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Consequences of Sediment Discharge from Dune Mining at Elizabeth Bay, Namibia

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ABSTRACT

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Nearshore turbidity owing to suspended fines is a natural phenomenon around much of the western coast of southern Africa. However, the potential impacts of diamond-mine-related sediment tailings on local biotic communities at Elizabeth Bay in Namibia have been the subject of comprehensive ongoing assessment. This paper discusses field measurements and mathematical modelling carried out to quantify the extent and relative influence of sedimentation and turbid plumes associated with the mining operation. Following validation of the various mathematical models using available field measurements, the models are used to predict shoreline evolution and nearshore turbidity response for various scenarios, including the situation towards the end of mining operations. The principal finding is that, although the mine discharge causes significant shoreline accretion and elevated turbidities in the nearshore regions of the bay, turbidity levels in the region of concern beyond the confines of the bay will remain below critical threshold levels for impacting on local biota.

ADDITIONAL INDEX WORDS: *Fine sediment plumes, circulation modelling, shoreline modelling, environmental monitoring, Elizabeth Bay, Namibia, diamond mining, impacts.*

INTRODUCTION

Elizabeth Bay, located some 30 km south of the harbour town of Lüderitz in Namibia (Figure 1), is the site of a diamond mining facility commissioned in 1991. The mine is one of several such operations within the *Sperrgebiet* ("forbidden territory"), which stretches for some 330 km along the southern coast of Namibia. Mining operations at the site involve the separation of undersized sediments (finer than 1.4 mm) from the diamondiferous ore contained in dune sands. This fraction, comprising some 75% of the total quantity of 20 million m^3 to be excavated, is to be discharged into the adjacent sheltered bay over a period of 10 to 20 years. Since the commissioning of the mine in 1991, an average quantity of about 1 million m^3/year of uncontaminated sediment has been discharged onto the beach via a number of discharge outlets located mainly in the centre of the bay (Figure 2).

Nearshore turbidity due to suspended sediment fines is a natural phenomenon around much of the western coast of southern Africa. However, sensitivities with regard to the potential environmental impact of diamond mining related sediment discharges at Elizabeth Bay in Namibia have led to the series of studies under discussion. A contributory factor in this regard has been a major drop in rock lobster catch volumes along the entire Namibian coast over the past decade.

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From the outset, the environmental authorities overseeing the mining operation at Elizabeth Bay accepted that the tailings disposal would have a significant impact on the shores within the bay. It was, however, stipulated that the discharge should have no impact beyond the confines of the bay, where there was a concern for impacts on adjacent rocky shores, an important habitat for rock lobster and other biological communities. In particular, there was a concern for impacts to the west of Elizabeth Point (Figure 2) where the authorities had observed sediment plumes. The primary concerns with regards to the discharge relate to:

- The loss of coarse- and fine-grained sand from the environs of the bay and consequent smothering of benthic communities located on the adjacent shores.
- Light attenuation and other negative influences arising from elevated suspended fine sediment concentrations, particularly those affecting filter feeders.

This latter impact arises as fine material is easily suspended in the water column and transported beyond the breakers by rip currents to form frequently observed plumes, which are further advected by wind and tidally-driven circulation in the bay.

An ongoing monitoring programme was implemented in accordance with an initial impact study (CSIR, 1988a) to record the development of any unfavourable conditions. However, it was also deemed important to investigate future possible impacts, particularly towards the end of mining. The issue of possible sand accumulation beyond the bay is being addressed by means of routine monitoring of the beach, com-

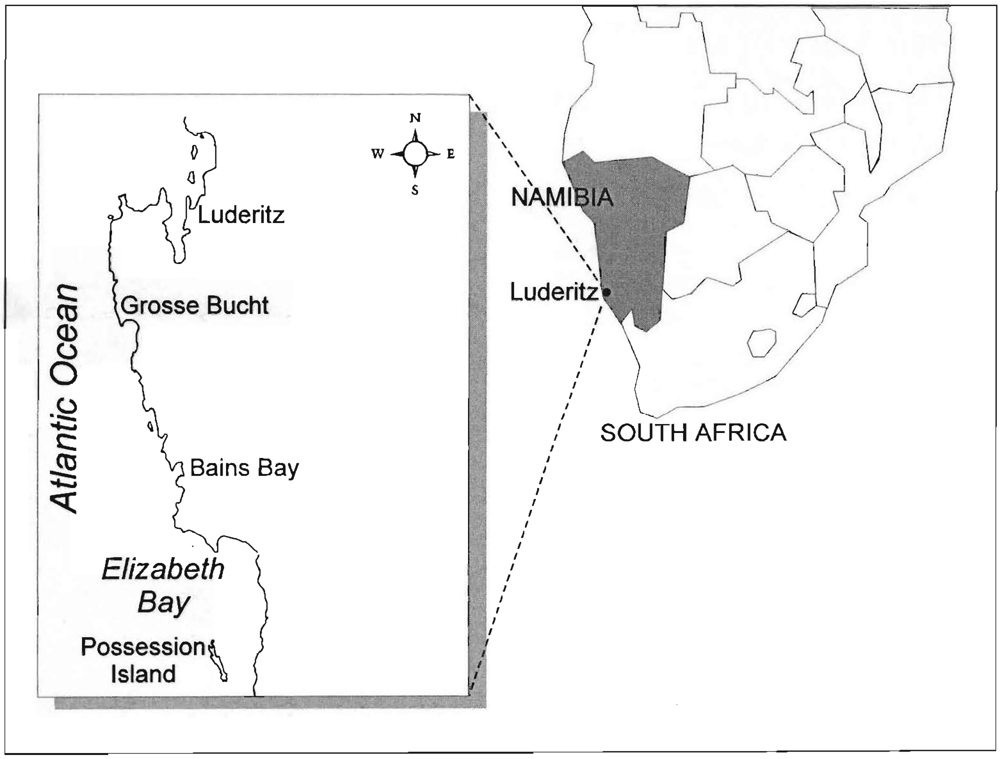

Figure 1. Location diagram.

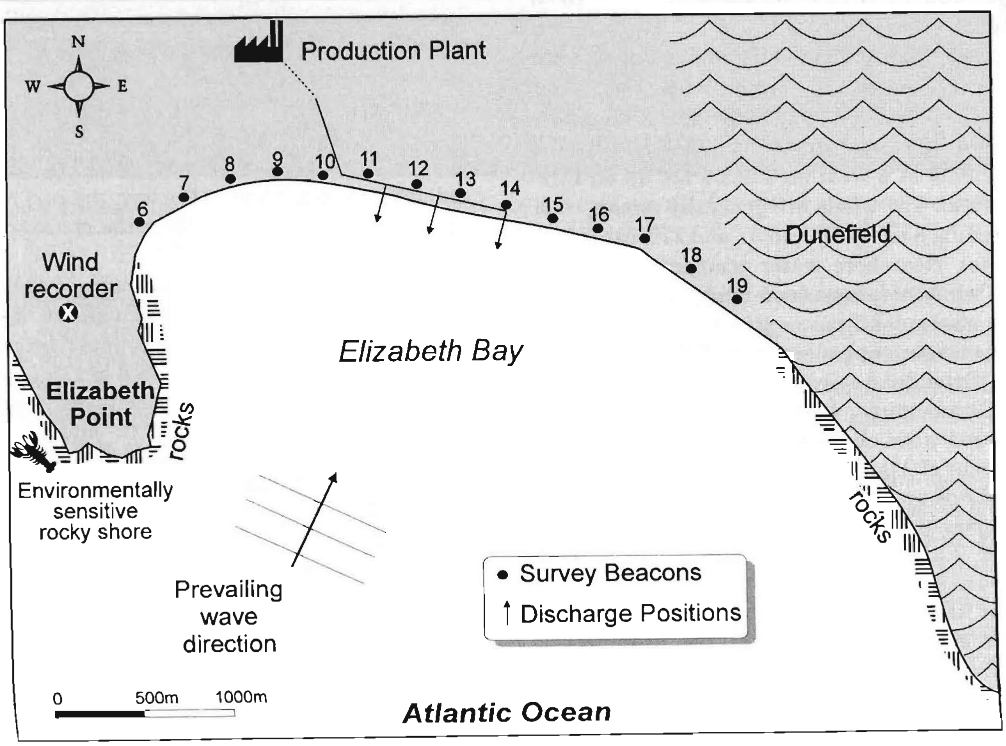

Figure 2. Schematic plan of Elizabeth Bay, showing sediment discharge locations.

prising regular sediment sampling and topographic and bathymetric surveys. The measured accumulation is assessed against the known discharge quantities in order to determine the fate of the tailings. In addition, the monitoring information has been used to validate a numerical model of the shoreline evolution that is used to predict the morphology of the bay shoreline towards the end of mining.

The monitoring programme, including regular aerial and ground observations, has also been invaluable for the assessment of turbid plume dynamics within and beyond the confines of the bay. The monitoring has been complemented by five separate field measurement programmes where wave, current and sediment concentration measurements have been made under a range of wind and tidal forcing conditions. Besides regular species health monitoring at selected transects, the impact of suspended sediment concentrations on biota is addressed by estimating the threshold concentrations above which impacts may occur (from available literature), and then comparing measured concentrations at Elizabeth Bay to this threshold. As an understanding of plume behaviour is constrained by the temporal and spatial scale limitations of isolated measurement exercises, a number of predictive models are applied. These models comprise simulations of the influence of waves in generating nearshore currents and in mobilizing and suspending sediment. In addition, a 3-dimensional predictive model of nearshore circulation and suspended sediment transport is used to assess the evolution and composition of plumes with respect to the existing and predicted bay configurations.

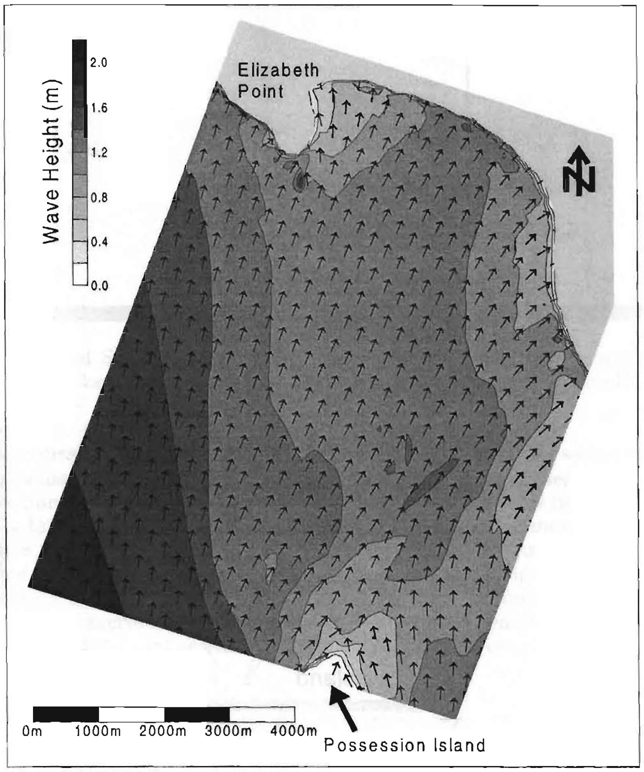

Figure 3. Simulated wave refraction pattern (H_{mo} = 2m, T_p = 8 s, $\ominus$ = 180° N).

Environmental Conditions

The approximately 4 km long beach within Elizabeth Bay is backed by hummock dunes and bounded on the east by a barchan dune corridor feeding the Namib Sand Sea (Figure 2). A prevailing southerly wind climate (with a 68% occurrence of SSE to SSW winds) is clearly evident from over seven years of measurements at a weather station set up on Elizabeth Point (Figure 2). The winds are generally strong, with 45% of winds exceeding 8 m/s (15.6 knots), and 27% exceeding 10 m/s (19.4 knots). Nearshore water temperatures range from 10° to 15° C, whilst tides are semi-diurnal with a mean spring tidal range of about 1.5 m.

No long-term measurements of wave condition have been made at the site. Extended recordings have, however, been made offshore of Oranjemund, located some 200 km to the south. This measured wave climate is highly energetic, with a median wave height of 2.0 m (measured in 20 m depth) and storm wave heights of up to 6 m occurring annually. Wave directions at Oranjemund generally range from south-south-east to south-west. Although Elizabeth Bay is subject to a similar offshore wave climate, the bay is somewhat sheltered by the headland of Elizabeth Point and by Possession Island to the south. This sheltering effect is evident in Figure 3, which depicts the wave refraction pattern of a typical wave condition (H_{mo} = 2m, T_p = 8 s, $\ominus$ = 180° N) calculated with the HISWA model (HOLTHUIJSEN *et al*, 1989). Although the offshore wave height in the simulation is 2.0 m, the predicted wave height in the bay does not exceed 1.4 m. Particularly apparent is the extreme wave sheltering in the west of the bay owing to the influence of Elizabeth Point. There is, however, a focussing of waves just offshore of Elizabeth Point on the western side of the bay where high waves break on a reef. Higher waves generally also occur in the central to eastern part of the bay. Considering that the pre-mining beach slopes did not vary much across the bay, the surf zone widths in the aerial view of Figure 4 confirm the above trends of predicted wave height variability.

The relatively sheltered wave climate at Elizabeth Bay was reflected in the pre-mining beach status. Before mining, the beach was relatively flat, with upper beach slopes ranging from 1:100 to 1:40 and composed of relatively fine sediment (average d_{50} from five samples taken from the inter-tidal beach near beacons 7, 11, 14, 18, and 19—see Figure 2—is 165 μm). However, in response to the discharge the beach has steepened considerably, with upper beach slopes in 1998 being as steep as 1:8, and the sand size has correspondingly coarsened (average d_{50} from 48 sets of samples of the inter-tidal beach near beacons 6, 8, 10, 12, 14, 16 and 18 for the period 1995 to 1998 is 527 μm).

The Mine Sediment Discharge

Within the period from commencement of mining activities (June 1991) until September 1998, a total of 6.9 million m^3 of sediment has been discharged onto the centre of the beach (see Figure 2 for discharge locations).

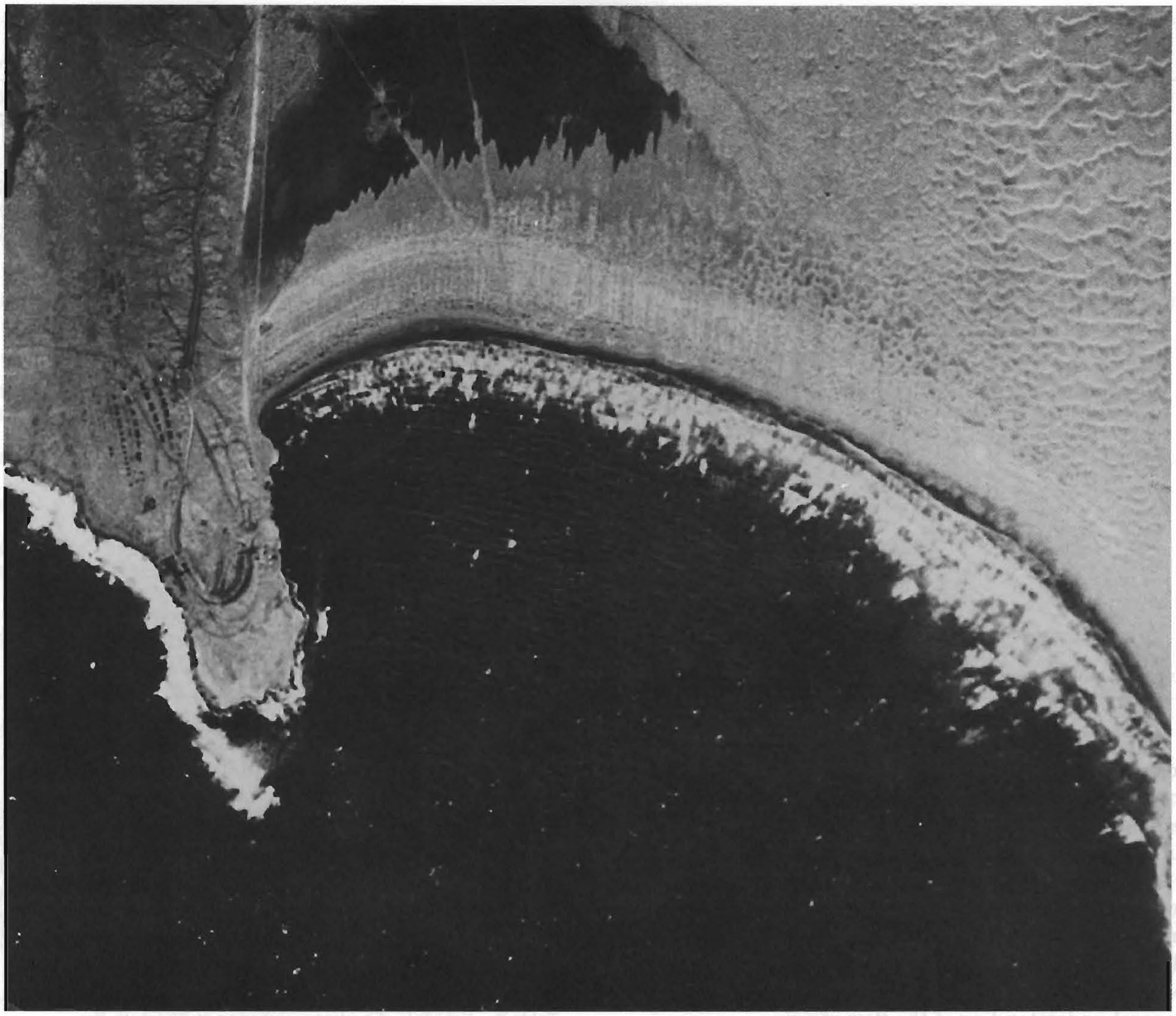

Figure 4. Aerial view of Elizabeth Bay (circa 1989). The dune corridor can be discerned (top right) as well as a salt pan (top centre).

Records of monthly discharge volumes (Figure 5) indicate that prior to 1993, when the mine plant was at full production, the discharge rate was approximately double that of recent years.

Table 1 provides the average grain size of the discharged material, compared to that of the natural beach prior to commencement of mining. While this comparison indicates that the discharge sediment is mostly coarser than the original beach, analyses also indicated a relatively small but significant fines component. On average, 0.7% of the discharged material is finer than 60 μm, and 3.6% of the material is finer than 100 μm.

METHODS

Monitoring and Field Exercises

A monitoring programme has been conducted for a period of about 10 years, comprising aerial photography (including control sites), plant discharge recordings (rates and composition), nearshore bathymetric measurements, beach surveys, wind recordings, bio-sampling and water sampling (see Table 2). This monitoring was supplemented by observations of plume configurations and estimates of breaking wave heights and surf zone widths.

In addition to these more routine measurements, five field measurement exercises were conducted (see Table 3). These exercises incorporated the deployment of an optical backscatter sensor (OBS) to investigate the vertical structure of turbid plumes. Calibration was achieved *in situ* by taking plume samples at the same location as the OBS in the water column. The OBS signal during the water sampling (duration approximately 15 seconds) was averaged and plotted against the sampled concentration as determined in the laboratory. This process was repeated several times and a linear relationship was fitted to the resulting data. The resulting cali-

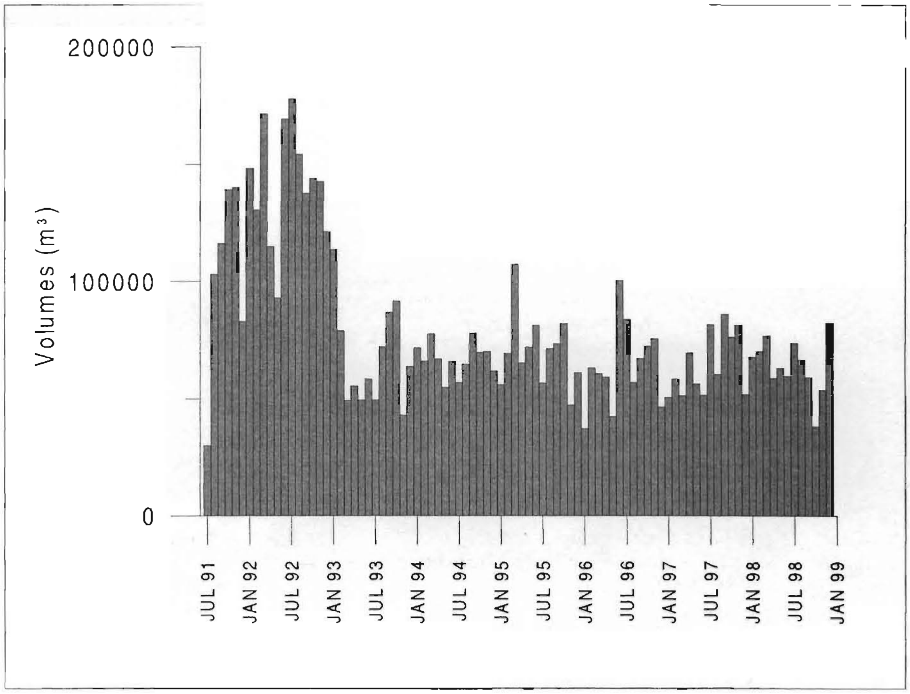

Figure 5. Monthly volumes of mine tailings sediment discharged onto the beach.

bration curve for data measured on 19 and 20 February 1997 is shown in Figure 6 (correlation coefficient $R^2 = 0.97$).

Measurements of water circulation included exercises using an Acoustic Doppler Current Profiler (ADCP) fixed to a boat, an impellor-type current meter (deployed at various locations from a boat), drogues and electromagnetic current meters deployed for periods of several days in fixed positions. In addition to these measurements, sketched turbid plumes served as effective tracers of surface currents, contributing to the general understanding of the flow regime.

Computational Modelling

Shoreline Modelling

The UNIBEST shoreline model (DELFT HYDRAULICS, 1994a) has been employed to explore the future evolution of the shoreline (SMITH *et al,* 1994). Utilizing a climate of refracted wave conditions and measured bathymetry and sediment sizes, this one-line model was set up to describe changes in the sedimentary shoreline as a result of wave-induced longshore drift. The historical record of discharges of sand onto the beach was incorporated as a source.

Table 1. *Grain sizes of discharged material (average) and natural beach sand.*

Material	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)
Natural beach	131	165	208
Discharged material	144	330	848

Wave-Generated Flow Modelling

The 2-dimensional finite element circulation model FEMCIRC (DIEDERICKS *et al,* 1999) was applied to investigate wave-generated flows that mobilize sediment discharged into the inter-tidal zone. The nearshore circulation that resulted from the storm wave condition recorded on 12 May 1997 was simulated (H_{mo} = 4 m, south-westerly, T_p = 12 seconds). Zero

Table 2. *Schedule of routine monitoring at Elizabeth Bay.*

Item	Frequency of measurement	Location/s of measurement
Aerial photography	Quarterly	Across the bay, and at control site
Plant discharge rates	Daily	At the mine plant
Plant discharge composition	Twice a month	At the mine plant
Nearshore bathymetry	Approx. every 2 years	Entire bay, to 20 m depth
Beach surveys	Every 3 months	21 stations along the beach
Wind recordings	Every 10 minutes	At Elizabeth Point (Figure 2)
Bio-transect (photographic recordings of flora/fauna)	Approx. 6-monthly	At Elizabeth Point
Water samples	Approx. monthly	2 stations at Elizabeth Point
Wave observations	Weekly to two-weekly	From the bay shoreline
Observation (sketches) of plume configurations	Weekly to two-weekly	From Elizabeth Point

Table 3. *Schedule of field measurements conducted at Elizabeth Bay.*

Exercise	Date	Measurement (and no. of positions sampled)	Wind	Waves
1	20 Feb 1992	Surface water samples (12)	Moderate S	Moderate
1	21 Feb 1992	Surface water samples (19)		
		Salinity and temperature profiles (9)		
		Drogue tracking (9 starting position)		
2	16 May 1992	Salinity and temperature profiles (17)	Strong SW	Moderate
2	17 May 1992	Surface water samples (16)	Moderate S	Moderate
2	18 May 1992	Salinity and temperature profiles (13)	Moderate S	Moderate
		Surface water samples (16)		
		Drogue tracking (5 starting positions)		
3	24 Feb 1995	Surface water samples (18)	Light W	Moderate to High
		Current velocity profile (14)		
		Salinity and temperature profile (10)		
		Bottom samples (18)		
4	17 Feb 1997	Surface water samples (9)	Very strong SSW	Moderate
4	18 Feb 1997	SEAPAC deployment	Strong S	Moderate
		Surface water samples (10)		
4	19 Feb 1997	Surface water samples (9)	Strong S	Small to Moderate
		Temperature, salinity, and turbidity profiles (9)		
4	20 Feb 1997	Surface water samples (11)	Strong S	Small
		Temperature, salinity, and turbidity profiles (11)		
4	21 Feb 1997	SEAPAC retrieval	Strong SSE	Small
5	6 May 1997	Aerial Photographs	Strong SSE	Small
		Surface water sampling (4)	Light WSW	Small
		Turbidity and temperature profiles (2)		
5	8 May 1997	ADCP measurements and periodic temperature and turbidity profiles (4)	Light S	Moderate
		Surface water samples and seabed sediment sampling (10)		
5	9 May 1997	ADCP measurements and periodic temperature and turbidity profiles (2)	Light WNW	Moderate
		Surface water sampling, temperature and turbidity profiles (5)		
5	10 May 1997	ADCP measurements and periodic temperature and turbidity profiles (4)	Light W	Moderate
		Surface water sampling, temperature and turbidity profiles (3)		
		Seabed sediment sampling (9)		
5	11 May 1997	Surface water sampling, temperature and turbidity profiles (11)	Moderate SSW	Moderate
		Drogue tracking		
5	12 May 1997	ADCP measurements and periodic temperature and turbidity profiles (4)	Light to Moderate SSW	High
		Surface water sampling, temperature and turbidity profiles (8)		
		Tracking plume edge		

velocity boundaries were used on all sides; this is appropriate for all the boundaries except for the western sea boundary, where some outflow tends to occur. A friction factor of 0.01 was employed, whereas eddy viscosities were derived from a k-ϵ turbulence closure model.

Wave action also results in the mobilization and resuspension of sediments settled on the seabed, which can result in the formation of turbid plumes where currents exist. In order to investigate this aspect, bed shear stress fields and the associated mobility and suspension fields were calculated.

Circulation and Fine Suspended Sediment Modelling

The modelling of circulation and turbid plumes in Elizabeth Bay was undertaken using DELFT3D-FLOW, the hydrodynamic module of the DELFT3D modelling suite (DELFT HYDRAULICS, 1996). This model, which solves the time-dependent shallow water equations in three dimensions, is designed to simulate tidal and wind-driven flows in shallow seas, coastal areas, estuaries, rivers and lakes.

In DELFT3D-FLOW the horizontal turbulent dispersive transport of momentum and other constituents, such as temperature, is computed using prescribed horizontal eddy viscosity and eddy diffusivity coefficients. The vertical eddy viscosity and diffusivity coefficients are computed using a k-ϵ turbulence closure model. The eddy viscosity and diffusivity coefficients essentially parameterise the sub-grid scale processes in the model and vary with grid resolution, generally being higher for larger grid sizes. In the absence of specific information for Elizabeth Bay, the contribution of the subgrid scale processes are parameterised using horizontal vis-

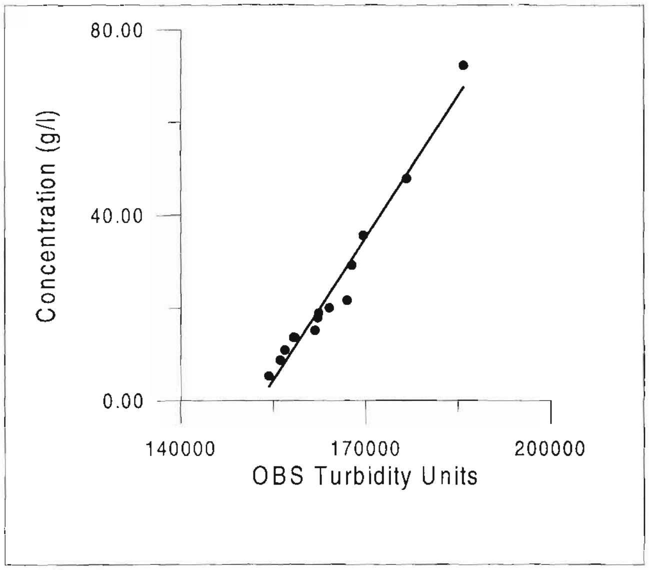

Figure 6. Optical Backscatter Sensor calibration result.

cosity and diffusivity coefficients of 1.0 $m^2.s^{-1}$. These values are within the range of horizontal viscosity (0.01 $m^2.s^{-1}$ to 20.0 $m^2.s^{-1}$) and diffusivity coefficients (0.1 $m^2.s^{-1}$ to 20.0 $m^2.s^{-1}$) used in similar three-dimensional modelling studies (DELFT HYDRAULICS, 1994b; NAKATSUJI *et al.,* 1989) and of the same magnitude as those used in more recent three-dimensional modelling studies by JANKOWSKI *et al.* (1996). A sensitivity analysis showed that a fivefold increase in the horizontal viscosity had very little effect on the model results. A sensitivity analysis for a similar three-dimensional modelling study by JANKOWSKI *et al.* (1996) indicated that the changes in the model results due to uncertainties in the magnitude of horizontal diffusivity are relatively small and certainly much less than those due to uncertainties in settling behaviour, current variability and vertical diffusivity.

The shear stress at the seabed induced by turbulent flow is assumed to be given by a quadratic friction law specified using the Chézy coefficient. Calibration of the DELFT3D-FLOW model in Elizabeth Bay indicates that a Chézy coefficient of 65 $m^{½}.s^{-1}$ is appropriate for determining bottom frictional stresses. Changes in the Chézy coefficient that result in a decrease of approximately 20% in bottom friction do not significantly modify the model results. The magnitude of the wind shear stress on the water surface is modelled by the following quadratic expression:

$$\tau_{wind} = \rho_a \cdot C_d\,(U_{10}) \cdot U^2_{10}$$

where ρ_a is the density of air in $kg.m^{-3}$, U_{10} is the wind speed in $m.s^{-1}$ at a height 10 m above the water surface and C_d (U_{10}) is the wind drag coefficient which is a function of wind speed. The wind drag coefficient used in the specification of surface wind stress follows the formulation of SMITH and BANKE (1975) where:

$$C_d(U_{10}) = 6.3 \times 10^{-4} + 6.6 \times 10^{-5}\,U_{10}$$

A sensitivity analysis indicated that the model results only change significantly if the wind drag coefficient is changed by more than 15%.

The computational grid used in DELFT3D-FLOW comprises an orthogonal curvilinear grid (38 by 68) in the horizontal direction and a total of 10 layers in the vertical. The thickness of the layers varied between 5% and 15% of the local water depth, with the thinnest layers located both at the sea surface and near the bottom in order to model more accurately the boundary layers. The corresponding bathymetry used is based on the most recent data available (bathymetry within the bay measured in May 1997).

At the open boundaries only sea levels (and, where appropriate, turbidities) are specified. In all of the model simulations, the imposed sea level variations at the open boundary are considered to be owing to tidal fluctuations only. Any change in sea level owing to remote wind-forcing is ignored. This omission reduces the ability of the model to accurately represent remotely-forced variability on the bay circulation. However, as will be demonstrated, the model calibration exercise shows that, in general, remotely-forced events seemingly have little effect on the circulation of Elizabeth Bay.

The discharge of sediments in Elizabeth Bay occurs onto the beach. However, the discharges specified in the simulations represent the amount of sediment in suspension exiting the surf zone into deeper waters. Two broad discharge regions were specified (at D1 and D2 in Figure 7), which represent the two areas where suspended material typically is observed to exit the surf zone via rip currents. The daily average discharge of fines was conservatively estimated to be about 80 m^3. This figure translates into a fine suspended sediment load rate into the bay of approximately 1.5 $kg.s^{-1}$, which amounts to about 4% of the total daily discharge rate since 1993. Based on observations of rip currents from aerial photographs, it is considered that one third of this material enters the bay at the western discharge location while the other two thirds are assumed to enter the bay in the vicinity of the eastern discharge location. The turbid plumes are modelled as a conservative tracer, which is a reasonable approximation if it is assumed that turbid plumes consist of fine sediments which have a long residence time in the water column. As will be demonstrated, this approximation is supported by an assessment of sediment mobility and transport that indicated appreciable bed shear stresses for even moderate wave conditions.

A number of monitoring sites were set up in the model (Figure 7). Site A (Elizabeth Point) monitors the suspended sediment concentrations in turbid plumes leaving Elizabeth Bay to the west by rounding Elizabeth Point. Site B (Northwest Bay Corner) monitors the turbidity in the stagnant region in the north-western corner of the bay. Site C (Eastern Bay) monitors the suspended sediment concentrations in the plumes leaving the bay to the south-east.

RESULTS

Beach and Nearshore Evolution

A pronounced "bulge" in the coastline developed between commencement of mining (July 1991) and December 1992,

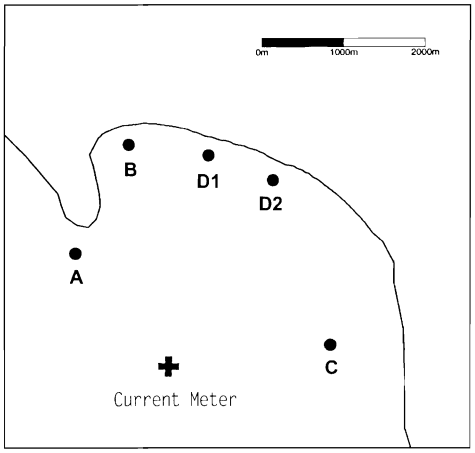

Figure 7. Model sediment discharge locations (D1, D2) and monitoring sites (A, B, C).

which extended about 270 m seaward of the original (pre-mining) coastline. This was primarily the result of a full production level discharge of 2.3 million m^3 of sediment concentrated within the more sheltered western half of the bay. As there was concern that this bulge may promote enhanced local rip current action and offshore sediment transport, a previously recommended strategy (CSIR, 1988b) of discharging with a wider alongshore distribution was adopted. With the additional effects of more intense wave action on the steeper accreted beach and a reduced discharge volume from the beginning of 1993, this strategy resulted in sediment being more efficiently distributed along the shoreline. This improvement is illustrated in Figure 8, which depicts a more even shoreline accretion around the bay by July 1999. By this time, the average position of the shoreline was situated between 200 m and 300 m seaward of its pre-mining configuration.

The effect of the early high discharge rates can also be seen in the two beach cross-sections illustrated in Figure 9, profile 12 being measured adjacent to the high discharge location and profile 16 being measured 1 km further eastwards (for profile locations, see Figure 8). The profiles cover the period from before mining (1990) up to 1997, by which time approximately 6 million m^3 of material had been discharged. The effect of the high, concentrated discharge rate on a relatively flat beach profile can be seen in profile 12 which shows that the beach accreted rapidly from the commencement of mining (1991) to December 1992. This area subsequently eroded when discharge at a lower rate was distributed more evenly in the bay. By early 1995 the shoreline location was still landwards of its December 1992 position despite significant sediment discharge in the interim.

Beach change at profile 16 was significantly different, manifesting limited accretion in 1992. Material took a longer period to be distributed to this easterly position, such that significant accretion is only evident by 1994.

The cross-sections manifest the steepening of the beach profile over time, owing to the discharge material being coarser than that of the natural beach. Profile close-out depth is seen to increase from west to east (*e.g.* it is approximately −4.5 m at profile 12 and −7 m at profile 16). This increase reflects the increase in wave heights towards the eastern half of the bay.

Considering the plan-shape stability of the bay, the pre-mining shoreline was assumed to be in equilibrium, based on its observed dynamic stability over time. Using the analytical method of HSU *et al,* (1989) an equilibrium bay fit was applied to this shoreline. Assuming the predominant angle of wave approach and the headland positions to remain constant, the equilibrium shoreline fit resulting from accumulation of sediment in the bay was then predicted (Figure 8).

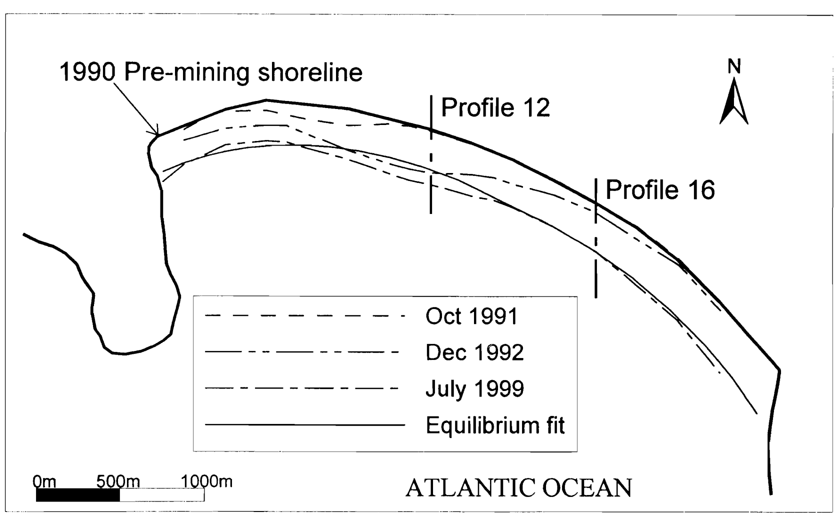

Figure 8. Measured shorelines (MSL-0 m contours) and a prediction of the equilibrium bay configuration in July 1999.

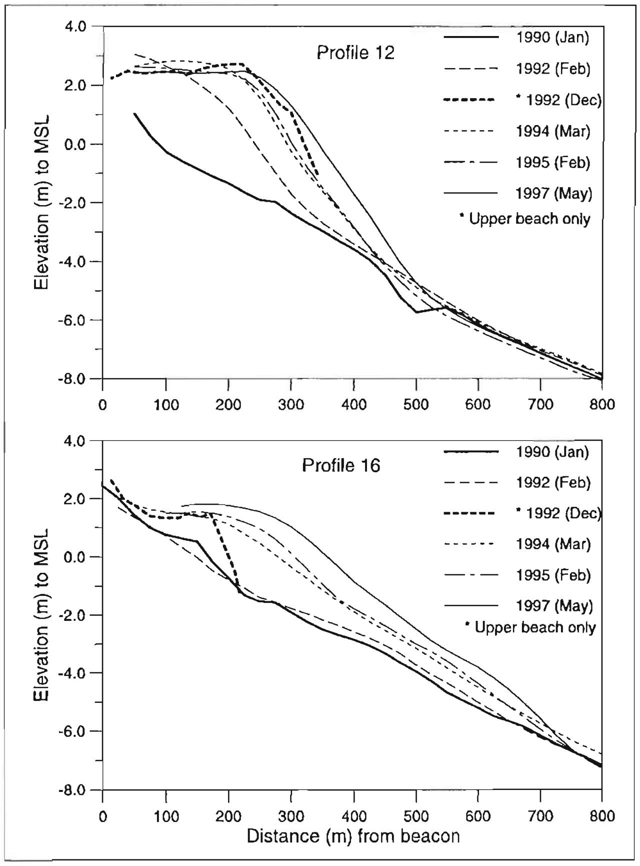

Figure 9. Beach and nearshore profiles 12 and 16.

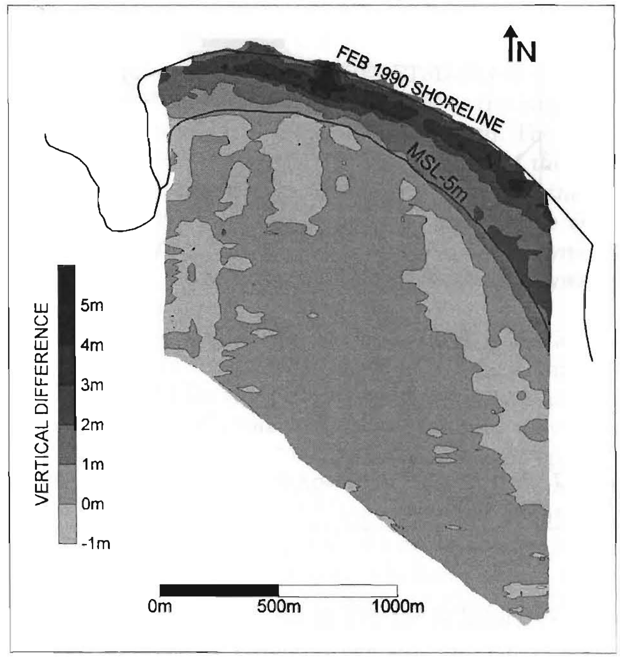

Figure 10. Bathymetry difference chart showing the distribution of vertical differences (as indicated by the shaded scale) between the measured surfaces of May 1997 and February 1990.

The July 1999 shoreline manifests a slight protrusion in the western half of the bay (opposite the discharge points), which interrupts the predicted equilibrium shape. It is likely that this protrusion will be eroded back to equilibrium when the discharge ceases, or during storm activity.

Although the shoreline has been shown to be close to equilibrium, it is vital that morphological changes at depth are also monitored. By taking the difference between nearshore bathymetric surveys, the first measured in the pre-mining period in February 1990 and the second measured in May 1997, the accreted volume within the bay can be assessed (Figure 10). As can be seen, most of the material is accumulated on the beach close to the original (Feb 1990) shoreline. Approximately 60% of accretion occurred above the MSL-2 m contour, with relatively little change detected below the MSL-5 m contour. The total accreted volume inside the bay, as determined from this analysis, is estimated to be 5.3 million m^3. This total compares reasonably well with the 5.8 million m^3 recorded to have been discharged over the analysis period, particularly considering that a region in the east (amounting to roughly 15% of the accreted surface area) is not accounted for. The latter region, which was not covered by hydrographic surveys owing to the presence of rock hazards, deserves future attention, as accumulated material is tending to extend toward this edge of the bay. Monitoring this area is essential to determine whether material will "leak" from the eastern flank of the bay and thereby impact on the neighbouring rocky shore.

The UNIBEST shoreline model was found to be well-validated against a large number of measured shorelines, with Figure 11 depicting comparisons between measured and modelled shorelines spanning a 5-year period (arrows show primary discharge locations). As may be seen, the measured shorelines evolving from discharge of material on the beach and the lateral transport of this material by wave action are well represented by the model. The validated model is used to predict the shorelines after the discharge of 15 million m^3 of sediment, as at the end of mining (Figure 12). These shorelines are predicted to be up to 500 m seaward of the original 1990 shoreline in some areas. The effects of an average rate of discharge (*i.e.* 0.7 million m^3/year) via two discharge points and a high rate of discharge (1.4 million m^3/year) through a single discharge point are also shown. The latter option causes a pronounced protrusion of the shoreline, whereas the former results in a preferred relatively linear coastline that is close to the predicted equilibrium configuration. Although prominent, the protruding coastline is predicted to be modified by wave action within a further two years to form a more desirable equilibrium configuration.

Fine Sediment Plumes and Circulation

Plume Structure

Overlaying the configurations of observed sediment plumes for the year provides an indication of the percentage of plume

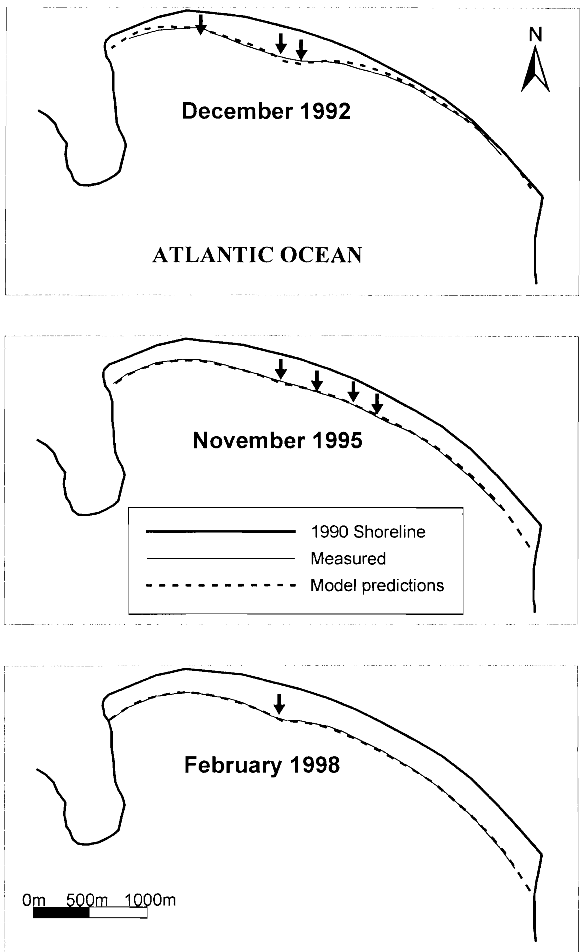

Figure 11. Shoreline model predictions compared to measured data at Elizabeth Bay.

occurrence at various locations in the bay. The pattern for 1994 (Figure 13) is similar to that observed in other years. Plumes were observed to occur seaward and to the west of Elizabeth Point for up to 10% of the observations. Up to 60% were observed in the nearshore region close to the discharge positions at the centre of the bay and to the west of the bay.

Based on the OBS calibration (Figure 6), the vertical structure of plumes could be resolved from OBS measurements made during the field exercises. 76 percent of observations indicated sediment concentrations within plumes to be fairly uniform through most of the water column with an increase near the bed (a typical example is shown in Figure 14(a)). However, 24 percent of observations indicated erratic distributions, at times even decreasing with depth. Beyond the extent of visible plumes, 75 percent of observations indicated concentrations to be uniform with relatively low values throughout the water column, generally increasing towards the seabed. (typical example—Figure 14(b)).

Concentration Threshold

The sediment discharge onto the shoreline at Elizabeth Bay is composed entirely of particulate inorganic matter (PIM). In the absence of experimental data, reference was made to the literature to estimate the PIM concentration threshold above which impacts to biota occur. At a PIM concentration over 100 mg/l, pumping rates were reported to be significantly reduced in the oyster *Crassostrea virginica* and the clam *Mercenaria mercenaria* (LOOSANOFF, 1961). In addition, PIM concentrations of 100 mg/l represent the lowest level of impact found on fish and their respective eggs and larvae in a study by APPLEBY and SCARRATT (1989). Furthermore, BROWN and HARTWICK (1988) found a similar impact on the oyster *Crassostrea gigas,* where they found an upper tolerance level at 100 mg/l. Thus, a PIM concentration of 100 mg/l was assumed to be the acceptable limit of turbidity for the Elizabeth Bay studies. It should be borne in mind however, that while this limit applies to the long-term, there are indications that organisms survive considerably higher concentrations for short periods under natural conditions (WHITE and DAGG, 1989).

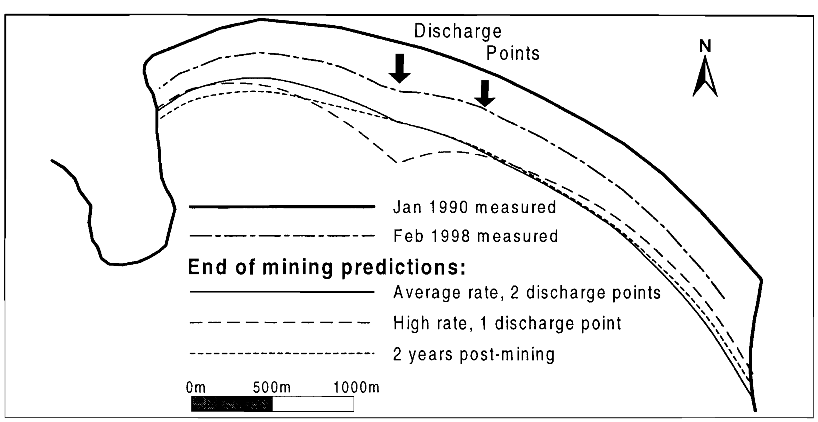

Figure 12. Predictions of the shoreline configuration after discharge of 15 million m^3 of sediment, and the situation 2 years later.

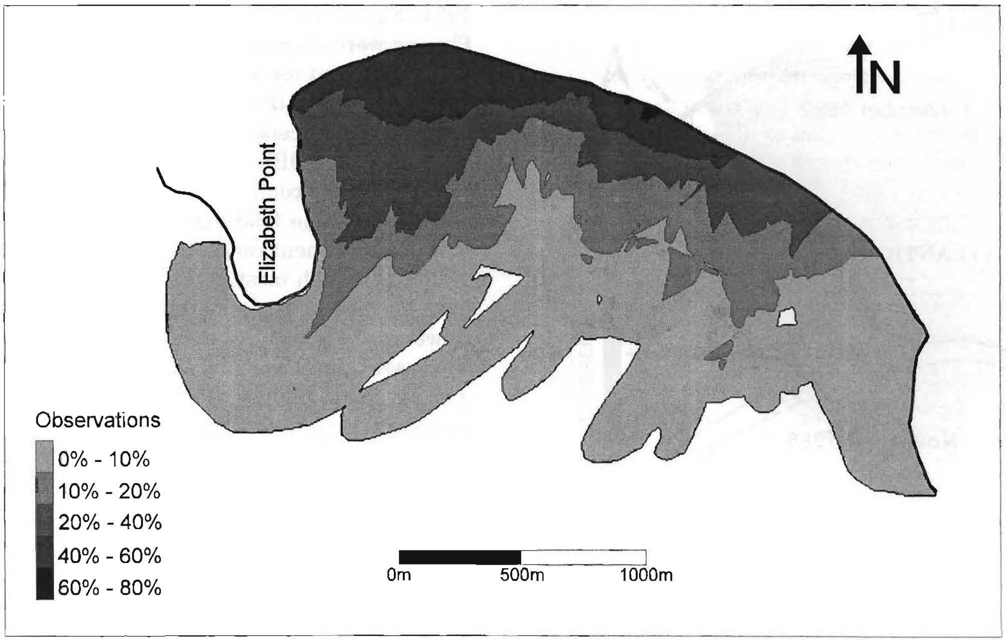

Figure 13. Plume occurrences, from observations in 1994.

Measured Concentrations

Against the background of the above-mentioned assumed concentration threshold, four exercises were conducted to obtain a correlation between the visual impact of turbid plumes and their corresponding sediment concentrations. Within water which was significantly discoloured due to suspended sediment, PIM concentrations were found to range from 10 mg/l to 54 mg/l. This finding indicated that even though plumes have a significant visual impact, their constituent concentrations may be well below the assumed 100 mg/l threshold for the study.

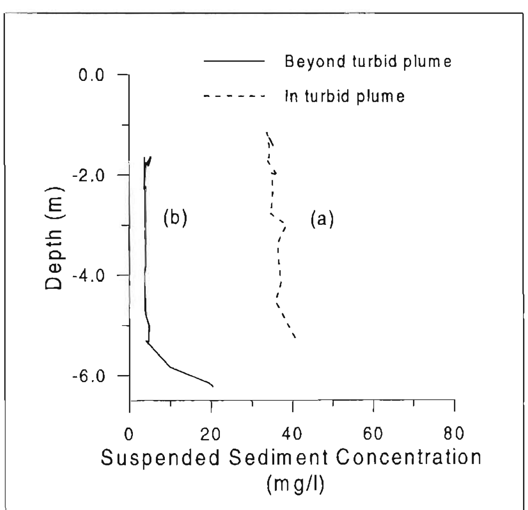

Figure 14. Suspended sediment concentrations measured (a) within and (b) beyond the limits of a turbid plume.

From the field measurements undertaken at Elizabeth Bay during five exercises, as well as from measurements undertaken routinely, PIM concentrations within plumes generally ranged between 15 mg/l and 50 mg/l. However, measurements also indicated intermittently high concentrations within the bay, with concentrations over the assumed threshold of 100 mg/l being recorded on four occasions, once in the eastern nearshore region, and three times in the western corner of the bay.

In the region of concern beyond the confines of Elizabeth Bay, PIM concentrations were far below the assumed threshold, all being below 13 mg/l and thus comparable to concentrations typically recorded on the Namibian and South African west coast (ZOUTENDYK, 1995), which range from 0.5 to 14 mg/l.

Measured Circulation

Under the prevailing southerly sector winds (68% occurrence), a primarily westerly flow was detected from plume observations and measurements conducted in the bay. Conversely, a primarily easterly flow was detected during westerly wind conditions (7% occurrence). During the high wave action and light winds occurring on 12 May 1997, localised wave-driven flows were observed in parts of the bay. For example, a north-easterly flow occurred which was related to the region of wave breaking at Elizabeth Point. In addition, an easterly flow was observed in the centre, nearshore region of the bay, while a southerly rip current flow was observed in the east of the bay.

Measurements provided considerable evidence of three-dimensional flows. Drogue-tracking results indicated a significant vertical shear in current velocities, the subsurface velocities being substantially less than those observed at the surface. For example, during the field exercise of February 1992, sub-surface flows were significantly smaller than the surface currents and more variable in direction. During the May 1992 field exercise, sub-surface currents were largely in the same direction as the surface currents but had velocities less than half those at the surface. Although there is some uncertainty in the drogue results owing to the effect of wind on the exposed part of the drogues lying above the water surface, the three-dimensional nature of the flows in this region is confirmed by ADCP data collected during the May 1997 field exercise. These data indicate that the currents are three-dimensional in the deeper water (> 20 m) but largely two-dimensional in the shallower water nearer the shore. As expected, the three-dimensionality was less apparent during the typically well-mixed conditions occurring during strong wind events. Nevertheless, these findings indicated the need for application of a three-dimensional hydrodynamic model to complement results from an earlier two-dimensional model study (CSIR, 1993).

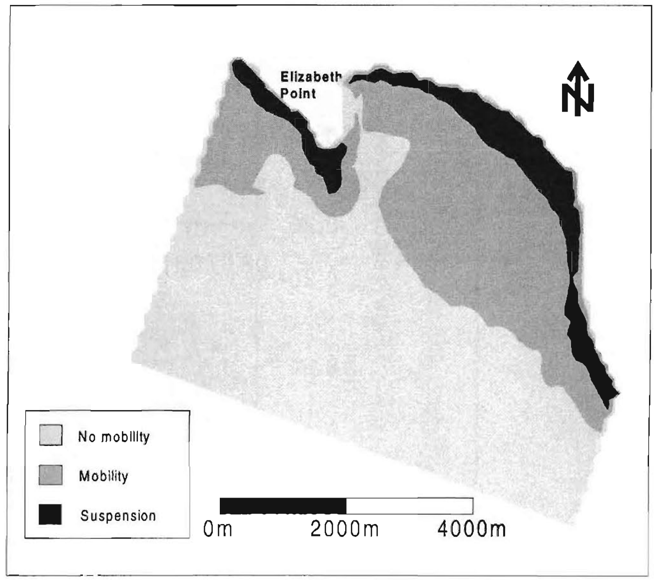

Figure 15. Predicted regions of sediment mobility and suspension (d_{50} = 300 μm, offshore wave conditions H_{mo} = 2 m, T_p = 8 s, wave direction = south).

Modelled Wave-Generated Circulation

The results of the FEMCIRC finite element circulation modelling reflected some of the measured and observed flow features. For example, a strong but localised north-easterly current was predicted in the region of Elizabeth Point, as has been measured by means of the ADCP. In addition, an eastward longshore current was predicted in the near-beach region in the centre of the bay, as has been observed in prototype. Furthermore, a number of circulation cells predicted in the east of the bay are representative of observed rip-current action in that region. Apart from localised strong flows near the point, predicted wave-generated flows were confined to the nearshore region. Besides contributing to littoral sediment transport, these flows play a role in injecting fine-sediment-laden water deeper into the bay by means of rip current action.

Modelled Sediment Mobility and Resuspension

The Shields (1936) criterion for initial grain motion under steady flows is adopted for the assessment of the capacity for sediment mobility throughout the system. In addition, a suspension threshold formulation of Van Rijn (1993) is used to test the likelihood of sediment suspension off the bed.

Using the computed shear stress field for average wave conditions (as in Figure 3), areas of sediment mobility and suspension are computed for a sediment grain size of 300 μm, which is representative of the average d_{50} for the discharge (see Figure 15). As may be remarked, sediment mobility occurs throughout most of the interior of the bay, with the exception of the area of a deep depression in the west of the bay. The area of sediment suspension is restricted to the nearshore region.

The implications of these findings are that it is unlikely that any of the finer fractions of discharged sediment will settle to the bed under the average wave action experienced at Elizabeth Bay. This conclusion tends to justify the simulation of the finer sediments as a conservative tracer in the plume simulations, as described below. However, if sediment had previously settled under relatively calmer conditions it would be resuspended during higher wave action, thus providing an additional background concentration in addition to that originating from the discharge point. This potential for resuspension, or natural turbidity generation, is supported by observations of turbid plumes in the bay made before commencement of mining activities.

Modelled Wind-Driven Circulation and Plume Evolution

Model Validation. The north/south and east/west components of the modelled current velocities (tidally and wind-driven) were compared against the measured current velocity components (Figure 16, top two frames). The latter were measured in 9 m depth just beyond the confines of the bay (see Figure 7 for position of current meter) in the month of May 1997. The general trends of flow variability compare reasonably, except for isolated deviations between measured and modelled results. The strong measured flows observed on 12 and 25 May coincided with high wave conditions (wave heights over 3 m were recorded). The strong eastwards flows measured on these days are consistent the influence of large waves on the currents in the bay. These effects are not reflected in the model simulations, as the model does not include wave-driven processes.

The discrepancies between the measured and modelled currents on 18 May are consistent with remotely-forced circulations associated with passage of the coastal lows and the associated NW wind conditions. These remotely-forced flows

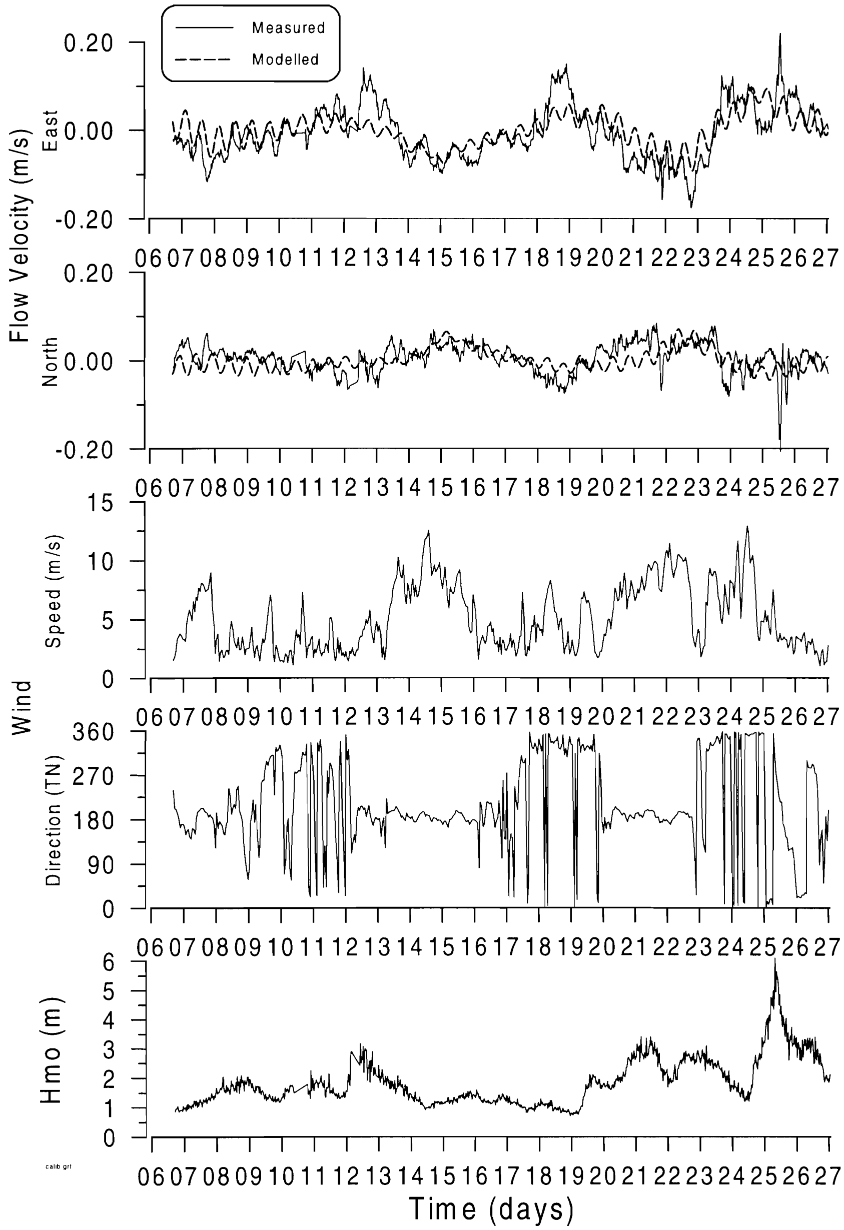

Figure 16. Modelled current velocities compared to observed velocities for May 1997 (Position of measurement, Figure 7, depth of measurement = 9 m, water depth = 20 m), and associated wind and wave conditions.

are expected to comprise a strong increase in the eastward component of the flows and an more moderate increase in the southward component of the flows at the current meter location. The flows measured on this occasion are consistent with the above expected flow conditions. As remotely-forced sea level changes were not included in the open boundary conditions of the model, these events are not reflected in the model simulations.

There is evidence that the discrepancy on 20 to 22 May is attributable to increased mixing effects in the water column as a result of high wave action (Hmo up to 3m—Figure 16) not being incorporated in the model.

Model Predictions

The simulated anticlockwise, westerly nearshore circulation correctly represents the circulation observed during strong southerly wind conditions (Figure 17). Deviating from the anticlockwise circulation in the bay is a relatively weak and small clockwise eddy in the western corner of the bay, which was predicted to occur occasionally. This closed circulation, together with the close proximity of the discharges to this eddy, is probably the reason why some high turbidities have been recorded at that location (exceeding 100 mg/l on three occasions). In addition, 77 out of 214 randomly observed

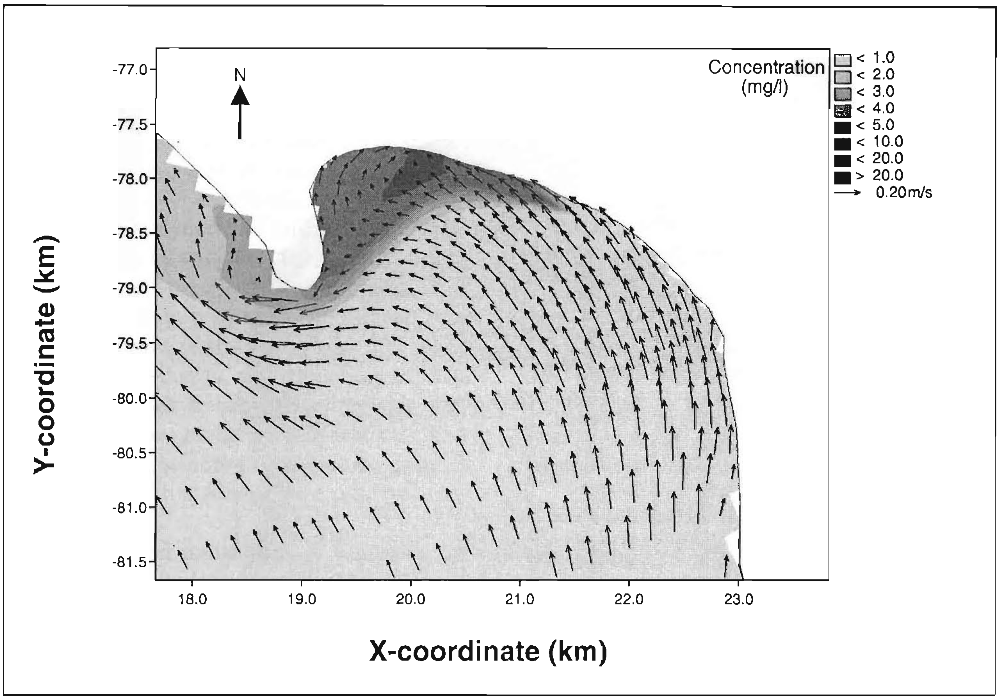

Figure 17. Predicted surface currents and suspended sediment concentrations during strong southerly winds.

plumes (recorded from 1992 to 1996) were observed in the western end of the bay and 80% of these observations occurred during southerly winds. These observations also support the idea of a transient closed circulation in the west of the bay under the prevailing wind conditions.

Also shown as shaded contours in Figure 17 are the predicted concentrations of suspended sediment. As can be seen, concentrations emanating from the source at the beach rapidly decrease, and in this case are less than 5 mg/l in the region of Elizabeth Point.

Modelling experience has shown that a sequence of changing wind conditions is frequently more relevant to plume evolution than a specific single wind condition (*e.g.* steady 15 knot southerly, as previously modelled (CSIR, 1993)). Thus four wind scenarios, as obtained from measured time series, were initially simulated (see Table 4). Two of these scenarios represent typical summer wind conditions with strong, consistent southerly winds. The other two wind scenarios ("Winter wind cases 1 and 2" in Table 4) represent conditions during which periods of strong southerly winds alternate with periods of light northerly winds, as evident in Figure 16. The latter conditions actually occur all year round but have a significantly higher occurrence during late autumn/winter. For each of these wind scenarios, the average and maximum sim-

Table 4. *Predicted average PIM concentrations and maximum PIM concentrations (shown in brackets) at the monitoring sites (Figure 7).*

Scenario	Discharge East (D2)	Discharge West (D1)	North West Corner B	Elizabeth Point A	Eastern Bay C
Summer wind case 1	14.91	13.20	7.21	0.67	0.04
(Oct 1993)	(61.93)	(35.11)	(10.46)	(11.06)	(2.17)
Summer wind case 2	12.30	13.53	7.52	0.83	~0.00
(Feb 1997)	(58.46)	(27.69)	(11.36)	(7.44)	(0.01)
Winter wind case 1	27.98	21.25	10.74	1.98	0.43
(April 1994)	(71.76)	(49.73)	(30.64)	(12.36)	(4.84)
Winter wind case 2	30.66	21.12	9.60	2.15	0.09
(May 1997)	(72.19)	(45.55)	(33.57)	(12.15)	(6.40)
End of mining					
bathymetry	34.58	18.26	9.84	2.28	0.76
(May 1997 wind)	(71.42)	(33.84)	(24.31)	(11.58)	(4.99)
Westerly discharge	7.94	40.89	14.36	2.20	0.73
(May 1997 wind)	(39.27)	(87.91)	(49.37)	(11.58)	(5.68)
Easterly discharge	42.14	11.57	7.30	2.13	0.92
(May 1997 wind)	(107.00)	(52.27)	(30.59)	(12.59)	(6.88)

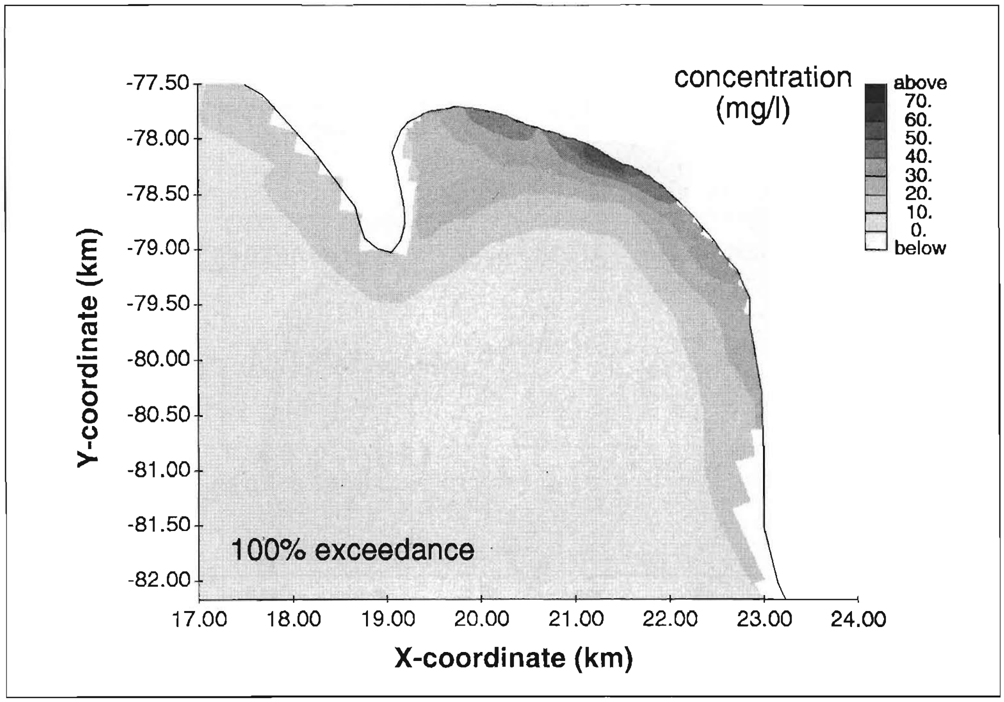

Figure 18. Predicted regions of exceedance of concentration thresholds (in mg/l indicated on the shaded scale) for May 1997.

ulated PIM concentrations for the modelling period (one month) were determined at the various monitoring locations in the bay (Figure 7). The values of both the average and maximum PIM concentrations (the latter in brackets in the table) during the summer wind scenarios are less than those during the typical autumn/winter wind scenarios (Table 4).

The PIM concentrations predicted at Elizabeth Point (near the environmentally sensitive region) were originally expected to be higher as a result of strong persistent summer southerlies advecting sediment plumes from the discharge location out of the bay. However, the model results indicate that the conditions which are typical in autumn/winter lead to the highest predicted concentrations at this location. As manifested by the modelling, this result derives from the frequently varying conditions during this period. During the calm or light northerly winds, fine material accumulates in the bay. Subsequently, when stronger southerlies occur, this material is advected out of the bay beyond Elizabeth Point. Despite this combination of autumn/winter wind conditions resulting in higher predicted PIM concentrations at and beyond Elizabeth Point, these concentrations are still well within the assumed threshold (of 100 mg/l) for marine fauna. A distribution of the regions where respective concentration thresholds are exceeded during the month of May 1997 (Figure 18) shows that in the region of and beyond the point, sediment concentrations of only 10 to 20 mg/l are predicted.

A key question in the study was how an accreted shoreline, as predicted to occur towards the end of mining (e.g. Figure 12), would affect plume evolution and concentrations. This scenario was tested using the "worst case" wind scenario simulated, namely the autumn/winter conditions of May 1997, with the predicted accreted bathymetry at the end of mining (assuming there were two discharge outlets and an average rate of discharge). The predicted average and maximum PIM concentrations for this simulation are indicated in Table 4. As may be noted, maximum concentrations are lower than for the partially accreted scenario (*i.e.* "winter wind case 2" which has bathymetry and wind as measured in May 1997) while concentration averages are generally similar. The reason for lower maximum concentrations is that the smaller bay dimensions result in less fine material accumulating in the bay during calm conditions. Thus less fine material is available to be advected beyond Elizabeth Point during subsequent southerly winds.

Another two scenarios which were explored were the concentration of the total discharge to either the westerly or the easterly discharge position. The predicted average and maximum PIM concentrations, again employing the May 1997 wind conditions, are indicated in Table 4. It may be noted that although isolated high concentrations are predicted (particularly close to the discharge locations), the concentrations at the extremes of the bay (at A and C) are not significantly affected by changing discharge location.

CONCLUSIONS

In investigating the fate of a massive sediment discharge at Elizabeth Bay, field monitoring and well-validated simulation models were valuable in understanding key processes. The monitoring and modelling studies included a quantification of the fate of sand discharged at the site as well as predictions of turbid plume behaviour. It was found that the bulk of discharged sand will continue to accumulate within the confines of the bay. This situation should continue to be closely monitored, particularly in the eastern end of the bay. Measurements and predictions of concentrations of suspended fines were found to be intermittently high in the bay, but generally well below the assumed acceptable limits, particularly in the region of concern beyond the bay confines. Simulations also highlighted the capacity for "turbidity storage" within the confines of the bay under mild wind forcing. The subsequent onset of strong winds results in the highest turbidity levels beyond the confines of the bay. From an operational perspective the measurements and modelling proved useful in optimising the tailings discharge strategy as well as for planning the scale of future monitoring operations. The result has been that it is now possible to scale down some of the measurement activities at this remote and relatively inaccessible site.

Finally, some of the identified limitations of the work include the modelling of turbidity as a conservative tracer, and the exclusion of wave effects (such as effects of bottom shear and vertical mixing on flows). However, these limitations may be remedied should a more comprehensive study be warranted. In addition a review of the assumed PIM concentration threshold, as additional research results become available, should be incorporated in any future studies.

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