PREDICTING AND EVALUATING TURBIDITY CAUSED BY DREDGING IN THE ENVIRONMENTALLY SENSITIVE SALDANHA BAY

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Abstract

Extension to the oil jetty at the Port of Saldanha will necessitate dredging of the entrance channel. This study was undertaken to determine the turbidity caused by the dredging and also the transport/dispersion of the dredging plumes. Hydrodynamic and water quality modelling were performed in order to determine the environmental impact of the dredging on the nearby mariculture activities, as well as to investigate possible deposition of mud in the Langebaan Lagoon. Turbidity levels due to storms and shipping were compared with the turbidity caused by the dredging. The environmental impact of the plumes is found to be within acceptable ecological limits and only insignificant sediment deposition is predicted in the Langebaan Lagoon.

1. Introduction

The environmental impact of dredging has recently come under increased public scrutiny within South Africa, especially when dredging is planned in an environmentally sensitive area like Saldanha Bay. The Port of Saldanha, situated 120 km north-west of Cape Town, was constructed mainly for the export of iron ore. Shelter from the swell conditions that occur there was obtained by building a sand (or spending beach) breakwater between the mainland and Marcus Island (Figure 1). A causeway and a jetty (extending 4 km offshore) were built in the lee of this breakwater for the loading of ore and loading/offloading of oil. This causeway divides Saldanha Bay into two: Small Bay and Big Bay (Figure 1). The adjacent Langebaan Lagoon, located some 9 km south of the oil and ore jetty of the Port of Saldanha, is a site of international (Ramsar) ecological significance. Mussel farming is practised within 1 km from the oil jetty, while commercial sea grass production areas are also in close proximity (Figure 1).

Plans to extend the oil jetty will entail dredging of up to 2.5 million m^3 of material in order to widen and deepen the entrance channel. Although the dredged material is to be disposed of in a confined disposal area, it is anticipated that "leakage" associated with the dredging will place a quantity of fine sediment into suspension. Transported by the ambient flow regime, the suspended material could conceivably

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move throughout the bay in the form of turbid plumes and so impair water quality and the surrounding habitat. An assessment of turbidity phenomena as a result of the proposed dredging operations constituted a specialist study (Mocke *et al.*, 1996) as part of a comprehensive environmental impact assessment.

This paper describes how the anticipated turbidity loading due to the dredging was determined and how the associated suspended sediment concentrations compared with ecological thresholds and estimated turbidity levels due to storms and shipping. (The turbidity loading (in kg/s) is the rate at which sediment is released into the water during dredging.) Also described are the mathematical modelling of the water circulation, wave refraction-diffraction and the dispersion of plumes which were performed to predict the extent and fate of the dredging induced plumes. In general, conservative assumptions were made and conservative values were applied in the study. The rationale behind this approach is that, if the severest or most extreme scenario produces acceptable environmental impacts, then a less severe scenario will be even more acceptable.

2. Environmental Conditions

Saldanha falls in a semi-arid region with mild (air) temperatures. *Fog*, which may influence dredging operations, occurs between 88 and 111 days throughout the year. The *wind* regime is dominated by the south-westerly to south-easterly winds (about 57% in total) while the opposing north-easterly to north-westerly winds occur much less frequently (about 24% in total). Wind velocities are below 4 m/s for about 39% of the time and above 10 m/s for about 13% of the time.

A Waverider buoy is situated within Saldanha Bay across from Marcus Island next to the entrance channel. These nearshore measured data show that seasonal differences in *wave* heights are fairly small. The majority of H_{mo} measurements (89%) fall within the range 0.5 m to 2 m and the majority of T_p measurements (73%) within the range 10.7 s to 13.5 s. The wave heights measured in Saldanha Bay are significantly smaller than those measured offshore. Wave directions estimated by voluntary observations from ships in deep water, the so-called VOS data, showed that southerly to south-westerly wave directions are dominant. Wave directions inside Saldanha Bay do not vary as much as those outside the bay.

The *tidal range* at Saldanha Bay is relatively limited, with neap and spring tidal ranges of 0.5 m and 1.5 m respectively. There are no *river* inputs into Saldanha Bay.

Wind forcing is the dominant mechanism controlling *current* direction and magnitudes in both Small and Big Bay. Current speeds are generally low, with some 80% of surface currents less than 0.12 m/s. Current directions are found to be closely aligned with wind direction, except for surface flow in Small Bay, which is mainly clockwise.

Upwelling occurs from spring to autumn. Surface waters attain a maximum *temperature* of around 19 °C and the thermocline (at 13 °C) is generally found to be at a depth of between 3 m and 6 m below the surface.

Essentially three *sediment types* were found, namely, a greyish, medium sand (the most commonly occurring type), silty fine sand and calcrete (limestone). It was found that about 15.5% of the bottom material was fine gravel (between 2 mm and 4 mm) and 72% is relatively fine sand with an average median grain size of around 0.23 mm. The mean percentage of silt/clay (mud) in the bottom material is estimated to be 12.5%, with a median grain size of around 4 micron. The only hard material to contend with during the dredging is hardpan calcrete, which occurs in layers between 0.3 m and 3 m thick. The uniaxial compressive strengths (UCS) of the calcrete varied from 3 MPa to 42.8 MPa with a mean UCS of 18.1 MPa.

3. Conceptual Dredging Plan

3.1 General

A conceptual dredging plan was drawn up so that the turbidity loading caused by the dredging can be determined. This is relevant because the type of dredging and the operation influence the generation of turbidity.

3.2 Dredging Required

The entrance channel to the port needs to be widened and deepened in order to provide access to larger ships. Up to 2.5 million m^3 of material has to be dredged in order to deepen the channel between 0.8 m and 1.3 m (the depth of cut for the dredger varies between 0.8 m and 10 m).

3.3 Physical Conditions Affecting the Dredging

The sediment type has a profound influence on the performance of the dredger and is thus a key element in deciding what type(s) of dredger should be used. The bottom material consists mainly of medium to fine sand interspersed between "moderately strong" calcrete layers. It is important to note that the thickness of these layers is on average 1.5 m. This means that they will not be broken out easily.

Wave action mainly adversely affects the vertical movement of the dredger. This is a problem particularly when cutting hard material because vertical movement causes damage to the cutting device. A H_{m0} of 0.8 m will be exceeded between 10% (protected part of the channel) to 80 % (outer part of the channel). Currents make marine operations more awkward due to the difficulty of maneuvering and of obtaining good anchorage for the dredger. Normally the current velocities are between 0.10 m/s and 0.20 m/s. Weather conditions such as rain and temperature should not cause problems with the dredging. This is because Saldanha lies in the semi-arid region which does not experience extreme temperatures. Wind makes the manoeuvring of all vessels more difficult and it can cause the dragging of anchors. Wind speeds exceeding 10 m/s occur about 13% of the time. Fog could influence dredging operations because of the limited visibility for about 88 to 111 days per year. However, because of modern position fixing systems and radar, it is unlikely that dredging operations would have to be suspended due to fog.

3.4 Spoil Disposal

The bottom material, being mainly medium to fine sand and calcrete, is generally suitable as fill material. The dredger spoil is thus considered a valuable resource which should be stored for later use during port extensions. The disposal of the dredger spoil will most probably be a land-based operation. It has been assumed that special precautions will be taken such as using stilling ponds. Therefore virtually no sediment-laden water will reach the sea. The marine environmental impact of plumes *from the disposal area* will therefore be negligible and will not be considered further.

3.5 Conceptual Dredging Plan

The conceptual dredging plan proposed is that a medium to large cutter suction dredger be used to dredge the medium to fine sand and the calcrete (blasting the calcrete will not be necessary). Dredging is expected to be done 24 h a day at a rate of about 1 100 m^3/h (a high production rate is required to limit the dredging period to 3 to 4 months). The down-time for a large cutter suction dredger was estimated to be between 10% and 80%, depending on where you dredge along the entrance channel. Disposal will take place by means of a pipeline to the reclamation site from where virtually no sediment-laden water will reach the sea. All the dredger spoil will be stored to be used as fill. The first section of pipe from the dredger will be a floating line to a large pontoon from where the rest of the pipeline will be submerged up to the causeway/ore jetty. From there the pipeline will run on land. A booster pump station will be necessary because of the distance between the dredger and the disposal site.

An alternative way of dredging could be by using a combination of a trailing suction hopper dredger and a cutter suction dredger. In this assessment only the most obvious dredging method, namely, of using a cutter suction dredger, has been analysed further.

4. Turbidity

4.1 General

The main purpose of this chapter is to determine the turbidity loading as caused by the dredging. The secondary purpose is to compare the turbidity caused by the dredging with the background turbidity and the estimated turbidity levels due to storms and shipping. It is believed that the background turbidity levels in Saldanha Bay are quite low (usually below 20 mg/l); however, this is based on very limited data which do not cover extreme conditions.

In order to determine the turbidity loading, it is necessary to know the settling velocities of the sediment fractions (Section 4.2) and the turbidity that will be generated at the dredger (Section 4.3) respectively. The turbidity loading is addressed in Section 4.4. Section 4.5 is a comparison of the turbidity caused by shipping and storms with turbidity due to dredging.

4.2 Settling Velocities

The settling velocity distributions of the *sand* were obtained in a standard settling tube. The average median settling velocity of the sand fraction was 0.023 m/s.

Laboratory tests were done to determine the settling velocity of the *mud* (silt and clay) fraction. These tests were done for a range of initial concentrations from 100 mg/l to 10 000 mg/l, with most of the tests done at 150 mg/l and at an average water temperature near the seabed of 13 °C. The 150 mg/l is the ecological threshold, determined from the level at which negligible effects on the mariculture will be found (Carter, 1995). All the tests were done in seawater taken from the site so as to ensure the correct salinity and typical background turbidity (and thus typical organic material in the water). A pipette withdrawal tube was used to determine the distributions of the settling velocity. Because limited variation in the settling velocity distributions was found, it was decided to schematise the settling velocity of the mud into three parts:

Fraction of the mud	% of the mud	Mean settling velocity (mm/s)	Conservative settling velocity (mm/s)
Part 1	30	0.05	0.005
Part 2	40	0.50	0.19
Part 3	30	2.00	1.25
Weighted mean		0.80	0.45

These values correlate well with the typical range of values (0.01 mm/s to 10 mm/s) given by Berlamont *et al.* (1993) and the typical value (0.21 mm/s) for the Øresund link (Brøker *et al.*, 1994) given for chalk/limestone (supposedly similar to the Saldanha calcrete).

4.3 Turbidity at the Dredger

The turbidity at the dredger was determined in two different ways: (1) measurements of turbidities around cutter suction dredgers at other sites around the world were used and compared with the environment at Saldanha; and (2) a comparison with the turbidity caused by different types of dredgers was used. According to Van Wijck *et al.* (1991), a cutter suction dredger causes about twice the turbidity associated with bucket-ladder and trailing suction hopper dredgers. For a seabed grab the ratio is 2.7. In this way the measurements of turbidity caused by other types of dredgers could be used to estimate roughly the turbidity that could be found around a cutter suction dredger.

Van Raalte and Blokland (1988) and Pennekamp and Quaak (1990) defined a number of variables related to turbidity:

t = time for the turbidity to decline to the background levels after cessation of dredging

S = the amount of sediment which is lost by suspension from the immediate vicinity of the dredger (kg of dry material per m^3 dredged).

Typical values for these variables are discussed below.

Kirby and Land (1991) did a comprehensive study of the turbidity generated by different dredgers. For cutter suction dredgers they found that a maximum of 1 100 mg/l was measured immediately adjacent to the cutter head. The turbidity decreased rapidly from the dredger to only a few tens of mg/l (20 mg/l to 90 mg/l) at a distance of 50 m away from the dredger. The turbidity was not influenced by the size of the cutter suction dredger. For normal operations, S is about 6 kg/m^3 while it is approximately 3 kg/m^3 if the dredger works with reduced swing and rotation speeds. Huston (1976) found in a series of tests an increase in turbidity (which varied considerably) above background levels only in the immediate vicinity of the cutter head. Little turbidity reached the water surface, especially from depths of 12 m and more. Yagi *et al.* (1976) recorded turbidity of generally less than 210 mg/l with a depth-averaged value of approximately 70 mg/l.

If one applies the ratios of 2 and 2.7 for the respective dredgers by Van Wijck *et al.* (1991) and calculate the equivalent turbidities that can be expected for cutter suction dredgers, one obtains a mean turbidity of about 250 mg/l. This corresponds reasonably with the values derived from measurements for cutter suction dredgers.

Based on these findings and also on the measurements reported by Kuo *et al.* (1985) and Nichols *et al.* (1990), the turbidity and the initial diameter of the sediment plumes were estimated. The conditions of the sites at which the above-mentioned turbidities were measured were compared to the conditions at Saldanha Bay. For example, the currents of between 0.10 m/s and 0.20 m/s at these sites correspond well to the Saldanha case. The following table was compiled for Saldanha as input to the plume modelling:

Plume scenario	Mean concentration over height of the water column (mg/l)	Height of plume column* (m)	Initial plume diameter (m)	Remarks
1	100	10-15	50	best estimate; still somewhat extreme
2	300	15	100-250	best estimate of extreme turbidity duration

*The height of the plume column is the height above the sea bottom up to where the suspended sediment extends (which can be less than the water depth).

The turbidity caused by previous cutter suction dredging during two previous projects in Saldanha Bay has not been measured before. Photographs, however, show light coloured plumes which were mainly confined to the vicinity of the dredgers. These plumes were mainly caused by chalk particles being suspended in the water during the cutting of the calcrete layers.

Van Raalte and Blokland (1988) and Pennekamp and Quaak (1990) found that within about 0.5 h to 1 h after dredging (of mainly mud), the turbidity returned to the background levels. Aerial photographs and observations by the port pilots confirmed these values of t: within about 0.5 h to an absolute maximum of 2 h, the plumes caused by shipping in Saldanha Bay are no longer visible.

Using the S values of 3 kg/m^3 to 6 kg/m^3 given by Kirby and Land (1991) for cutter suction dredgers, the percentage leakage can be determined if the *in situ* density of the bottom material is known. Assuming typical densities between 1 600 kg/m^3 and 1 800 kg/m^3, leakages of 0.2% to 0.4% were obtained. Kuo and Hayes (1991) give leakage percentages for bucket-ladder dredgers of 0.11% to 3%. Nichols *et al.* (1990) recorded a value of 12% for a trailing suction hopper dredger. Brøker *et al.* (1994) quoted an upper limit value of 5% based on test dredging; this is a combined figure for the whole dredging operation (the type of dredging is not given). Based on these values the following leakage scenarios have been assumed for Saldanha: (1) 0.4% - 2% (best estimate, still somewhat conservative); and (2) 12.5% (best estimate of extreme turbidity generation, assumes that all fines will be lost).

4.4 Turbidity Loading

Four different approaches were used to determine the turbidity loading at the dredger, namely:

(1) A sediment balance (based on continuity considerations) was drawn up to calculate the loading required to achieve the turbidities obtained in the two plume scenarios given above. Essentially the method supposes that the sediment entering a cylindrical element of the water at the dredger is balanced by settling and transport of material out of the cylindrical zone of initial mixing. Lateral mixing is ignored, which is slightly conservative. It is also assumed that an equilibrium will be reached soon after the start of dredging.

(2) The percentages of leakage were combined with the possible production rate of the dredger to obtain the turbidity loading. Note that this method is independent of the turbidities that have been estimated to occur around the dredger.

(3) The behaviour of the turbidity plumes was considered in two dimensions and averaged over depth by using the advection-diffusion equation. This equation was solved with the modelling approach of Kuo and Hayes (1991) by assuming different loadings to obtain the required turbidity in the plume as given above as the plume scenarios (Section 4.3).

(4) The results acquired with the above-mentioned three approaches were correlated with turbidity loadings given in the literature. This was done to verify the results from other methods.

Two turbidity loadings were recommended for use in the plume modelling, namely: (1) 9 kg/s (best estimate loading, still somewhat conservative); and (2) 70 kg/s (best estimate of extreme loading). The 70 kg/s was determined by assuming pipeline failure (which is unlikely), the duration thereof and where it will occur. The turbidity loading was determined by assuming that all the fines (12.5% of the material) will stay in suspension whilst the sand and gravel will settle out. By using the production rate of 1 100 m^3/h, the turbidity loading of 70 kg/s quoted above was obtained. This value was checked by computing the pumping rate in the pipeline. Good agreement was found. Very conservatively, it was determined that the duration of the turbidity loading is 12 h. The place where pipeline failure would have the biggest impact is in the turning circle of the entrance channel because it is the closest to the mussel rafts. It was assumed in the modelling that the failure will occur in this most critical area.

4.5 Turbidity Caused by Shipping and Storms

Shipping

It is expected that, after the expansion of the oil transfer operations, about 297 ships will visit the port annually, that is, about one ship every 1.2 days.

Detailed turbidity measurements at Rotterdam during the normal passage of a bulk carrier (of similar size as the ships expected at Saldanha), revealed no increase in the turbidity (Pennekamp *et al.*, 1991). This is despite the fact that the bottom sediment is predominantly mud. Kirby and Land (1991) found, during the passage of a vessel in the Lower Rhine with a muddy bottom, that the disturbed sediment soon settled. This is in accordance with the results by Hochstein and Adams (1989) in St Mary's River in the

USA/Canada. The bottom material there was smaller than 0.075 mm and yet they found no noticeable degradation of water quality. This they attributed to the sediment settling within the 34 minutes before another ship passes. Recalling from above that for dredging, it took about 0.5 h to 1 h for the turbidity to decline to background levels. Compare these values to the 1.2 days between ships expected at the port. This means that most of the material in suspension will settle before the next ship arrives. It can therefore be concluded that normal sailing contributes very little to turbidity (Kirby and Land, 1991).

Because turbidity is mainly caused during manoeuvring such as turning and berthing, this aspect should be considered further. From the literature, measurements at 5 sites (including Saldanha) show that the increase in the turbidity due to shipping is typically between 100 mg/l and 210 mg/l (Pennekamp *et al.*,1991, Pennekamp and Quaak, 1990 and Kirby and Land, 1991). These values show that the increase in turbidity is not very large despite the fact that the bottom material is mud. The bottom material in the enlarged turning circle will be medium sand with some calcrete layers present. Comparing this material with the soft mud that was encountered during the above-mentioned measurements (except possibly Saldanha), it is clear that turbidities will generally be lower at Saldanha than the values quoted above. This is enhanced by the calcrete layers which armour the sea bottom and reduce the suspension of material.

It can therefore be concluded that it is unlikely that the turbidity caused by shipping, even during manoeuvring, will be significant at Saldanha during the operation of the extended oil jetty. Most of the time the turbidity caused by shipping in its immediate vicinity will be below the ecological threshold of 150 mg/l.

Storms

For a large number of *sites* from around the world, depth-averaged sand concentrations (turbidities) that were measured outside the surf zone ranged from 29 mg/l to 901 mg/l (Van Rijn, 1991). In a review Appleby and Scarratt (1989) found natural turbidity levels in estuaries of up to 1 200 mg/l. High turbidities therefore occur naturally. *Sand* concentrations were computed for 4 typical storms. Two different models were applied to calculate the sand concentration, namely, those of Van Rijn (1989) and Schoonees (1998). Most of the depth-averaged concentrations ranged between 8 mg/l and 80 mg/l. The two approaches yielded reasonably similar results although the Van Rijn (1989) formulation showed a wider range. Typical turbidities due to the suspension of the *fine fraction* were estimated by assuming that all the fines will be washed out of a layer of material on the sea bottom. These fines are then supposed to be redistributed in the water above the layers from where they originated. Typically the increase in turbidity due to the fines (mud) will range between approximately 10 mg/l and 60 mg/l.

In the study in the Thames River and the eastern Long Island Sound, Sosnowski (1984) found that the concentrations during storms are nearly an order of magnitude larger than those due to dredging. Dredging induced suspension was found to be a near-field or local phenomenon while storms have a regional impact. When comparing the dredging induced turbidity at the dredger at Saldanha with natural fluctuations during storms, it is clear that the concentrations are of the same order of magnitude. It can therefore be concluded that the turbidity that will be encountered during dredging will be similar to that occurring naturally during storms.

5. Modelling of Wave and Current Regimes

5.1 Waves

Modelling of the wave refraction/diffraction was done for two reasons: (1) to determine what effect the deepening and widening of the entrance channel would have on wave conditions throughout Saldanha Bay and therefore if the coastline would be affected by the dredging; and (2) the wave regime inside the bay was required in order to be able to calculate bed shear stresses due to wave and current action. Because the effect of the dredging on the coastline does not form part of this paper, only results related to the second objective will be considered.

The scope of the study did not allow for a comprehensive numerical refraction/diffraction study of the total deep water wave climate. Instead a number of average and extreme wave conditions was modelled using both the present bathymetry and a post dredging bathymetry as input. Wave conditions were decided upon based on the wave data described in Chapter 2.

A widely used wave refraction model, Hiswa (Holthuijzen *et al.*, 1989), was used to transform the deep-water waves through nested grids up to the entrance of Saldanha Bay. As Hiswa allows only for wave refraction to be calculated and not wave diffraction, a wave refraction/diffraction model based on the mild slope equation was used to transform waves from the entrance into the bay.

Figure 2 contains a plot of wave heights for an average deep-water wave condition of H_{mo} = 2 m, T_p = 12 s and a deep-sea direction of south-west. From this figure it can be seen that wave heights along the south-eastern beaches of Big Bay are for the most part less than 1.2 m with the highest waves occurring opposite the entrance to the bay. Diffraction around the sand breakwater ensures that waves with heights in the order of 0.2 m to 0.4 m enter Small Bay.

5.2 Currents

The Delft3D-FLOW hydrodynamic model (WL|Delft hydraulics, 1996a) was used to simulate the three-dimensional flow regime in the semi-enclosed Saldanha Bay system. The processes included in the model were tidal forcing, wind forcing, Coriolis effects, baroclinic flows due to thermal stratification and the drying and flooding of tidal flats in the lagoon. The model uses constant eddy viscosity and diffusivity coefficients in the horizontal direction while a k-ε turbulence model is used in the vertical direction. An orthogonal curvilinear grid with cell sizes ranging from 200 m in the areas of interest to 1 000 m near the model boundary was used in the horizontal direction, with eight σ-coordinate layers used in the vertical.

The model was calibrated based on current and water temperature data measured at four locations in the bay for a 12 day period. Measured wind, water level and thermistor string data were used at the model boundaries. The following coefficients were found to give the best correlation to the measured data: Chezy coefficient for bottom friction = 65 $m^{0.5}/s$, horizontal eddy viscosity = 1 m^2/s, horizontal eddy diffusivity = 0.5 m^2/s, wind coefficient = $6.3x10^{-4} + 6.6x10^{-5}.U_{10}$ (Smith and Blanke, 1975) where U_{10} is the wind speed 10 m above the water surface. Figure 3 indicates a good comparison between the measured data and model currents. The water temperature is modelled less accurately since in this case the air-sea interaction module was not used and the thermal stratification is driven by the imposed open boundary conditions only.

Figure 4 depicts the predicted three-dimensional current structure at outgoing and incoming tides with a 10 m/s south-westerly wind under non-stratified conditions.

The predicted current magnitudes are generally below 0.5 m/s, except in the constriction at the entrance to Langebaan Lagoon where currents may exceed 1.0 m/s at spring tide. Under stratified conditions and the dominant southerly winds, the exchange between the bay and the adjacent shelf revealed cold water entering the bay near the seabed on the incoming tide and warmer water leaving the bay near the surface on the outgoing tide. This phenomenon will have a significant impact on the supply of nutrients to the primary producers and thus the mariculture activities in the bay as well as on the residence time of pollutants in the bay.

6. Turbid Plume Dispersion

The Delft3D-WAQ water quality model (WL|Delft hydraulics, 1995, 1996b) was used to simulate the advection, dispersion, settling and deposition of the turbid plumes arising from the dredging operations. This model solves the advection-diffusion equation in three dimensions including settling of particles and deposition or erosion based on specified critical shear stresses. The bed shear stress is computed as the sum of the stress due to currents and waves. The hydrodynamic database is obtained from the Delft3D-FLOW simulation via an offline coupling.

The silt/clay material (< 63 microns) was subdivided by mass into three fractions each with a characteristic settling velocity and a critical shear stress for deposition. Settling velocities of 0.05 mm/s, 0.5 mm/s and 2.0 mm/s (Section 4.2) and corresponding critical deposition shear stresses of 0.1 Pa, 0.2 Pa and 0.3 Pa were used in the simulations.

As discussed in Section 4.4, a best estimate loading of 9 kg/s for material less than 63 microns and an extreme loading of 70 kg/s due to a failure of the pipeline from the dredger were simulated. Based on occurrence statistics, a representative range of winds, tides and wave heights was selected. The model was used to obtain the following output: contour plots of the maximum turbidity for each scenario, maximum turbidity and exposure times at the ecologically-sensitive sites in the bay as well as contour plots of the deposition thickness throughout the bay upon completion of dredging. Figure 5 shows the predicted turbidity plume due to the extreme loading case of 70 kg/s.

The turbidity at the ecologically sensitive sites was predicted to be below 25 mg/l, which is within the range of the natural background turbidity. Wave-generated bottom shear stresses were found to have a significant influence on the results by inhibiting deposition of the finer mud fractions in the exposed areas of the bay and thus causing a pervasive spreading of these particles into the lagoon and also out to sea. The maximum deposition thickness in the lagoon, however, totalled less than 2 mm over the dredging duration of 4 months. Based on these results the ecological impact of the proposed dredging was predicted to be low.

7. Conclusions and Recommendations

The turbidity loading caused by the proposed dredging could be determined with reasonable accuracy. The circulation in Saldanha Bay was well modelled, with predicted currents generally below 0.5 m/s, except at the entrance to Langebaan Lagoon where currents may exceed 1 m/s under spring tidal conditions. The turbidity at the ecologically sensitive sites was predicted to be below 25 mg/l, which is within the range of the natural background turbidity and far below the ecological threshold of 150 mg/l. Wave action will inhibit deposition of the finer mud factions in the exposed areas of the bay, thus causing a pervasive spreading of these particles into the lagoon and also out to sea. The maximum deposition thickness in the lagoon will, however, be insignificant. These results showed that the environmental impact of the plumes will be within acceptable limits.

It was found that the turbidity caused by the dredging (having a local effect) will be of a similar order to that occurring naturally during storms (a widespread effect). The turbidity caused by shipping is short-lived and not significant.

It has been recommended that the background turbidity levels be monitored before commencement of the dredging, particularly under storm conditions. In addition, it is required to measure the turbidity levels in the vicinity of the dredging and in the ecologically sensitive areas while dredging is taking place.

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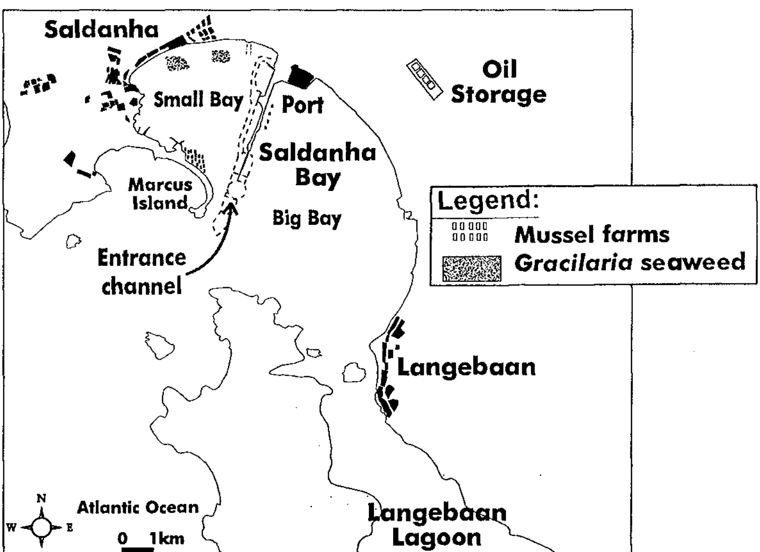

Figure 1: Location map

Figure 2: Modelled wave heights in Saldanha Bay

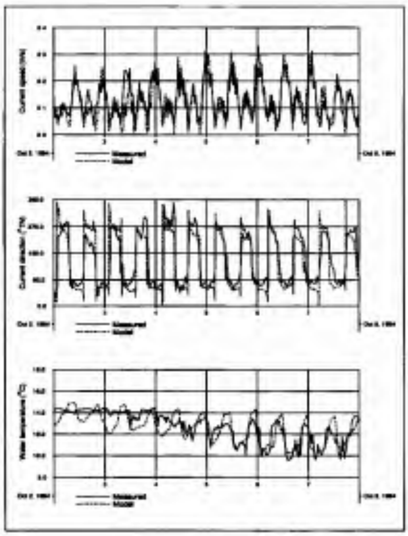

Figure 3: Comparison between measured data and model results in Saldanha Bay

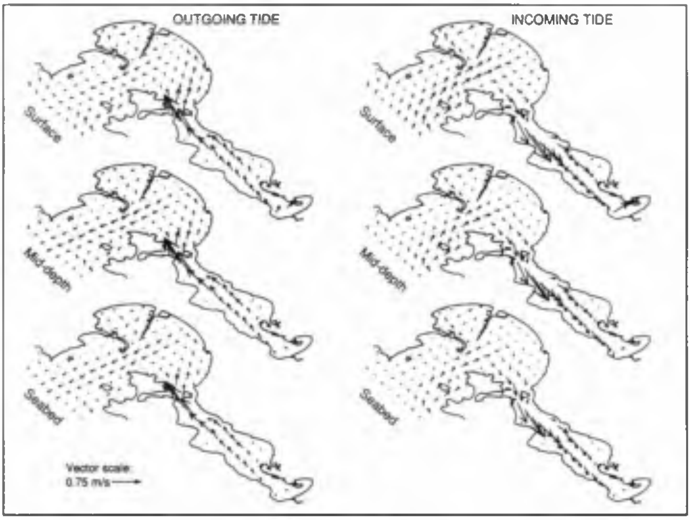

Figure 4: Modelled currents in Saldanha Bay at neap tide with a 10 m/s SW wind

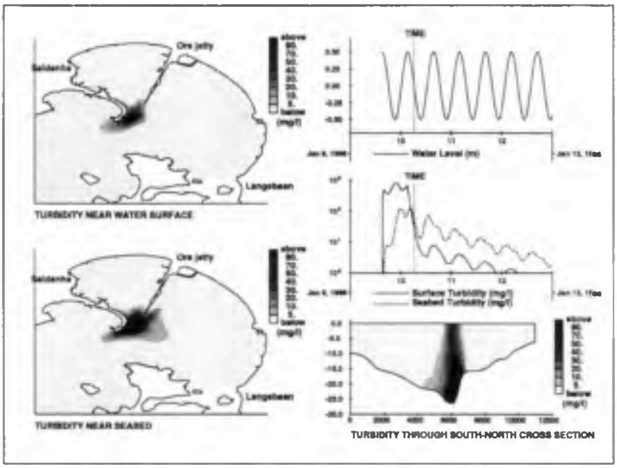

Figure 5: Predicted turbidity plume 3 hours after a simulated failure of the dredge line has been repaired