CHAPTER 240

MODELLING AND ANALYSIS TECHNIQUES TO AID MINING OPERATIONS ON THE NAMIBIAN COASTLINE

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ABSTRACT
The extraction of diamondiferous ore deposits along the coastal strip of southern Namibia has called for novel mining techniques. Quantitative analysis of coastal processes incorporating the prediction of short and long term shoreline response has proved particularly useful in optimizing such techniques. Further attention has been given to assessing the impact of mining operations on the nearshore ecosystem through comprehensive monitoring and modelling analyses.

1 INTRODUCTION
Diamond mining operations in the southern coastal region of Namibia involve temporary coastal protection and beach reclamation schemes as well as the projected discharge of mine overburden material into the nearshore zone. In the extreme south of Namibia, near the town of Oranjemund (Figure 1), NAMDEB construct sand seawalls to protect mining operations. These seawalls have been successfully used to reclaim precious mining terrain in a highly dynamic wave climate (Moller and Swart, 1988). The continuation of these reclamation efforts over an area where reduced quantities of seawall replenishment material is available has however called for optimization. In this regard the construction of massive groynes for enhancing shoreline progradation has been investigated.

A proposed initiative incorporates the use of a dredger so as to mine the overburden of a coastal region. As a result of the dredging, some 26 million m^3 of sediment will be discharged onto the neighbouring beach. The accretion resulting from this nourishment will effectively reclaim land and provide a protective beach which reduces water seepage during final mining operations. Coastline modelling has

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proved extremely useful in the planning and assessment of this mining initiative.

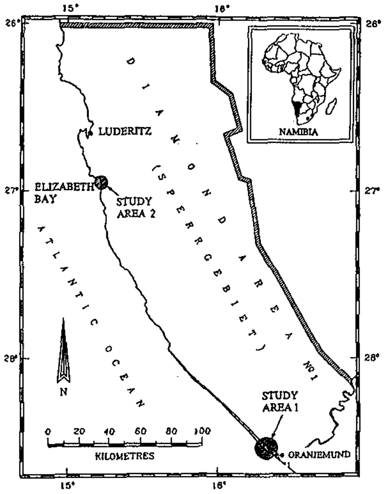

Figure 1: Location map indicating the diamond mining region within Namibia

Further north at Elizabeth Bay (Figure 1), NAMDEB mining operations involve the separation of undersized sediments from the diamondiferous ore. This fraction, comprising some 75% of the total excavated quantity of 20 million m^3, is discharged onto the beach in the adjacent sheltered bay. Due to the proximity of lobster and other biological communities, the necessity for assessing the environmental impact of such operations beyond the confines of the bay was identified. A comprehensive ongoing monitoring program, incorporating environmental measurements and predictive coastline and circulation modelling, was initiated for this purpose before commencement of mining operations.

2. ORANJEMUND

2.1 Environmental Conditions

The dynamic wave climate at Oranjemund, as derived from local Waverider buoy recordings has an average significant wave height of 2,2 m (average wave period is 12 seconds). Storms occur frequently, with significant wave heights over 4 m occurring about 25 times (average duration ~ 11,8 hours) per year. The predominant wave direction ranges between 180° and 200°.

The coastline is relatively straight, and lacking features such as headlands, is unprotected from wave attack. Vertical profile excursions of up to 4 m reflect the dynamic environment, where a sand grain size of approximately D_{50} = 500 μm occurs on the steep beach face.

Longshore sediment transport calculations as determined via a wave refraction study indicate a northward transport rate of 1,4 Mm3/yr. This rate was further verified via one-line modelling simulations (CSIR, 1979; CSIR, 1994a).

2.2 Seawall Mining Operations

Several attempts have previously been made to protect the coastal mining operation from wave action and to increase the mining area by mining closer to the waterline. One such attempt involved the placing of cobbles on the seaward face of a sand seawall, however the cobbles were removed and strewn across the beach. Various geofabric options such as covering the sand seawall with tarpaulins and protecting the seawall toe with cloth bags were also unsuccessful. In addition, short groynes were made from metal frames and filled in with boulders. However these structures did not penetrate sufficiently into the surf zone to interrupt the longshore sediment transport to cause accretion. Sheet piles were also used for a time, which allowed the mining of bedrock some 25 m closer to the sea. It was intended to re-use the piles as mining operations proceeded along the coast. However the percentage of sheetpiles which could be re-used was lower than predicted and the method was therefore found to be uneconomical. A further attempt involved the use of interlocking concrete blocks. These were interlocked laterally, but could slide downwards as sand was scoured from beneath them. This system was destroyed during the larger storms, however and took 8 to 10 days to re-establish. Since this system was also uneconomical, it was stopped. The most recent such initiative involved the use of flexible mattress, which failed principally due to toe scour.

The most successful of the protective structures has simply been a massive sand seawall (Figure 2), which has been practical to construct from the sand overburden material, and which is stripped almost to bedrock at a depth of some 20 m in places. Constant sand nourishment to the eroding seaward face of the seawall, which is 300 m to 800 m in length, ensures its structural integrity. At one stage of the mining operation, advantage was taken of the abundant sand overburden by advancing the seawall up to 300 m seaward. This ambitious scheme involved the placing of massive quantities of sediment on the seawall.

An interesting aspect of the study is that although a total of 12.7 million m^3 is used for the construction and maintenance of seawalls during the 5 year period, records show that at most 8 million m^3 of this amount was obtained from the mine. Thus a deficit of some 4.7 million m^3 exists. It is assumed that much of this material was rehandled, i.e. the material fed onto the wall is eroded and subsequently deposited to the north, where it is re-excavated and again fed to the wall.

Figure 2: Seawalls protecting the adjacent mining operations

Constant erosion from the seawall of average length 600 m occurred as it advanced northwards. Thus the quicker mining operations advanced, the less the total amount of material needed for the seawall. This is borne out by the optimization curve shown in Figure 3 which is constructed from data obtained during the mining operation. A regression analysis yields the equation of the curve:

$V = 1450000R^{-0.963}$

where: V = Volume of material used per metre length of the wall (in m^3).
R = Rate of northwards advance of the wall (in m/year).

As can be seen from the curve, a rate of advance of less than about 500 m/year is detrimental since it requires in considerable maintenance. High advance rates are, however, constrained by available resources and the necessity to maintain long seawall sections.

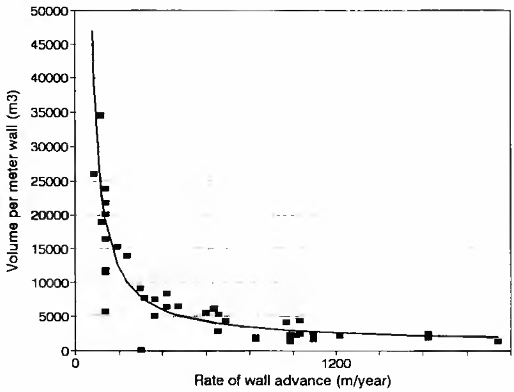

Figure 3: The relationship between rate of wall advance and sediment volume place on the wall.

Further support for mining operations has been provided through an early warning system for wave attack. With the dominant incident southerly wave conditions at the site a remote link to waveriders to the south provides up to 12 hours of advance warning of extreme events.

2.3 Groyne "sand trap"

A unique initiative to capitalize on the high longshore transport rate, which is enhanced by the above-mentioned nourishment, is to construct groynes and thereby facilitate land reclamation updrift. A site favourable for both mining reasons and for groyne construction (i.e. foundations on a rocky outcrop) was selected, and one-dimensional coastline model simulations formed the basis of a detailed feasibility study.

Figure 4 shows the calibration of the one-line UNIBEST model for a 2 year period, over a 10 km coastline extent width. The relevant sediment sources are input to the model. This includes the beach nourishment as supplied to seawalls in the region, which varies between 60 000 m^3 and 270 000 m^3 at various locations along the coast. In addition, the point discharge of sediment from a processing plant is included (as indicated in the figure). This amounts to about 1.7 million m^3 of material; however this is somewhat finer material than that discharged to the seawalls.

As seen in Figure 4, the measured shoreline after 2 years is reasonably well predicted, taking into consideration that the measured beach cusps are not simulated by the model. In particular, the coastline accretion near the discharge point as well as a promininent coastline inflection point are well simulated.

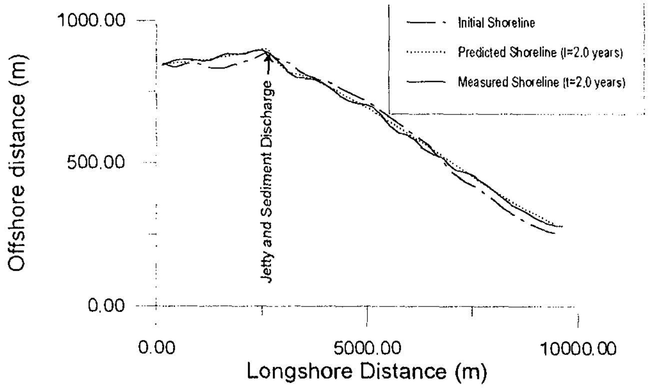

Figure 4: Coastline calibration prior to groyne accretion predicitions

On this basis the coastline evolution due to groyne lengths of 150 m, 200 m and 300 m was assessed. For each case, two scenarios were considered. The first assumed a large sand seawall which is built so that it extends 40 m beyond the coastline. This calls for considerable input of sediment to maintain wall integrity with estimates from a modelling exercise indicating this to be from 540 000 m^3/year to 740 000 m^3/year. The second scenario assumed a protective sand wall (termed a "beachwall") constructed about 40 m above mean sea level. The anticipated maintenance quantity for this wall involves between 105 000 m^3/year and 144 000 m^3/year.

Table 1 illustrates the accreted areas obtained for each of these scenarios. Between 10% and 20% extra area is gained through the inclusion of seawalls. This is due to the land reclamation facilitated by the seawalls *per se*, as well as the extra sediment input which accretes at the groyne. The benefit of a longer groyne is obvious. As may be observed the accretion from a 300 m groyne is more than double that of the 150 m structure for the beachwall case.

Table 1: Accreted areas

Groyne length	Beachwall (m^2)	Seawall (m^2)
150 m	151 400	181 800
200 m	222 400	248 700
300 m	363 100	297 400

A conceptual structural design of the groyne was carried out in parallel with this study. There was a number of unique constraints associated with the design; namely security limitations restricting the hire of plant, unsuitable armour rock material in the region and a groyne lifespan limited to about 6 years. Concrete armour and Caisson-type structures were found to be the most suitable under the above constraints.

2.4 Dredge Discharge

A proposed initiative is the removal of some 26 million m^3 of sand overburden via dredging. This material extends to a depth of -26 m MSL globally and has a sand composition which is roughly similar to the beach sediment. It is intended to discharge this volume of material, after screening for diamond extraction, onto the beach, where the coast has already accreted by some 300 m due to sediment from discharge at an adjacent processing plant. Considering the prevailing dynamic wave climate and sediment composition, high offshore losses of sediment from the discharge can be expected.

Primary objectives of the study are to assess shoreline changes for input to seepage rate calculations as well as to co-ordinate the discharge in order to maximise accretion of the coastline during the final stages of mining. The reason for this is to minimise seepage from the sea into the deep mining area which is totally dewatered at this final stage. In addition the mining region must be protected from wave attack which could lead to flooding of the working area.

The calibration of the one-dimensional coastline model is illustrated in Figure 5, in which historical coastlines were obtained from a topographical map, aerial photographs and a recent beach survey. The simulation is run from the initial shoreline of 1971. As can be seen, each of the measured shorelines is reasonably well predicted by the model. Of particular interest is the period between 1979 and 1986, during which a decrease in the discharge rate led to the retreat of the coastline.

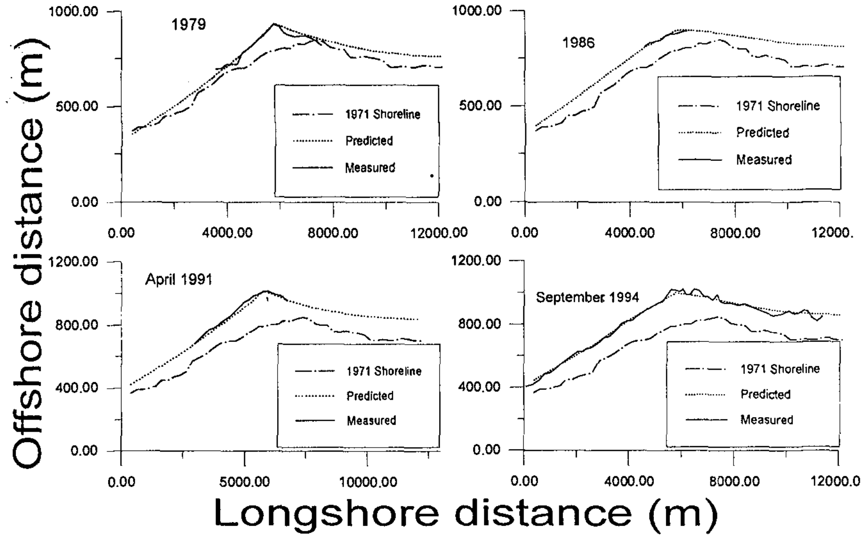

Figure 5: Calibration of the coastline model - dredge region

Further verification of the model was conducted by modelling a 20 km stretch of coast (Figure 6). In this simulation all of the major sediment inputs to the system were included as they occurred over the 23.4 year period. As seen, the model is fairly well validated against the measured coastline. The exception is in region of +5000 m, where unusually large accretion occurred.

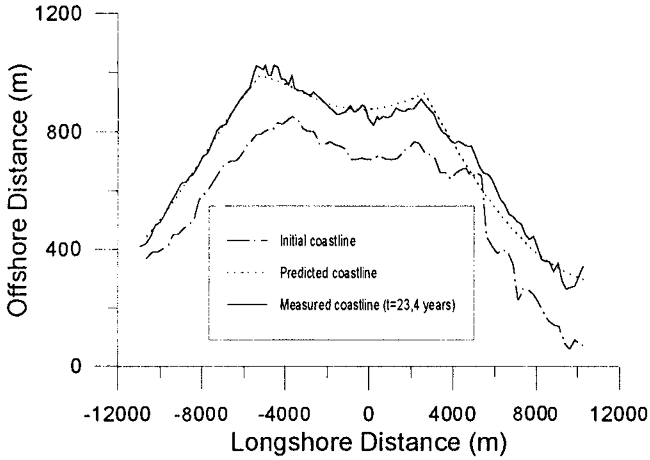

Figure 6: Calibration of the coastline model - extended region

With the validaty of the model verified, various scenarios were explored. Figure 7 illustrates the accretion resulting from an optimised strategy from 4 discharge points. As seen, the accretion fillet at the completion of the discharge is centered opposite the final region of dredging. With the intention being to mine the region subsequently; the predictions of 0.5 and 1.0 year later show that the accreted coastline is still centered around the appropriate region in spite of considerable erosion.

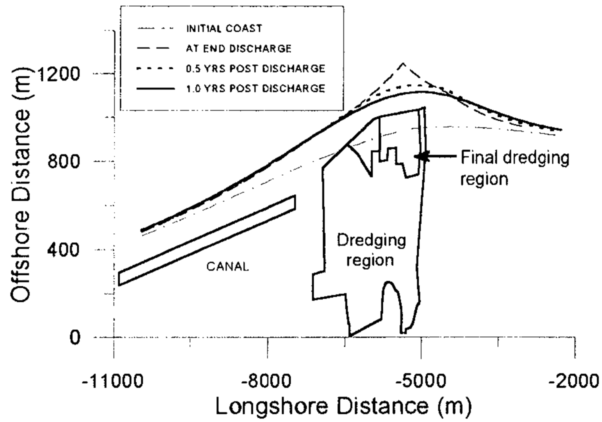

Figure 7: Coastline evolution in response to the optimised discharge strategy

3. ELIZABETH BAY

As schematized in Figure 8 some 75% of the mined ore deposit is discharged onto the beach within Elizabeth Bay. Although expected impacts on the sandy beach system within the bay have been deemed to be inconsequential, concerns have been expressed regarding potential impacts on lobsters and other biological communities beyond the confines of the bay. The primary sediment input into the bay is at the eastern boundary, with a prominent sink the indicated aeolian dune corridor. The bay is relatively protected from incident waves, which are from a dominant southerly direction.

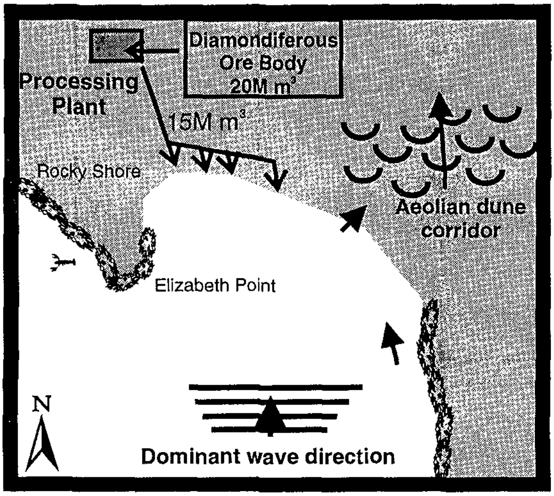

Figure 8: Schematisation of the sediment transport processes at Elizabeth Bay

3.1 Monitoring Programme

In anticipation of the commencement of mining operations at Elizabeth Bay in July 1991 a comprehensive monitoring programme was initiated the previous year. Data emanating from regular monitoring is supplemented by recordings made during the course of an earlier impact assessment (CSIR, 1988) as well as two field measurement compaigns (CSIR, 1992).

The principal components of the monitoring programme comprise aerial photography (including control sites), plant discharge (rates and granulometry), nearshore bathymetry, beach surveys, nearshore and beach observations (pro forma), wind recordings (two weather stations) and a bio-sampling transect.

3.2 Data Analysis

3.2.1 Morphological response

Beach and nearshore bathymetric surveys recorded prior to mining operations constitute an effective baseline for assessing the impacts of discharge operations. The minimal changes apparent in these pre-mining surveys attest to a state of morphodynamic equilibrium within the bay.

For approximately the first 18 months of discharge operations an average monthly volume of the order 130 000 m^3 of sediment was discharged to the beach. This discharge, which was somewhat higher than originally anticipated, was concentrated at the outlet DP1 shown in Figure 9. Following a reduction in processing volumes, monthly rates have reduced to approximately 50% of the above figure since early 1993. Discharge was further extended to the more easterly outlets shown in Figure 9.

As further illustrated in the figure, shoreline response to the initial concentrated discharge is characterised by a local protrusion. A reduced and more distributed discharge thereafter, however, results in more even alongshore progradation.

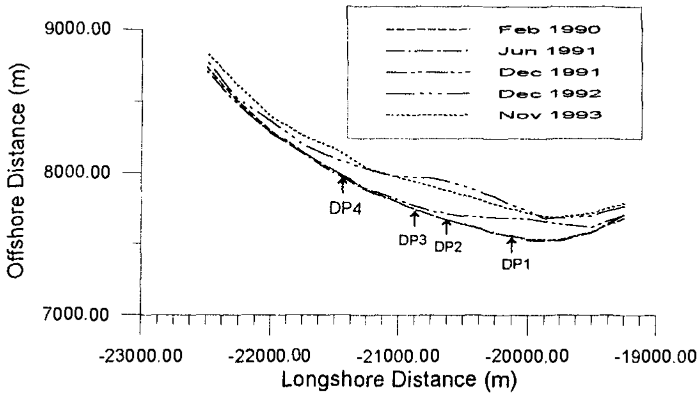

Figure 9: Coastline evolution at Elizabeth Bay and principal discharge stations

The measured cross-shore profile response at a location near the area of maximum discharge is depicted in Figure 10. Within the context of an an original impact assessment (CSIR, 1988) the SEAGAR2 cross-shore profile model was employed for determining equilibrium profile response due to the discharge. The significantly steeper measured profile reflects only limited alongshore and cross-shore redistribution of beach material.

With an average D_{50} grain size in the range 0,25 mm - 0,4 mm the discharge fraction is somewhat coarser than the native material ($D_{50} \sim 0,15$ mm). In the medium term an equilibrium profile somewhat steeper than the native state will therefore result. As anticipated in the original impact assessment, this will have an initial negative impact on the intertidal biotic community.

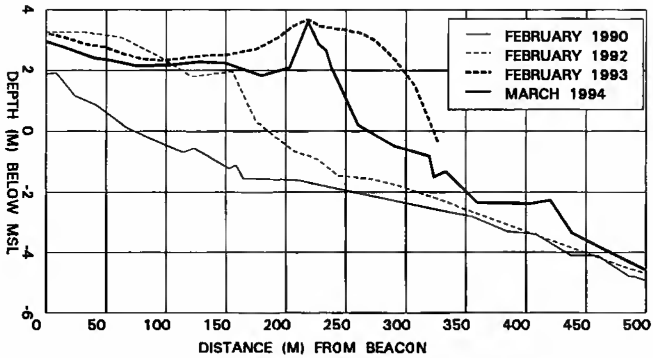

Figure 10: Cross-shore profiles measured at Elizabeth Bay

The difference chart comparing the pre-mining February 1990 bathymetric survey to that of March 1994 illustrates how morphological changes have been confined to the nearshore area. Although the most significant variability occurs at the western end of the bay near the discharge point, some seawards movement of material is evident near the eastern extent of the survey area. As will be discussed in 3.2.2 this area is coincident with a flow convergence zone and associated rip-current.

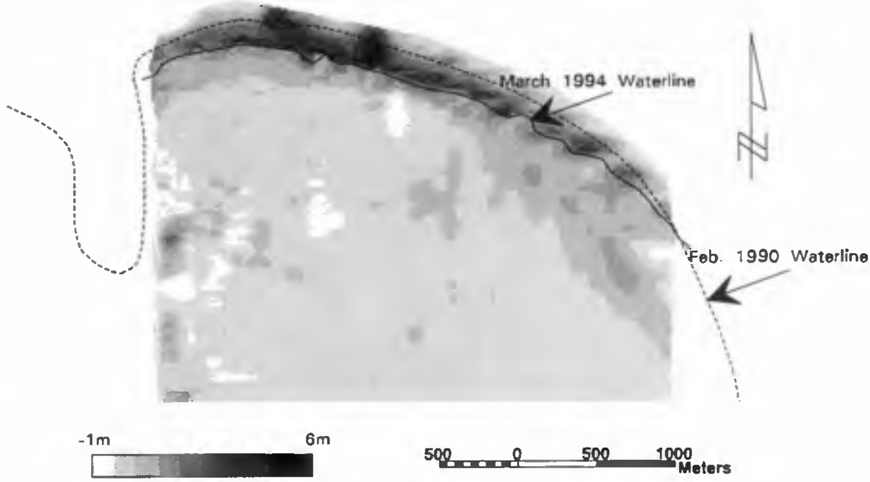

Figure 11: Bathymetric difference chart (February 1990 - March 1994)

3.2.2 Sediment budget

Schematized in Figure 8 are the primary constituent components of the sediment budget at the study site. A theoretical analysis incorporating wave refraction modelling predicted an influx into the bay of the order 0,25 Mm^3/yr. This longshore transport rate may be seen to be substantially less than further south at Oranjemund, which is a far more exposed section of coast. It further reflects the influence of aeolian sediment pathways feeding the Namib desert, of which the study site constitutes a prominent component. Field and theoretical barchan dune movement studies have estimated an annual transport in the range 0,15 Mm^3 to 0,3 Mm^3. With a negligible flux of sediment around the prominent Elizabeth Point at the western boundary, it is likely that the influx into the bay and the aeolian sink are in approximate natural balance.

A summation of volume charges computed from beach survey measurements accounts for roughly 70% of the total 3,1 Mm^3 discharged to January 1994. The 30% discrepancy with the discharge quantity is primarily attributable to the restriction of volume calculations to the limiting depth of surveys, which is of the order of 1 m below MSL. Other factors are bulking errors and increased aeolian losses due to an enlarged deflation zone following beach progradation. A further factor, discussed below, is the offshore transport of suspended fines. With up to 8% of the discharge material having a diameter less than 0,1 mm it likely an appreciable proportion of the pumped discharge is lost in this manner. A reliable summation of these variable contributions appears to account for the discrepancy.

Turbid plumes

An ubiquitous feature of the study coastline is the apparition of turbid plumes. Aerial photographic and on site monitoring has highlighted an increase in extent and frequency of such plumes since the commencement of mining operations. Such plumes are, however, primarily manifested within the confines of the bay. During the course of two field exercises (CSIR,1992) under contrasting wind and wave conditions plume related parameters such as temperatures, salinities, currents and suspended matter characteristics were measured. In Figure 12 is schematized recordings of particle inorganic matter (PIM) concentrations over the study domain. Although elevated near the discharge area concentrations are considered to be within the range of naturally occurring turbidity (~ 5 mg/ℓ).

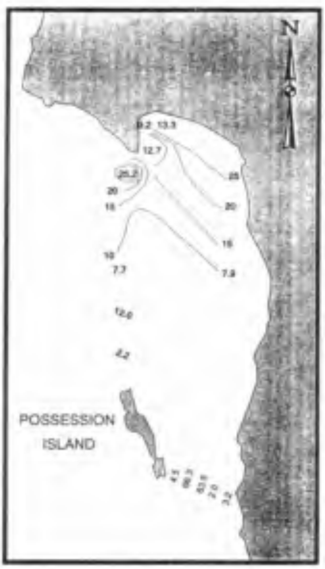

Figure 12: Particle inorganic matter distribution on 18 May 1992

3.3 Predictive Modelling

3.3.1 Plume dynamics

The two dimensional hydrodynamic TIDEFLOW model was used to simulate tidal and wind driven circulation in the study area. Such a model, which was calibrated against drogue measurements, was considered to be appropriate due to the vertically well mixed state of the bay as recorded during the dominant strong wind conditions. The computed hydrodynamic flow field was coupled with the PLUME dispersion model for the prediction of turbid plume response within the bay. Measured concentrations were used for validation of this model. In Figure 13(a) is shown the simulated plume response under the dominant southerly wind conditions. Although relatively high concentrations are evident in the vicinity of the discharge area, values beyond the bay confines are minimal. Somewhat higher values in the vicinity of the point are evident for the infrequent NE wind conditions (Figure 13(b)), however, values remain within the range of naturally occurring turbidity. Scenario modelling showed increased movement of turbid water beyond bay confines in the event of a prograded coastline, however, this was remedied by moving the discharge points further east.

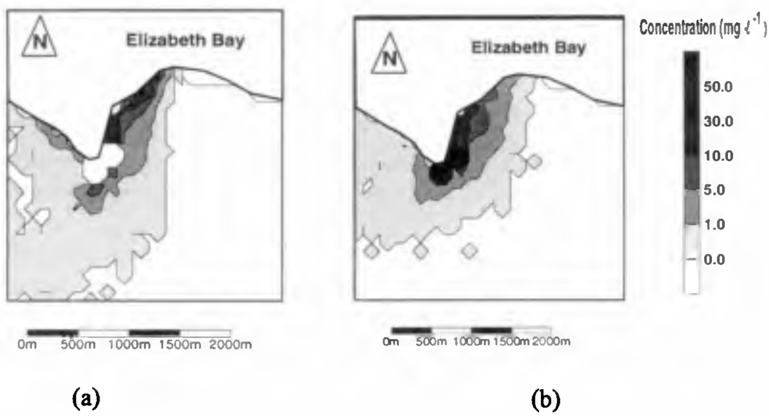

Figure 13: Modelled plume response after 48 hours for (a) a southerly and (b) north-easterly wind of 10 m/s

3.3 Shoreline Response

Shoreline response to projected discharge was modelled, with reference made to the sediment budget discussed in Section 3.2.2 for definition of appropriate boundary conditions. The dominant contributions in this regard are an equivalent sediment influx and sink of the order 0,25 Mm^3/yr at the eastern boundary and aeolian corridor respectively. Reference was made to the measured and equilibrium profile characteristics for the definition of short and longterm effective depths for the model.

As illustrated in Figure 14, the model is reasonably well validated against measured shoreline changes to date. Projecting the model to variable discharge scenarios, Figure 15 shows the enagerated promontory developed by a concentrated discharge. A preliminary analysis of 2-D wave driven currents demonstrate the susceptibility to rip-current generation of such a prominent coastline feature. As is also shown in Figure 15, a distributed discharge strategy results in a more even progradation due to enhanced alongshore spreading of material.

Such an evolution will mitigate against prominent rip-current features, which may enhance seawards movement of different sediment size fractions.

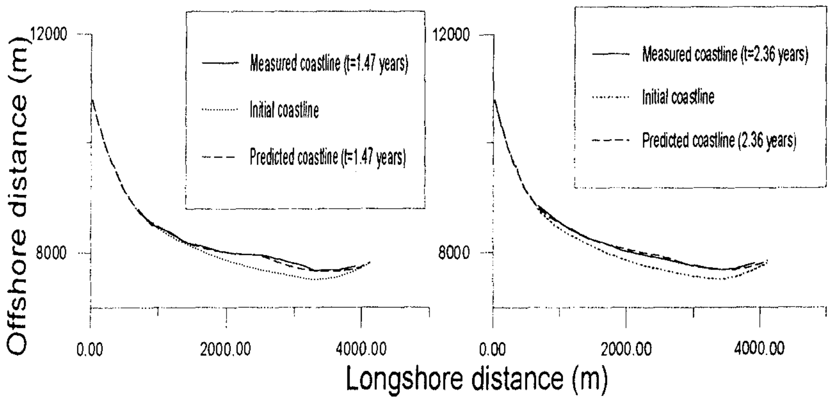

Figure 14: Calibration of the shoreline model at Elizabeth Bay

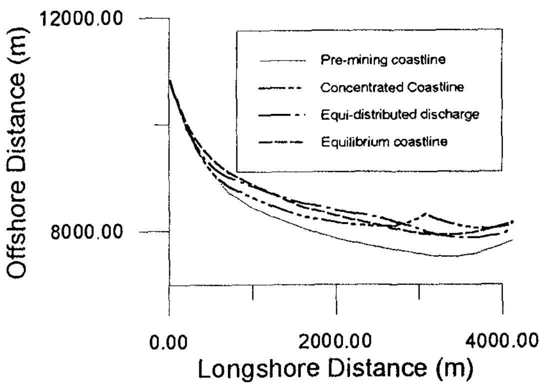

Figure 15: Discharge scenario simulations at Elizabeth Bay

CONCLUSIONS

The comprehensive monitoring and analysis of environmental data has provided a critical underpinning element to coastal mining operations in Namibia. Assessments of the morphological response to variable mining strategies, which have led to the optimization of mining techniques, have been greatly facilitated by predictive modelling methods. Such methods, validated against available monitoring data, have further proved vital in assessing the potential impacts of such operations on adjacent eco-systems. In this regard, a controlled discharge strategy is not expected to pose a threat to biological communities beyond the confines of the bay.

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