline are the result of giant cusp formations, a study was focussed on these. A coastal section of some 20 km at the study site was investigated, with the use of photographs taken prior to the commencement of any significant mine sediment discharges (i.e. in 1943 and 1964) as well as later (1976, 1978 and 1993). In Figure 11, the average width of cusp (i.e.shore perpendicular extent) are indicated, while numbers indicate total cusps recorded in the study region and the error bars provide the standard deviation of the width. A definite increase in cusp width is evident after the commencement of discharge of mine sediment onto the beach in the early '70's. The pre-mining cusps average about 30 m width, while the later cusps average about 40 m width. The number of cusps observed also increases. The average cusp length for all the measurements is 383 m, with a standard deviation of 115 m.

Additional measurements

The "more conventional" measurements of waves, sediments and bathymetry/topography are supplemented with regular photographs and measurements (from a series of fixed beacons) of the debris line. The photographs provide a useful qualitative assessment of cusps, beach slopes and wave conditions, while the debris-line measurements provide an indication of the maximum extent of wave runup. The latter is useful for verifying wave runup calculations and for assessing safe setback distances.

Trials are in progress to improve measurement techniques. A system of digital video recording is being tested. Analysis of the digital images will ultimately provide more comprehensive data on intertidal topography, wave runup, and some indication of nearshore bathymetry. In addition, it is intended to improve measurement of bathymetry through the surf zone through the deployment of a helicopter-borne survey. This method is the obvious choice in a region to which rapid access is difficult, calm days are limited, and where a mine helicopter is readily available. Referring to trial surveys conducted in 1990 (Coppoolse *et al*, 1992) and the technique of Pollock (1994) improved survey techniques have been explored. In Figure 12(a), the method involving deployment of a stand is illustrated. Using ranging rods or a differential geographical positioning system (DGPS) with a graphical display, the helicopter is positioned. The 5 m high stand is lowered onto the sea bed. The elevation and distance to the prism cluster are obtained by means of a shore-based total station. This method is practical provided conditions are reasonably calm. Preliminary tests indicate that the method is functional in wave heights of over 1 m.

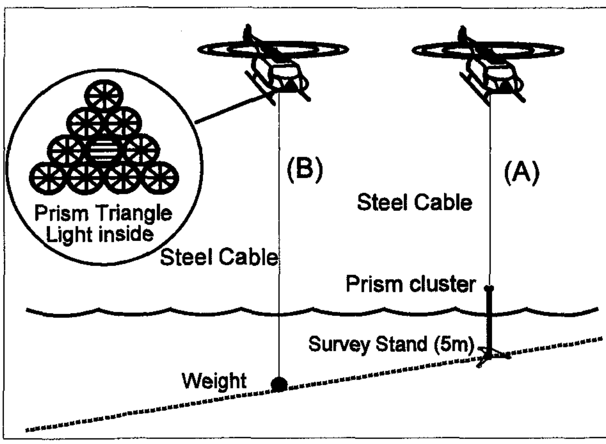

***Figure 12:** Helicopter survey techniques for (a) the near-beach region and (b) further offshore*

Although not yet tested, figure 12(b) provides a possible method for surveying in deeper water. As for the above, the helicopter would be positioned by means of ranging rods or DGPS. The weight at the end of the steel cable is then lowered and carefully observed by the flight engineer. At the instant that the weight touches the sea bed, the flight engineer depresses a light switch. Until this time a prism triangle would have been tracked from the shore-station, from which the position of the helicopter prism is logged as the light is switched on. Since the line has a predetermined length, the position of the bed can be recorded.

Predictive Modelling

Shoreline model predictions

The measured wave data were synthesized into 7 offshore swell conditions (representing 94% of the measured swell conditions) and 5 offshore sea conditions (representing 80% of the sea conditions). Wave refraction for these conditions was computed with the HISWA model. With the use of the resulting nearshore wave data, an extensive set of survey data (incorporating 17 measured shorelines) and historical records of sediment inputs to the beach (from mine plant tailings discharges and from nourishment of sand seawalls), the shoreline model UNIBEST was set up over a coastal extent of 16 km. The relatively featureless coastline is ideal for a shoreline model application, and the "fixed sediment transport" boundaries were situated far enough from the region of interest to have any impact. Figure 13 illustrates the result of the shoreline model validation. As can be seen measured shorelines, which display on/offshore excursions of up to some 200 m over a 21 year period, are well predicted.

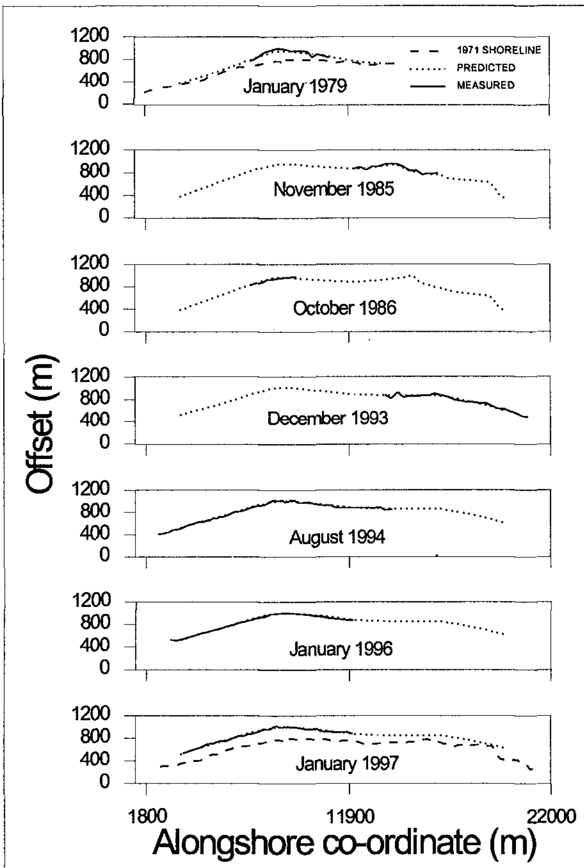

***Figure 13:** Shoreline model predictions against measured data (pre-dredging)*

This validation of the shoreline model provided a firm basis for the prediction of shoreline evolution as a result of dredger tailings discharge along part of the shoreline. Extensive data on discharges and shorelines (6 surveys extending up to 9 km along the study coast) available since commencement of dredging in April 1997 allowed an updated validation of the model, some of the results of which are depicted in Figure 14. Here the model generally predicts the shoreline evolution well within 20 m of measured shorelines, while at isolated points the accuracy is within 30 m. This accuracy margin is within the limits of short-term shoreline changes, such as due to cusps and storms.

Although the shoreline model is well verified, a considerable degree of uncertainty exists for predictions of shoreline evolution as a result of the massive sediment input proposed for the next few years. A key question in this regard is how longshore transport and offshore loss of finer material will be affected by the rapid steepening of the beach and corresponding increase in wave breaking intensity. Violent plunging breakers observed on site will certainly be extremely effective in suspending and transporting sediment. An additional uncertainty is the exact rate and volume of sediment to be discharged from the dredging operation. These uncertainties were accommodated by simulating several scenarios which test the sensitivity to wave conditions, grain size, sediment discharge rates and sediment discharge volumes. For example, Figure 15 illustrates shoreline model sensitivity to the volume of sediment discharged. A standard case was run, with the model based on the boundary conditions as for the model verification, and the volume of sediment as is anticipated at present. The result at the end of dredging in January 2004 is depicted in the figure. If the total volume discharged is 25% more, but at the same rate of discharge, the coastline is predicted to be some 30 m to 40 m seaward (in July 2005). On the other hand, 25% less material results in a predicted shoreline of some 40 m to 50 m shoreward of the standard case.

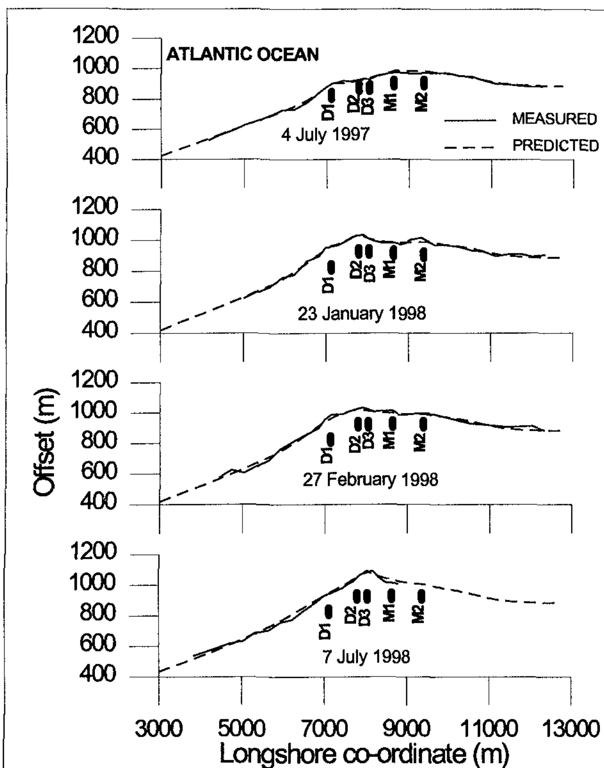

***Figure 14:** Shoreline model predictions against measured data (during dredger discharge)*

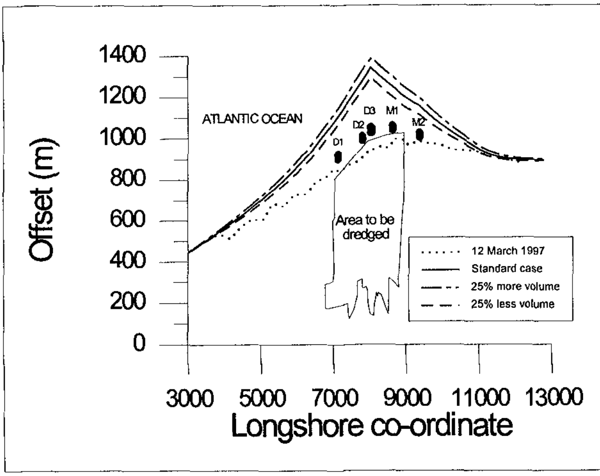

Figure 15: Predicted shoreline evolution sensitivity to the volume of material discharged

A notable feature of the predicted shorelines is that the accretion occurs opposite the dredging area. This has been carefully planned to ensure that seepage to the area, which will have a lowered water level near the end of dredging, is limited. This facilitates minimal pumping to maintain an area of exposed bedrock to be mined (as in Figure 4(b))

Table 2 indicates the results of further sensitivity tests. In each case, the condition of the shoreline at the end of dredging is compared to the standard case, and the maximum shoreline variation relative to the standard case is indicated. In general the scenarios tested were "pessimistic", in order to explore worst cases for the mine.

Table 2: Shoreline model sensitivity test results

SCENARIO	Max. Shoreline variation from the Standard Case (m)
1. 5% higher waves, 5 degrees more southerly	-52
2. Sediment size decreased by 100 μm	-34
3. Sediment size decreased by 170 μm	-58
4. Decreased discharge rate by 25%	-52
5. 25% more material discharged	+35
6. 25% less material discharged	-46

As may be noted, considerable variations in the wave, grain size and sediment discharge conditions cause variations in the shoreline of the same order of magnitude (i.e. approximately 50 m).

Cross-shore profile model predictions

In order to obtain comprehensive shoreline predictions, short-term shoreline variations must be superimposed on the long-term shoreline model predictions. In addition to the insights obtained from empirical data, cross-shore profile modelling provides an assessment of erosion during episodic events such as storms. Figure 16(a) shows a validation of the SBEACH profile model predictions against beach profile measurements made over a storm event (i.e. the 1 in 2 years storm as described above). Unfortunately nearshore data were not available for a full calibration of the profile. Nevertheless, the "dry" beach profile behaves approximately as would be expected, i.e. material is eroded from the upper beach and deposited on the lower profile. Based on this calibration, the response to more severe storm action can be explored. Figures 16(b) and 16(c) depict predicted profile changes under storms of return periods 1:10 and 1:50 years respectively. The effect of these storms on the shoreline (MSL+2m contour) are recorded in Table 3.

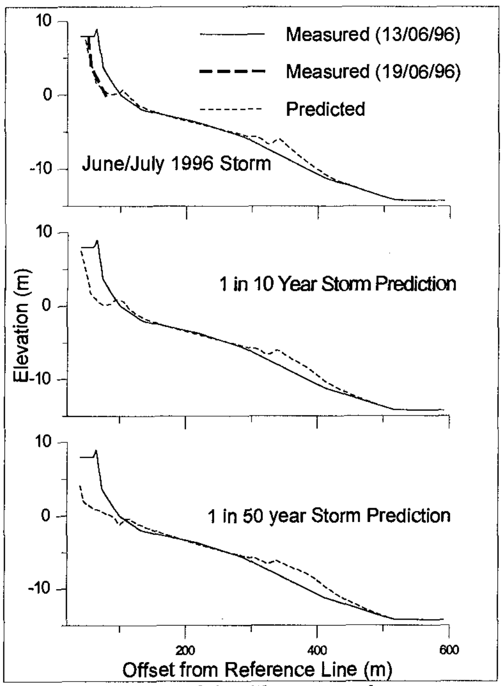

Figure 16: *Cross-shore profile model calibration and storm erosion prediction*

Table 3: Predicted shoreline retreat as a result of storms

Storm return period	**Predicted retreat of the MSL+2m contour (m)**
1:2 years	20
1:10 years	37
1:50 years	43

Based on these results, together with results of cusp analysis and wave runup calculations, a safe setback of 90 m was recommended for mining operations. This is however provided that protection against waves overtopping the beach berm is in place, and does not take account of longer-term erosion due to longshore transport. A maximum erosion of 40 m, and intrusion of wave runup by a further 30 m, was recorded prior to dredging. As short-term erosion of a temporarily accreted shoreline is likely to be more extreme, the above-mentioned setback estimate is considered reasonable.

Conclusion

The accreted condition of over shoreline in combination with the massive quantity of sediment to be discharged some 5 years set the scene for a totally unique project. An open, relatively straight coast, together with large sediment inputs and significant coastline changes, provide ideal conditions for the application of a one-dimensional shoreline model. With the availability of extensive data, a reliable validation of the model was possible. Together with model sensitivity tests, reasonable predictions of future long-term shoreline evolution scenarios were made.

Further analyses of survey and aerial photograph data facilitated, together with the application of a cross-shore profile model, an understanding of the short-term shoreline fluctuations. Combining these with the long-term predictions results in the provision of essential input to mining operations.

Acknowledgments

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