Assessment of the Cumulative Effects of Sediment Discharges from On-shore and Near-shore Diamond Mining Activities on the BCLME

BEHP/CEA/03/03

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BCLME
Benguela Current Large Marine Ecosystem Programme

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EXECUTIVE SUMMARY

Background

Near-shore and coastal diamond mining involves the discharge of tailings, generally comprising sediments only, into the marine environment of the Benguela Current Large Marine Ecosystem (BCLME). In recent years, some mining operations (associated with overburden sand removal by dredging) have resulted in the discharge at a single site of up to several million tons of tailings annually. Several future mining operations are planned to be of a similar scale.

A frequently employed means of mining diamonds in the inter-tidal and near-beach region is through the construction of massive seawalls to prevent erosion and flooding due to waves and tides. These seawalls require replenishment with large volumes of sand as they are eroded away by wave action. The eroded sand is distributed by waves and currents in the near-shore region.

Both seawall construction and tailings discharges may contribute to alteration of sub-tidal and inter-tidal habitats as a result of the following effects:

1. Smothering by sediment depositing on the sea-bed;
2. Increased turbidity causing reduced sunlight penetration and consequent possible reduced growth of marine vegetation;
3. Increased sediment concentrations resulting in decreased efficiency of filter feeders, clogging of gills, and other effects;
4. Possible scouring of reef habitat (or of reef-dwelling biota) by near-bed transported sediment;
5. Possible oxygen depletion (as will be seen, this is not a major concern in the project area shallower than 40 m in depth).

Numerous previous impact assessment studies have focussed on the sediment discharge from a single mining project (i.e. not in combination with other past, present and future sediment discharges). The effects (such as points 1 to 5 above) of such a project have generally been found to be localised, short term and minor. **However, there is a concern that cumulative effects (over time and space) of discharges from several mining operations may be found to be severe.** This project focuses on such cumulative effects. The focus is particularly relevant when recognising (1) the probable increase in future near-shore mining activity as terrestrial diamond sources become depleted and (2) that new technologies are likely to result in mine sediment discharges nearby to existing sediment discharges (e.g. proposed mining of the surf zone by means of walking jack-up platforms may occur close to existing and future inter-tidal sedimentary mine tailings discharges).

Project Objectives

The objectives (based on the project terms of reference) are as follows:

1. To address the question: What quantities of suspended sediment are transported into the <40 m depth zone by rivers, wind and coastal currents? How does this compare with the quantity of sediment re-mobilised/discharged by land-based and near-shore mining activities and what are the relative particle-size distributions of these various sediment inputs?

2. To address the question: How far, and in which directions, are the above-mentioned sediments transported and by what mechanisms, and where in the near-shore zone are they deposited?

3. To address the question: What is the extent and duration of the natural deposition of unconsolidated sediments on near-shore reefs and how does this compare with the potential smothering of reefs as a consequence of discharged and mobilized mining-related sediments?

4. To assess the cumulative effects of sediment input as a result of on-shore and near-shore marine diamond mining activities.

5. To make recommendations for any appropriate monitoring required in order to improve response to the above issues in future.

6. To address the question: How can the tailings discharges be managed in order to minimise any effect on the rock lobster resources and on other marine biota?

Project Approach

An approach is adopted whereby recent and existing monitoring programmes are drawn upon, in combination with the computational modelling of sediment inputs, transport, settlement, deposition and resuspension. The application of relevant data relating to diamond mining impacts (as well as model validation data) from recent and existing monitoring programmes fulfils the objectives of this project in the most cost-effective manner.

The transport and fate of fine sediment (silt or clay, having a grain size of less than 63 μm) and the transport and fate of coarse sediment (generally sand with grain size range of 63 μm to 2000 μm) in the near-shore region are assessed separately in this study, because of their different behaviour and associated separate approaches to modelling**.**

The project entails the following steps:

1. Identify mechanisms of impact resulting from mine sediment discharges and define the actual impacts resulting from these mechanisms, indicators of the impact mechanisms and, where possible, thresholds of these indicators above which impacts are likely to occur. (Indicators will be predicted by means of computational models and compared to thresholds to assess of impact.)
2. Select key sites at which to apply computational model studies of the suspension, transport and deposition of sediment. Provide descriptions of computational models applied in this study.
3. Collate and prepare model input data for model set-up. Validate models against measurements where possible, in order to quantify the accuracy of model results and thereby to ensure model integrity.
4. Compile an inventory of both mine and natural sediment inputs to the project area (and a description of their associated grain sizes). This addresses objective 1 as outlined above.
5. Employ the validated models to assess the suspension, transport and deposition of fine sediments (both naturally occurring input and input from diamond mining operations). From available information on the spatial distribution and configuration of near-shore reefs, assess the extent and duration of fine sediment deposition (both

naturally occurring input and input from diamond mining operations) on these reefs. This addresses objectives 2 and 3 (for fine sediment) as outlined above.

6. Employ the validated models to assess the transport and deposition of coarse sediments (both naturally occurring input and input from diamond mining operations). From available information on the spatial distribution and configuration of near-shore reefs, assess the extent and duration of coarse sediment deposition (both naturally occurring input and input from diamond mining operations) on these reefs. This addresses objectives 2 and 3 (for sand/coarse sediment) as outlined above.
7. Assess areas of cumulative impact, drawing on existing modelling studies and conducting additional modelling. This addresses objective 4 as outlined above.
8. Test the sensitivity of model outputs (predictions of sediment concentrations/deposition) to model input data (sediment data, environmental data). This will allow an assessment of (1) which data are most relevant in the assessment of cumulative impacts of sediment inputs and (2) the impact of gaps in the data. This information will aid in providing monitoring guidelines, thus addressing objective 5 above.
9. By applying computational modelling, explore strategies to better manage tailings discharges in order to minimise effects on rock lobster resources. This addresses objective 6 as outlined above.

The project terms of reference stated that only the region shallower than 40 m in depth would be considered (this is the region where wave action dominates in such a way that fine sediment discharged from mining operations does not deposit on the bed for any extended period). In this study, meaningful impacts of mine sediment discharges from large-scale mining were not found to extend more than a few kilometres from their source. Therefore, a **project area,** which considered only regions where large-scale mining is actively practised or planned, was defined as follows: *from the high-water mark extending to 40 m in depth, and from the Olifants River in the south to Spencer Bay in the north*.

As mentioned, demonstration areas were selected based on certain predefined criteria. An advantage of sites being in Namibia is that this is where most data and operational computational models are available (established for previous impact studies), facilitating a cost-effective study. In addition, in Namibia the policy is to discharge tailings into the marine environment (unlike South Africa, where tailings are discharged into slimes dams) and therefore this is where impacts are most likely to be found.

The disadvantages of a focus on Namibia are: a) lack of attention paid to the rock lobster in the Port Nolloth/Kleinzee area, and b) since mine tailings in South Africa are discharged into slimes dams (as opposed to into the sea in Namibia), the potential to provide a comparison between the two major classes of mine tailings treatments (on-land in South Africa versus into the sea in Namibia) has been lost. It is one of the recommendations of this study that any future regional studies on cumulative impact focus on accessing available data, monitoring and analysis of the South African coastal mining impacts, and of South African rock lobster in order to provide this comparison.

Project Findings

With reference to the six project objectives outlined above, the findings and associated recommendations of this project are:

1. Sediment inputs to the project area

What quantities of suspended sediment are transported into the <40 m depth zone by rivers, wind and coastal currents? How does this compare with the quantity of sediment re-mobilised/discharged by land-based and near-shore mining activities and what are the relative particle-size distributions of these various sediment inputs?

In the last few decades the estimated Orange River sediment input has ranged from an average of 34 million tons/year (1960 to 1969) to an average of less than 17 million tons (1980s). Based on these values, it is likely that 400 to 800 million tons were discharged from 1968 to April 2005. In comparison, 404 million tons of sediment input to the coastline was estimated from available mining data, indicating the volumes from the two sources to be of the same order of magnitude for that period.

A primary difference between natural sources and mine sediment sources is the rate of discharge: while mine sediment discharges tend to have a relatively constant rate, flood sediment discharge tends to be large and more intermittent. For example, during a major flood such as that of 1988, an estimated 64 million tons of sediment, discharged in a few months, is roughly equivalent to four times the annual average Orange River sediment discharge mass. This volume of flood sediment discharge is also approximately equivalent to about four times the annual average mine sediment discharge to the project area in Namibia over the last 15 years.

While millions of tons of windblown fine sediment have been estimated for the total BCLME, only a fraction of this would be delivered to the <40 m depth region, from where it would be rapidly mobilized by wave action and transported into deeper water. Windblown sand (coarse sediment) input is also estimated to be relatively minor.

Sediment input to the project area from coastal currents is also estimated to be relatively minor.

Natural sediment input to the project area tends to be fine. For example, about 84% of sediment from the Orange River is indicated to be fine material. Most of the remaining 16% coarse sediment is fine sand. Most of the estimated windblown sediment input, primarily from bergwinds is fine. On the other hand, most of the sediment discharged from mining is medium to coarse sand, with a small percentage fines – generally less than 5%.

2. Fate and deposition of fine sediments

*How far, and in which directions, are **fine** sediments (input to the near-shore region either naturally occurring or from mine discharges) transported and by what mechanisms, and where in the near-shore zone are they deposited?*

*What is the extent and duration of the natural deposition of unconsolidated **fine** sediments on near-shore reefs and how does this compare with the potential smothering of reefs as a consequence of discharged and mobilized sediments?*

It was evident from model predictions (and supported by observations) that fine sediment is mobilized by wave action and is transported rapidly, generally northward, by wind-driven currents. The result of this rapid transport is that fine sediment that is discharged moves beyond model domains extending tens of kilometres from discharge sites (generally moving northward) within periods of weeks to months.

In the case of fine mine sediment discharge, concentrations which could have an impact on biota are generally limited to with a few hundred metres of the discharge position. In the case of fine sediment discharges from floods, sustained concentrations are one to two orders of magnitude higher than for the mine discharge cases.

For the case of the floods simulated, predicted deposition was considerable (order of millimetres to centimetres) and extended over several square kilometres. On the other hand, for all cases of mine sediment discharge, deposition is generally predicted to be an order of magnitude less than 1 mm.

For both floods and mine discharges, predicted fine sediment deposition tends to occur in water depths greater than 40 m and does not tend to deposit (with significant thickness or for a significant duration) on the near-shore reefs.

3. Fate and deposition of coarse sediments

*How far, and in which directions, are **coarse** sediments (i.e. primarily sand, input to the near-shore region either naturally occurring or from mine discharges) transported and by what mechanisms, and where in the near-shore zone are they deposited?*

*What is the extent and duration of the natural deposition of unconsolidated **coarse** sediments on near-shore reefs and how does this compare with the potential smothering of reefs as a consequence of discharged and mobilized sediments?*

Studies have clearly demonstrated that sand is naturally transported northward by littoral drift. However, sand discharged from mining operations generally results in accretion. Of a total 361 million tons of sediment (primarily sand) estimated to have been discharged from 1970 to recent years, about 294 million tons or 81% of the discharged sediment is accounted for by measured accretion of the shore and near-beach region. The remaining sediment (particularly the fine sediment component) is deemed to have been transported offshore and to the north. The lack of observed obvious accretion offshore and in northern regions suggests that this volume of sediment was "absorbed" by the system.

Measurements of natural beach variations provide an indication that near-shore reefs can be seasonally covered and re-exposed. However, as demonstrated by both modelling and measurements, discharge of large volumes of sand can result in long-term (years to decades) deposition on reefs, which overshadows natural trends.

The total of about 3 km of rocky inter-tidal and near-shore sub-tidal smothering of reef in the demonstration areas will have occurred by 2013. This estimate is based on measured accretion to date and future accretion based on planned mining rates, on known reef areas. The smothered area comprises only 1%-2% of the rocky shore in the Namibian part of the project area. Nevertheless, it is important to verify that the impacted shore does not constitute a unique and important habitat.

From available information it is evident that as much as 100 km of seawalls have been constructed in total, which must have caused smothering of beach biota at the time of construction. In addition, beach steepening has occurred. While fauna on most of the wave-exposed beaches appear not to have been severely affected by this steepening, indications are that the change in conditions and grain size associated with steepening has affected community structure at the relatively wave-sheltered Elizabeth Bay beach.

4. Cumulative effects

> *What are the cumulative effects of sediment input as a result of on-shore and near-shore marine diamond mining activities.*

Model simulations of fine sediment behaviour indicated that simultaneous vessel and land-based mining operations could result in a detectable cumulative effect. However, this effect was predicted to be minor, in the sense that no meaningful cumulative impacts resulting from the fine sediment discharges would occur.

In the case of coarse sediment, all of the southern Namibian operations are connected by means of littoral sand transport. As a result of this connectivity there is a potential for cumulative effects of mine sand discharges. In this study the fate and impact of coarse sediment discharges in southern Namibia have been addressed in a cumulative sense by the project approach (i.e. all of the sediment inputs from all plants for the entire period of mining – and a future scenario of these sand inputs – have been considered). The associated impacts of these inputs are as discussed above (Section 3: Fate and deposition of coarse sediments).

The Pocket Beach Area operations are also inter-connected (and connected to the southern mining operations) by means of littoral sand transport, indicating a potential for cumulative effects. From survey, aerial laser survey and orthophotograph data, shorelines to date are indicated to be stable (apart from that at currently operational mining sites 2, 3 & 4). The lack of observed accretion in this region suggests that no significant cumulative effects of coarse sediment discharges have occurred to date.

5. Monitoring

Make recommendations for any appropriate monitoring required in order to improve response to the above cumulative impact issues in future.

Model sensitivity tests provided some insight into how the accuracy of various parameters affects sediment concentrations and deposition. This assessment aids in defining which parameters are important to measure accurately, in order to accurately predict the behaviour of discharged fine and coarse sediment. The following guidelines to monitoring are recommended in order to facilitate the accurate prediction of sediment transport, concentrations and deposition:

- A detailed log of the hourly/daily rates of all sediment discharges should be recorded, together with frequent (daily/weekly) measurements of the grain-size distribution of the discharge (this includes assessment of floods);
- Accurate directional wave measurements should be conducted representative of mining areas: 5 to 8 years of accurate directional wave measurements are needed to characterise conditions. A compromise would be to employ hindcast wave data (predicted from pressure and/or wind data). However, this hindcast data should be validated against at least one year of measurements.
- Accurate wind data should be measured, representative of mining areas. Ideally, several years of wind data would be needed to accurately define the average conditions, but it is estimated that five years would be adequate for assessment of aeolian sediment transport. A compromise may be to employ model data, but these should be validated against at least a year of measurements.
- Where possible, *in situ* sediment settlement, sediment deposition shear stress and sediment resuspension shear stress must be measured, since both sediment concentrations and sediment deposition are highly sensitive to these parameters.

Monitoring details (e.g. responsible party, frequency and duration of measurement) are provided in this report.

Apart from the identified monitoring needs which originate from modelling, other data gaps have been identified in this project, which highlight further monitoring needs. These needs are as follows:

- It has been identified that wind-driven exchange of sediment between the near-shore/surf zone and the beach is highly dependent on the grain-size distribution of material being blown into the sea and the grain-size distribution of material on the beach. A detailed coastal sand sampling programme is therefore recommended. This will aid in the clarification of the volume of sand depositing in the marine environment via wind.
- Estimates of wind-blown sand transport vary considerably. Monitoring of aeolian sand transport rates is recommended in order to validate calculations of annual rates of transport.
- Sand discharge from rivers is not accurately determined. For example, sampling of river-borne sediment concentrations in the Orange River (e.g. Bremner *et al.,* 1990) has been relatively crude and intermittent. A more detailed programme of sampling of suspended and bed-load sediment transport, particularly during floods, is recommended.
- A major potential source of sediment in the form of bergwind-transported airborne dust was identified. It is recommended that this be quantified by means of monitoring and/or satellite image interpretation.

6. Tailings and associated beach accretion management

How can the tailings discharges be managed in order to minimize any effect on the rock lobster resource (and on other marine biota)?

There is little doubt that there is considerable opportunity for management actions to be conducted in order to mitigate the effects of discharged sediment, as follows:

- Modelling studies demonstrated that discharge at a more wave-exposed site will result in more rapid dispersion **of fine material** than at a wave-sheltered site, with the result that lower concentrations will be experienced near the discharge point. (However, this must be evaluated against the sensitivity of the discharge site and economic issues relating to a possible need to separate fine from coarse sediment, etc). Consideration should be given to this disposal approach.
- Modelling should be employed in order to site both fine and coarse sediment discharges relative to sensitive sites (e.g. power station water intake, estuary).
- The modelling of fine sediment discharges indicated that elevated concentrations (which may have an impact) are generally limited to within a few 100 m of the discharge location (this distance is in the order of a kilometre for large discharges). This provides a rough guideline for the siting of fine sediment discharges relative to sensitive areas and/or relative to existing fine sediment discharges.
- Consideration should be given to the potential discharge of mine tailings into mined-out areas. Numerous benefits can be achieved from this approach, one of which is avoiding discharge into the marine environment. However, consideration must be given to salinity (and associated groundwater effects) and to the composition of sediment (the latter to avoid possible creation of a bog with excessive fine sediment). In addition, consideration should be given to possible subsequent erosion of the coast to cause formerly discharged material (at a near-coast mined-out area) to enter the marine environment;
- Consideration should be given to mechanical means of managing tailings, e.g. by means of thickening/degrit processes (the product of this process would be coarse material which could be used to infill mined-out areas without creating a bog);
- Consideration should be given to the use of bulldozers and dredging to aid the process of natural erosion and retreat of accreted beaches.

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BCLME	Benguela Current Large Marine Ecosystem
CDM	Consolidated Diamond Mines (former name of the mining company Namdeb)
DWAF	Department of Water Affairs and Forestry, South Africa
DP	Discharge position (where mine tailings are discharged)
H_s	Significant wave height (statistical parameter representative of the average of the highest third of waves observed in a record).
HWL	High water line. A line based on the beach debris line, approximately representative of the shoreline.
MFMR	Ministry of Fisheries and Marine Resources, Namibia.
MSL	Mean sea level (surveying vertical datum)
NCEP	National Centre for Environmental Predictions, USA
PTF	Pre-treatment facility
SWAN	Simulating Waves Nearshore – a computational wave transformation model.
WOMS	Wet overburden mining system. Name given to a proposed Namdeb on-land dredging project

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1. INTRODUCTION

1.1 BACKGROUND

Near-shore and coastal diamond mining involves the discharge of tailings, generally comprising sediments only, into the inter-tidal and near-shore zone (defined in this project as the area from the inter-tidal zone, extending offshore to a depth of 40 m). In recent years, some mining operations (associated with overburden sand removal by dredging) has resulted in the discharge at a single site of up to several million tons of tailings annually. Several future mining operations are planned to be of a similar scale.

A frequently employed means of mining diamonds in the inter-tidal and near-beach region is through the construction of massive seawalls to prevent erosion and flooding due to waves and tides. These seawalls require replenishment with large volumes of sand as they are eroded away by wave action. The eroded sand is distributed by waves and currents in the near-shore region.

Both seawall construction and tailings discharges may contribute to alteration of sub-tidal and inter-tidal habitats as a result of the following effects:

1. Smothering by sediment depositing on the sea-bed;
2. Increased turbidity causing reduced sunlight penetration and consequent possible reduced growth of marine vegetation;
3. Increased sediment concentrations resulting in decreased efficiency of filter feeders, clogging of gills and other effects;
4. Possible scouring of reef habitat (or of reef-dwelling biota) by near-bed transported sediment;
5. Possible oxygen depletion (as will be seen, this is not a major concern in the project area shallower than 40 m depth).

Cumulative effects

This project focuses on cumulative effects. A definition of cumulative effects by Hegmann *et al.* (1999) is as follows: "…*changes to the environment that are caused by an action in combination with other past, present and future human actions*". The "action" in the context of this project is the discharge of sediment from diamond mining activity. Numerous previous impact assessment studies have focussed on the sediment discharge from a single mining project (i.e. not in combination with other past, present and future sediment discharge). The effects (such as indicated in points 1 to 5 above) of such a project have generally been found to be localised, short term and minor. (For example, at Elizabeth Bay in Namibia impacts on biota were estimated to last for a few years and to be limited primarily to within the confines of the bay (CSIR, 2002)). **However, there is a concern that the cumulative effect (over time and space) of discharges from several mining operations may be found to be severe.** For example, in the case of Mining Area 1 (extending from the Orange River to about 100 km north) sediment discharged from proposed processing of dredged material may merge with sediment discharged from existing plants (i.e. "other past, present and future human actions") in order to cause a cumulative effect.

Cumulative effects occur when (Council on Environmental Quality, 1997):

- Impacts on the environment take place so frequently in time or so densely in space that the effects of individual impacts cannot be assimilated; or
- The impacts of one activity combine with those of another in a synergistic manner.

The former situation would probably result in an **additive** cumulative effect. This is when the magnitude of the combined effects is equal to the sum of the individual effects (an example would be sand from two adjacent mine discharges depositing in the same place at approximately the same time). The latter situation would result in a **synergistic** cumulative effect. This is when the magnitude of the combined effects is greater than the sum of the individual effects (an example would be two high concentrations of sediment from separate sources mixing at a point. The consequent elevated concentration may hinder the settling out of material, resulting in concentrations of the mixture being greater than the sum of the two separate concentrations).

The focus on cumulative effects of mine sediment discharges is particularly relevant when recognising (1) the probable increase in future **near-shore** mining activity as terrestrial diamond sources become depleted, and (2) that new technologies are likely to result in mine sediment discharges nearby to existing sediment discharges (e.g. proposed mining of the surf zone by means of walking jack-up platforms may occur close to existing and future inter-tidal sedimentary mine tailings discharges).

Furthermore, although not part of the classical definition of cumulative effects, little consideration has been given to the possible cumulative effect of a natural event (e.g. a major flood) simultaneous to a major mine sediment discharge.

1.2 OBJECTIVE AND SCOPE

Against the above background, the primary project objective is defined as follows:

To assess the cumulative effects of sediments input as a result of on-shore and near-shore marine diamond mining activities in order to manage more effectively the impacts of these activities on the living marine resources and the ecosystem as a whole.

Key questions to be addressed in this study BEHP/CEA/03/03 are:

1. *What quantities of suspended sediment are transported into the <40 m depth zone by rivers, wind and coastal currents? How does this compare with the quantity of sediment re-mobilised/discharged by land-based and near-shore mining activities and what are the relative particle-size distributions of these various sediment inputs?*
2. *How far, and in which directions, are these sediments transported and by what mechanisms, and where in the near-shore zone are they deposited?*
3. *What is the extent and duration of the natural deposition of unconsolidated sediments on near-shore reefs and how does this compare with the potential smothering of reefs as a consequence of discharged and mobilised mining-related sediments?*
4. *How can the tailings discharges be managed in order to minimise any effect on the rock lobster resources?*

In addition to addressing these questions, this study will make recommendations for additional monitoring.

Link to another BCLME project

It is recognised that a review of existing information relating to coastal and marine diamond mining impacts is the objective of BCLME project BEHP/CEA/03/02: “Data Gathering and Gap Analysis for Assessment of Cumulative Effects of Diamond Mining Activities on the BCLME Region”. Close links have been maintained with this project. The present project (BEHP/CEA/03/03) has benefited from information provided by project BEHP/CEA/03/02 (e.g. on mining operations, sediment discharges, information on impacts on biota). At the same time, the present project contributes to project BEHP/CEA/03/02 by providing insight into the extent and severity of gaps in available data by testing the sensitivity of model-predicted effects of mine sediment discharges to limited or inaccurate data.

Project limited to <40 m depth

As defined by the project terms of reference, this project considers the region extending from the high-water mark to a depth of 40 m. This is a region where (a) wave action is dominant and affects the behaviour of sediment, and (b) which defines the maximum limit for most lobster fishing activities.

Modelling experience, such as will be described in this study, and calculations of sediment resuspension indicate that up to a depth of roughly 40 m, fine sediment (primarily clay and silt – which have grain sizes less than 63 µm) such as is discharged from mining operations, will tend not to accumulate on the sea-bed, as it will frequently be re-suspended by wave action. These re-suspended fine sediments tend to be transported to greater depths where near-bed flows due to waves and current are weak, such that long-term deposition will occur. Thus, the region shallower than about 40 m depth is a region where wave action dominates in such a way that fine sediment discharged from mining operations does not deposit on the bed for long periods.

Coarse sediment, i.e. mainly sand (with grain sizes from 63 µm to 2000 µm), also manifests behaviour in the shallow, wave-dominated region which is different to its behaviour in deep water (>40 m depth). In particular, sand discharged on or near the beach tends to remain part of the near-shore profile, where it is transported primarily by breaking waves and where it can contribute to shoreline accretion. Thus, shallow-water sand discharges from mining should also be considered separately to deep-water discharges (> 40 m depth), where sand will tend to settle to the sea-bed and deposit where it initially settles for relatively long periods.

The 40 m limit defined in this project is also related to lobster fishing activity. In Namibia fishing is primarily conducted with traps set in 10-40 m depth from wooden deck boats (Pisces, 2004); although lobster have been caught deeper, the industry focuses on shallower regions.

Definition of project area

It is assumed for the present that significant impacts from mining operations will not extend to more than a few kilometres from mining areas (this assumption will be reviewed later in this study). Therefore, the total area of potential cumulative impact can be determined based on the extent of coastal and near-shore (<40 m depth) concession areas, as indicated in Clark *et al.* (1999). Thus the ***project area*** for this study is defined as ***the coastal and near-shore zone from the high-water mark extending seaward to a depth of 40 m, and extending from the Olifants River in the south to Spencer Bay in the north*** (locations: Figure 1.1). Limited mining has occurred further north (e.g. on the Skeleton Coast), but is not considered to be of a scale which would significantly affect the Benguela Current Large Marine Ecosystem.

1.3 PROJECT ASSUMPTIONS

The following assumptions (most of which were clarified in the project proposal) are applied in this project:

Discharge focus

As indicated by its title, this study assesses the effect of sediment “discharged” (e.g. in the form of tailings, dredger overspill and or seawall construction). This is definitely by far the largest influence in mobilising sediment in the near-shore zone shallower than 40 m, and is therefore the focus of this study. Other influences on mobilising sediment, such as disturbance of the sea-bed by anchors and mining tools, are considered to be secondary (and in any event are more prevalent in >40 m depth).

Sediment focus

Past experience has shown that the primary mechanisms of impact on biota are increased suspended sediment concentrations and potential smothering by deposited sediment, from mining activities. This study focuses on (1) confirming these impact mechanisms, and (2) conducting computational modelling directed at predicting these phenomena.

Lobster focus

As mentioned above, this study focuses on the prediction of the physical phenomena of sediment concentrations and deposition. While the impacts of these phenomena on all living marine resources will be considered, the effect on the West Coast rock lobster (*Jasus* *lalandi*), and specifically on the habitat of this species, will be given particular attention where possible.

Data

It was assumed that the project would have free access to all institutional and mining company data sets from the region that are required to set up, run, calibrate and verify various computer models required to address the project issues.

Project area

It is reiterated that the project area is based on the extent of mining concession areas, and thus extends from the Olifants River in the south to Spencer Bay in the north (and from the high-water mark to a depth of 40 m). It is assumed that impact from mining in this area will not extend more than a few kilometres beyond this defined area. This assumption is to be reviewed from available data and modelling results within this study.

1.4 PROJECT APPROACH

An approach is adopted whereby recent and existing monitoring programmes are drawn upon, in combination with the modelling of sediment inputs, transport, settlement, deposition and resuspension. Application of relevant data relating to diamond mining impacts (as well as model validation data) from recent and existing monitoring programmes will fulfil the objectives of this project in the most cost-effective manner. In addition, reference is made in this study to the results of the inception workshop held for both projects BEHP/CEA/03/02 and BEHP/CEA/03/03 and the associated report (Penney and Smith, 2004).

The overall project approach entails the following steps:

1. Identify mechanisms of impact resulting from mine sediment discharges and define the actual impacts resulting from these mechanisms, indicators of the impact mechanisms and, where possible, thresholds of these indicators above which impacts are likely to occur. This is achieved in Chapter 2.
2. Select sites at which to apply computational model studies of the suspension, transport and deposition of sediment. Provide descriptions of computational models applied in this study. This is achieved in Chapter 3.

3. Collate and prepare model input data for model set-up. Validate models against measurements, where possible, to ensure model integrity. This is provided in Chapter 4.
4. Compile an inventory of both mine and natural sediment inputs to the project area (and a description of their associated grain sizes). Relevant available data are reported in Chapter 5.
5. Employ the validated models to assess the suspension, transport and deposition of **fine** sediments (both naturally occurring input and input from diamond mining operations). From available information on the spatial distribution and configuration of near-shore reefs, assess the extent and duration of **fine** sediment deposition (both naturally occurring input and input from diamond mining operations) on these reefs. Results of these efforts are presented in Chapter 6.
6. Employ the validated models to assess the transport and deposition of **coarse** sediments (both naturally occurring input and input from diamond mining operations). From available information on the spatial distribution and configuration of near-shore reefs, assess the extent and duration of **coarse** sediment deposition (both naturally occurring input and input from diamond mining operations) on these reefs. Results of this work are presented in Chapter 7.
7. Assess areas of cumulative impact from the modelling studies (Chapter 8).
8. Test the sensitivity of model outputs (predictions of sediment concentrations/deposition) to model input data (sediment data, environmental data). This will allow an assessment of (1) which data are most relevant in the assessment of cumulative impacts of sediment inputs, and (2) the impact of gaps in the data. This information will aid in providing monitoring guidelines. Sensitivity and monitoring are discussed in Chapter 9.
9. By applying computational modelling, explore strategies to better manage tailings discharges in order to minimise effects on rock lobster resources (Chapter 10).
10. In Chapter 11 conclusions and recommendations are provided.

Separate fine sediment and coarse sediment assessment

As indicated above, the transport and fate of fine sediment and the transport and fate of coarse sediment (generally sand) in the near-shore region are assessed separately in this study, because of their different behaviour and associated approaches to modelling**. Fine sediment (silt or clay, which have grain sizes of less than 63 μm)** discharged into the near-beach zone is generally suspended in the water column for an extended period, and is transported considerable distances before being deposited on the sea-bed. **Coarse**

sediment (mostly sand, having a grain size range of 63 µm to 2000 µm, and limited gravel coarser than 2000 µm) discharged into the near-beach zone is generally transported by wave-driven currents, sometimes for long distances alongshore, but is mostly deposited within a few hundred metres from the shoreline.

Mine geographical references

In this study, reference is made to mine terminology in places. This is done in order that the mines can quickly relate to and confirm information relating to mine sediment inputs. In Mining Area 1 (extending from the Orange River to Chameis Bay some 100 km north), geographical mine coordinates extend from the Orange River northwards. From south to north, these are the "G" (Gemsbok), "U" (Uubvlei), "M" (Mittag), "K" (Kerbe Huk), "H" (represents Affenrucken) and "C" (Chameis) areas. Within each area, one unit corresponds to 100 m, and numbering is from south to north. Thus G75 is 7500 m from the southern end of the Gemsbok area. This information is generally supplemented with generic descriptions, e.g. distance relative to the Orange River, and should therefore not cause confusion.

Reference is also made to various numbered sites in the "Pocket Beach" mining area. Few of the mining sites are actually *pocket beaches* in the classical sense (defined as: "A beach, usually small, in a coastal re-entrant or between two littoral barriers (often rocky headlands)" – US Army Research and Development Centre website: http://chl.erdc.usace.army.mil). While the mine pocket beaches generally are sandy beaches with rocky outcrops at either end, these rocky outcrops do not always serve as "littoral barriers". It is likely that these beaches were pocket beaches at some former time, which resulted in their being defined as pocket beaches.

Capacity-building workshops

This study involved a project inception workshop, the results of which have been documented (Penney and Smith, 2004). In addition, a capacity-building workshop was conducted, involving Namibian and Angolan students (Details: Appendix O).

Depth Datum

All depths referred to or displayed in this report are relative to Mean Sea Level (MSL).

2. DEFINITION OF IMPACTS, INDICATORS AND THRESHOLDS

2.1 INTRODUCTION

In order to address the various questions posed in the "project objective and scope" (Section 1.2), particularly the question of cumulative effects of mine tailings, it is necessary to define the discharges, the effects of these discharges, and the associated potential impact mechanisms of the discharges. An example of an effect of a discharge may be the deposition of sediments on the sea-bed, while the associated potential impact mechanism would be smothering of benthic biota.

Following the definition of the potential impacts, appropriate indicators of impact that can be predicted with models or can be measured will be identified. An example of an indicator of sediment deposition would be the spatial distribution, thickness and duration (these parameters may be measured or predicted) of sediment deposited on the sea-bed. In addition, thresholds (of the indicators) need to be specified above which impacts are expected, in order to subsequently assess whether impacts occur or will occur. For example, an impact on biota may occur when a specific thickness of sediment deposits for a specific time. By assessing predicted or measured indicators against such thresholds, impacts (and ultimately cumulative impacts) of sediment discharges can be assessed.

2.2 TYPES OF MINING RESULTING IN SEDIMENT DISCHARGES

In assessing the various discharge effects, potential impact mechanisms, indicators and thresholds, the primary types of mining operation which result in significant sediment discharge are considered. These are as follows:

2.2.1 Coastal Mining

Coastal mining involves removal of overburden sediment or sand (from the land surface to as much as about 20 m deep in places) to access diamondiferous gravel. This overburden sediment removal is achieved by conventional means (e.g. excavators and trucks) or by means of dredging (in a coastal pond). Diamondiferous material is transported to screening plants, where material is separated based on size. "Undersize" material (generally finer than about 2 mm) is discharged onto the beach in Namibia. However, in South Africa this material is discharged into slimes dams.

Mining close to the beach (i.e. within less than 100 m from the shoreline) requires protection from wave action by means of massive sand seawalls (Figure 2.1). In Namibia these seawalls are typically constructed to some 4 m above beach crest height (i.e. to about 8 m above sea-level) and up to 20 m wide at their crests. At times these seawalls have been constructed seaward of the original shoreline, in order to reclaim mining terrain. Significant volumes of sand (several million cubic metres have been recorded in a period of a few years) erode from the seawalls. This sand is mechanically replenished as it erodes.

Since 1997 large-scale dredging has been employed in southern Namibia to remove overburden sand (Figure 2.2). Dredged material is deposited in the inter-tidal zone (Figure 2.3). This deposition may occur after screening out various size fractions of material. In general, dredging rates are high, the rate of discharge of tailings is rapid (in the order of several million cubic metres annually) and the total volume of tailings is large.

Land-based mining operations also result in the creation of mine dumps and slimes dams (in South Africa). Some of the sediment on these dumps/slimes dams may be mobilised by wind and transported into the sea.

2.2.2 Shore-based and boat-based divers

From available data, it appears that these relatively small-scale diving operations do result in sediment tailings deposition. However, the volumes of input are small – such that the effect of sediment deposition will probably be eliminated within weeks to months, apart from localised deposition of coarse material (e.g. cobbles). For example, in the Alexkor region 17 thousand cubic metres (roughly 31 thousand tons) of gravel was pumped from ship- and shore-based diving operations in a 17-year period up to 1993 (Zoutendyk, 1994). This amounts to about 0.05% of the volumes of material discharged in the region up to some 15 km north of the Orange River for the same period, i.e. about 65 million tons).

Effects not related directly to sediment deposition, such as the creation of boulder beds from “oversized” material, and land-based effects, are not addressed in this study.

2.2.3 Near-shore mining platforms

Mining companies are presently investigating the feasibility of mining the inter-tidal and near-shore zones by means of walking platforms. A prototype is presently being tested near Oranjemund. It is estimated that these platforms could result in considerable discharge of tailings sediment from the mining process into the near-shore zone in the future.

2.2.4 Offshore ship-based mining

Present mining operations in deep water involve the deployment of large-diameter drills combined with airlift pumps and the deployment of remote-controlled crawler vehicles. Material is processed on board these mining ships and tailings are discharged overboard.

2.2.5 Marine dredging

Namdeb Diamond Corporation has conducted a trial of the feasibility of mining diamonds from the sea-bed by means of a Trailer Suction Hopper Dredger. It is intended that this approach will ultimately be employed to remove overburden and mine the exposed diamondiferous gravels in areas which are both uneconomical for, and inaccessible to, the current offshore mining fleet. During the trial, sediment and mined gravel was discharged to land through a pipeline, which was established across the surf zone, to a safe depth of about 15 m. Sediment was stockpiled in a 'panel' which was previously mined to bedrock. From this location, gravels were transported by means of conventional earthmoving equipment to a nearby plant for treatment. Sediment tailings from this plant were discharged onto the beach.

The success of this trial project indicates that further trials and ultimately large-scale mining by means of this approach will occur.

2.3 MECHANISMS OF IMPACT

For each of the above-mentioned types of mining (apart from the small-scale operations), the source of sediment, the effects associated with this sediment source, and the resulting mechanisms of impact are detailed in Table 2.2 below (most of this information is derived from the inception workshop – Penney and Smith, 2004). Also listed are the indicators (physical parameters that could be measured or modelled that indicate the extent or severity of the impact mechanism) and the thresholds above which impact can be expected.

Most of the potential mechanisms of impact as listed in Table 2.2 are common to the different sources of sediment associated with the various types of mining. A discussion of these mechanisms, their associated indicators and thresholds of impact follows.

2.3.1 Beach and near-shore steepening

Discharge onto the beach of a large quantity of sand containing a component of coarse sediment can result in an increase in turbulent wave action in the swash zone, steepening of the beach profile and a corresponding increase in inter-tidal beach sediment grain size. This has been particularly evident from studies at Elizabeth Bay (CSIR, 1998c). Such physical changes induced by sand discharge at Elizabeth Bay has resulted in reductions in invertebrate species richness, abundance and biomass (McLachlan and De Ruyck, 1993; McLachlan *et al*.,1994). Clark (1998) indicates that benthic invertebrates are part of the diet of many surf fish species. A reduction in this benthic food supply may also negatively affect fish abundance and diversity (waders and coastal birds foraging in the swash zone may also be negatively affected). Furthermore, a steeper beach and near-shore profile resulting from sand deposition will also result in a narrower and more turbulent surf zone. A narrower surf zone implies a reduced surf zone habitat. The narrowed surf zone, together with increased turbulence, may be unsuitable for some fish species (Clark *et al.*, 1998).

The measurable indicator of beach steepening will simply be an increase in beach slope, obtained from surveyed profiles of the beach and near-shore area over time. Associated changes in surf zone width can also be calculated or measured. Associated increases in beach sediment size can be discerned from sampling and grain size analyses.

It should be possible to define thresholds related to these parameters (surf zone width, steepening, and grain size). A decrease in surf zone width (corresponding to increased turbulence) and beach steepening generally occur simultaneously to a grain size increase (resulting from a mine sand discharge). A rule of thumb is that most “non-crustaceans” do not survive conditions where the grain size exceeds 500 microns (associated with very turbulent swash wave action) (Ronel Nel, KZN Wildlife, pers. comm.).

2.3.2 Scouring/abrasion of reefs

An experiment investigating scouring in natural pools on the coast of Oregon, USA, indicated that this was due to “rocks and other debris” in suspension (van Tamelen, 1996). Abrasion of coral reefs can occur, e.g. by broken coral pieces (SAREC, 2000) being moved by wave action. Thus, it is evident that abrasion of reefs by rock/debris pieces is possible. However, abrasion by sediment of rocky reefs *per se* seems less clearly documented, as reflected by a dearth of literature. Intuitively, it is deemed unlikely that the abrasiveness of tiny sediment particles in suspension will be severe.

Although sand may not meaningfully abrade rock reefs *per se,* sand transported close to the bed (bedload) and over reefs could irritate and abrade certain organisms and deter them from living on the reef. A review by Pulfrich (2002) indicates that the abrasive action of suspended particles may result in the abrasion of algal thalli or mollusc shells. This abrasion effect could be induced or aggravated when additional sand originating from mine tailings is transported in high concentrations or as bedload across reefs by waves and currents.

An indicator of abrasion would be the measured or calculated near-bed sand transport across reefs. However, this near-bed transport is not easily calculated or measured very accurately. Therefore it may be difficult to distinguish the amount of additional sediment transport (and associated abrasion) occurring due to additional sediment from a mine discharge. Furthermore, no clear threshold of impact of scouring has been identified.

2.3.3 Deposition of sediments

Deposition of sediments can lead to smothering, which involves a reduction in light, nutrients and oxygen, and clogging of feeding apparatus (Eggleston, 1972), as well as affecting initial recruitment/choice of settlement site (Hiscock, 1983; Rodrýguez *et al.,* 1993) and post-settlement survival (Hunt and Shebling, 1997).

The measurable, predictable indicator of the severity of deposition is the thickness of deposited sediment, as well as the area and duration of the deposition. From a review of available information (Pisces, 2004) it appears that adult populations of both flora and fauna are highly adaptable to considerable burial by sediment on rocky reefs. Similarly benthic fauna dwelling on/in unconsolidated sediments are indicated to be adaptable to deposition (Steffani and Pulfrich, 2004). However, indications are that a layer/coating of sediment on rocky reefs may affect recruitment of both macrophytes and invertebrates, including rock lobster (Pisces, 2004). Therefore, it is expected that long-term deposition may impact on near-shore reef communities and also on rock lobster.

Some idea of impact thresholds of deposition thickness and duration can be obtained from a recent impact study on dredging-related sediment impacts (Pisces, 2005) in which sub-millimetre deposition which was relatively short in duration (hours to days at most) was reported to have an impact of neutral status (i.e. neither positive nor negative) and of low significance. This result is supported by the findings of Engledow and Bolton (1994), who find that the diversity of inter-tidal seaweeds in Namibia is strongly affected by sedimentation only when the level of deposition rises above 5.6 kg of sediment/m^2 (i.e. in the order of 3 mm of sand deposition on average). The same study on dredging-related impacts (Pisces, 2005) also reported sustained deposition (of several years to decades) of centimetres to metres thick on inter-tidal and sub-tidal reef habitats to have a negative impact of high significance. These reported results provide some indication of what extent of deposition is acceptable and what is not acceptable, and is used as a guideline threshold of impact in this study (Table 2.2). However, unambiguous guidelines for deposition are not at this stage available and informed biologists are required to provide direction.

A more extreme case of deposition is the construction of massive seawalls on the beach. This would generally involve sediment deposition in the order of metres thick in a matter of hours, which is likely to have a severe and sudden impact on beach fauna/flora.

2.3.4 Elevated sediment concentrations

Mine sediment discharges load the water with inorganic suspended particles that may affect the feeding and absorption efficiency of filter feeders (Pisces, 2004) and other suspension feeders. Reduced feeding efficiency owing to excess sediment may curb growth of some species. As growth rate is an important factor in determining competitive ability (Buss, 1986), this implies that elevated suspended sediment concentrations may affect the outcomes of competitive interactions. In addition, high concentrations of suspended sediment cause clogging of gills in fish (Pisces, 2004). This clogging can occur in lobster as well.

Turbidity of the water caused by the suspended sediment is another impact mechanism associated with high solids concentrations in suspension. Sediment suspension reduces light penetration, thus affecting primary production of phytoplankton and seaweeds (Pulfrich, 2002). Turbidity can affect avoidance responses, prey selection and capture efficiency, and feeding mode of marine animals (Appleby and Scarret, 1989). Turbidity can provide cover for fish (to avoid predators); however, the same turbidity may reduce the availability of food for these fish, due to inhibited primary production.

Acceptable suspended solids concentration limits, as provided by international guidelines, appear to be relatively stringent (when compared to measured mine-induced suspended solids concentrations typical of the BCLME). For example, the South African guidelines (RSA DWAF, 1995) indicate that suspended solids should not be increased by more than 10% of ambient concentrations. Australia/New Zealand guidelines recommend employing the 80th percentile (minimum 10 observations) of the background levels for establishing a maximum concentration threshold (ANZECC and ARMCANZ (1999). Canadian guidelines (CCME, 2002) indicate an increase of 25 mg/l relative to background levels to be an acceptable limit for short-term exposure (e.g. 24 hours), and an increase of only 5 mg/l above background to be acceptable for long-term exposure. Guideline limits from these sources are similarly stringent for turbidity.

As will be made clear from both measurement and modelling results (Chapter 6), both mine sediment inputs and floods cause concentrations which frequently exceed these international suspended solids concentration guidelines. Recognising the risk associated with exceedance of international guidelines, reference is made to international literature in order to assess the resilience of various marine species to suspended sediment concentrations. In Table 2.1 key findings are summarised. It is evident that some impacts occur for suspended solids concentrations in the order of 20 mg/l and more, but that only concentrations over 100 mg/l cause significant effects in the form of appreciable mortality or adverse effects on fish and bivalves. It is highlighted that the duration of exposure (in addition to the concentration) is also important when assessing impacts (Newcombe and MacKonald, 1991; Newcombe and Jensen, 1996). Data on fish (incorporating adults, eggs and larvae) suggest that elevated concentrations lasting for roughly one day would be lethal to some marine species. Fortunately fish are able to move away rapidly from relatively limited suspended sediment plumes. Data on bivalve larvae and adults (Embecon, 2004) indicate that elevated concentrations (over 100 mg/l) for more than some 5 days would be lethal to some species.

Table 2.1: Effects of suspended solids on marine fauna

Suspended Sediment Concentrations mg/l	Effect	Reference
5	Increased filtering in mussel *Mytilus edulis*.	Kiørboe *et al.* (1981)
6-25	Increased food absorption efficiency in bivalves	Robinson *et al.* (1984)
8	Maximum recommended concentrations for oysters *Crassostrea gigas*.	Brown and Hartwick (1988)
13,5 – 35,5	Avoidance thresholds for juvenile herring. Linked to reduced light cues.	Wildish *et al.* (1977)
20	Food-sorting ability in oyster *Crassostrea virginica*	Urban and Kirchman (1992)

Suspended Sediment Concentrations mg/l	Effect	Reference
	deteriorates.	
20	Decreased growth of the mussel *Mytilus edulis* over 20 days. Reduced respiration in the clam *Mya arenaria* after 1.5 hour exposure.	Kiørboe *et al*. (1981) Grant and Thorpe (1991)
100	Bivalve filtering rates reduced. Upper limit for oyster *C. gigas*.	Moore (1978) Brown and Hartwick (1988)
100	Delayed egg hatching for the freshwater spawners, striped bass (*Morone saxatilis*) and white perch (*M. americanus*) for 24 h exposure	Clarke and Wilber (2000)
100	Increase amount of food rejected as pseudofaeces by the surf clam, *Spisula solidissima.*	Robinson *et al*. (1984).
100	Decline in clearance rate by the clam *Ruditapes decussates.*	Sobral and Widdows (2000)
100	Depleted nutritional state and reduced growth in the clam *Mercenaria mercenaria* for a 2 week exposure.	Grant and Thorpe (1991)
100 - 119	Induced pseudofaeces production in *M. arenaria* over 2 hours.	Grant and Thorpe (1991)
188	Decrease in normal development of *C. virginica* eggs.	Davis and Hidu (1969)
250	Egg development in *C. virginica* retarded.	Loosanoff (1961)
250	Upper threshold of normal development in clam *Spisula* sp. Larvae.	Davis (1960)
250	Egg production in estuarine planktonic copepod *Acartia tonsa* reduced by 40% at low food concentrations.	White and Dagg (1989)
500	90% mortality in clam *Spisula* sp larvae.	Davis (1960)
500	No effect on fish egg hatching but reduced larval survival in estuarine fish.	Auld and Schubel (1978)
500	Induced mortality in 4 species of fish larvae for 2 – 4 day exposures.	Auld and Schubel (1978)
500	Results in 10% mortality in *C. virginica* after 12 day exposure.	Davis and Hidu (1969)
580	24 hour LC10* for Atlantic Silverside *Menidia menidia* (estuarine fish).	Appleby and Scaratt (1989)
650	Elevated hemacrit levels in white perch *M. americanus.*	Sherk *et al*. (1974), cited in Clarke and Wilber (2000)
750	Oyster *C. virginica* larvae growth reduced.	Loosanoff (1961)
750	Clam (*M. mercenaria)* and oyster (*C. virginica*) egg development impaired.	Davis (1960)
1000	Upper limit for highly sensitive fish species (e.g. pelagics) and fish larvae.	O'Connor *et al.* (1976)

Suspended Sediment Concentrations mg/l	Effect	Reference
1000	Reduced egg production in estuarine planktonic copepod *A. tonsa* in high food concentrations.	White and Dagg (1989)
1000	Upper limit of acclimation in surf clam *Spisula solidissima*.	Robinson *et al.* (1984)
1000	Upper limit for acclimatisation to SS by the surf clam *S. solidissima.* Concentration of natural silt that affects normal development of *M. mercenaria* larvae.	Davis (1960)
1500	Growth of *M. mercenaria* larvae retarded (natural silt).	Davis (1960)
2000	Causes 10% larval mortality in *M. mercenaria.*	Davis and Hidu (1969)
3000	Caused 100% larval mortality in *C. virginica* larvae.	Davis and Hidu (1969)
4000	Induced 70% larval mortality in *M. mercenaria* and 10% mortality in *Ostrea edulis* over about a week.	Davis and Hidu (1969)
1000 – 10 000	24 hour LC10 for sensitive fish species, e.g. Bay anchovy *Anchoa mitchilli.*	O'Connor *et al.* (1976)
9850	24 hour LC50 for White perch *M. americanus* in natural resuspended harbour sediments	O'Connor *et al.* (1976)
10 000	Natural turbidity associated with storms in Louisiana coastal waters.	White and Dagg (1989)
>10 000	24 hour LC10 for tolerant fish species.	O'Connor *et al*. (1976)
96 000	200 hour LC50 for mussel *Mytilus californianus.*	Peddicord *et al.* (1975)
100 000	120 hour LC10 for mussel *M. edulis*	Peddicord *et al.* (1975)
117 000	240 hour LC80 in English sole *Perophyrus vetulus*	Peddicord *et al.* (1975)
175 000	Causes appreciable mortality in many species of fish.	Pillay (1992)

***LC10 = Lethal concentration for 10% of the species**

Based on the information above, it is proposed that a concentration of 100 mg/l persisting for "more than a few hours to days" is a reasonable threshold above which adverse impacts would be expected. This semi-quantitative threshold of impact (indicated in Table 2.2) will be employed *in lieu of* more data/information. Previous studies on the Southern African coast have employed a concentration threshold of 100 mg/l as an acceptable limit for filter-feeding organisms. In a dredging impact study, Pisces (2005) reported concentrations over 100 mg/l to be acceptable to marine biota for short periods and occurring over limited areas. Studies at Elizabeth Bay also employed the 100 mg/l impact limit (CSIR, 1998c; CSIR, 2002). Studies in an environment where aquaculture is practised employed a higher acceptable threshold of 150 mg/l (CSIR, 1998d).

As highlighted in BCLME project BEHP/LBMP/03/04 (Taljaard, 2006): "where scientific assessment studies or monitoring results reveal that recommended quality guideline values are exceeded, this should trigger the incorporation of additional information or further investigation to determine whether or not a real risk to the ecosystem exists…". Measurements of background suspended solids concentrations have been limited in scope to date. Comprehensive measurements would be required which must cover both seasonal effects and event-scale effects (Taljaard, 2006) in order to derive guideline values (thresholds of impact). In particular, the effect of floods and offshore bergwind events which supply sediment to the near-shore must be recorded. Monthly measurements should cover a period of over two years. Modelling may be used to assess the effect of events. Site-specific assessments of impacts on marine biota are even more valuable. Such studies on the effects of mine tailings on rock lobster in mining areas in Namibia are in progress.

2.3.5 Oxygen depletion

Crushed organisms returned to the sea in the overspill from dredging operations may cause organic enrichment (Newell *et al.*, 1998). For benthos in the near-shore area, the introduction of organic material could have negative effects. Coastal upwelling regions (such as occurs north of the Orange River and Lüderitz upwelling areas) are frequently exposed to hypoxic conditions (<0.5 ml/l of O_2) owing to extremely high primary production and subsequent oxidative degeneration of organic matter (recent surveys in the Chameis Bay and Kerbe Huk areas seem to confirm hypoxic conditions - measured oxygen concentrations as low as 0.1 ml/l of O_2 in water depths of 25 m appear to persist for long periods - Pulfrich, pers. comm.). A further increase in organic matter with associated bacterial decomposition in bottom waters, which are already oxygen-depleted, is considered deleterious (Herrmann *et al.*, 1999). Thus, a potential impact from dredging operations is identified. However, it is suggested that this potential impact would be insignificant for two reasons:

1. Aggravation of oxygen-depleted conditions would require long-term deposition of such organic mined/dredged matter on the sea-bed (i.e. long enough to allow bacterial decomposition). Wave-dominated conditions in the <40 m depth zone are considered too active to allow such long-term deposition.

2. The scale of oxygen depletion from mining effects is probably insignificant compared to natural effects. Spatial and temporal variability in oxygen-depleted waters follow primary productivity over the Benguela continental shelf and lead to the occurrence of

large-scale low-oxygen water conditions over shelf regions. In the inshore regions of the Benguela system, primary productivity is driven by upwelling of deep nutrient-rich waters onto shelf areas (Bailey, 1991). Upwelling is driven by longshore winds, the shape of the coastline, shelf characteristics and the earth's Coriolis Effect. The mining region on the West Coast contains two upwelling cells; one at Luderitz, which shows perennial characteristics, and the seasonal Hondeklip Bay upwelling cell, which is most intense in summer months when south-easterly winds prevail. Deposition of organic matter downstream (northward) of upwelling cells maintains low-oxygen water conditions over shelf sediments (Bailey, 1991). Compared to this major mechanism for low-oxygen water generation, the potential generation and/or resuspension of organic material as a result of mining operations is considered minimal.

Table 2.2(a): Coastal Mining sediment discharge/seawall construction: Sources of sediment, effects of the sediment discharge, associated mechanisms of impact, the associated indicators of these mechanisms, and thresholds of these indicators above which impacts occur.

Source of sediment	Effect	Possible mechanism/s of impact	Associated indicator/s	Threshold of impact
Discharge of mine tailings into the sea or inter-tidal zone or sediment input to the sea from seawall erosion.	Steepening of the beach and near-shore profile (which is associated with an increase in grain size).	Reduction in invertebrate richness, abundance, biomass, from changed environment. Consequent reduction in food supply for fish. Reduction in surf zone width (and nursery habitat) Increased turbulence unsuitable for some fish.	Beach and near-shore slope (and associated hydrodynamics). Grain size distribution.	Non-crustaceans don't survive when grain size increases to >500 micron (rule of thumb). For impacts on fish, no clear thresholds have been developed.
	Scouring of reefs (abrasion by sand near-bed).	Abrasion and irritation of flora/fauna on the reef.	Local sand transport rate.	Not well defined.
	Deposition of discharged sediments on reef or sea-bed.	Smothering of fauna/flora and associated reduction in light, nutrients and oxygen: clogging of feeding apparatus; reduction in initial recruitment/choice of settlement and post-settlement survival.	Thickness, area and duration of sediment deposition.	Sub-millimetre sediment deposition lasting hours to days = low, neutral impact. Sediment deposition centimetres to metres, lasting years to decades = high impact.

Source of sediment	Effect	Possible mechanism/s of impact	Associated indicator/s	Threshold of impact
	High fine sediment concentrations in suspension	Reduced feeding and associated knock-on effects. Clogging gills of fish/lobster. Reduction in light penetration – resulting in reduced growth of flora, kelp.	Concentration of sediment in suspension (and associated duration).	100 mg/l, for more than a few hours to days.
Construction of seawalls on the beach.	Instantaneous smothering of coastal habitat as sand is deposited.	Smothering of coastal total destruction of any vegetation and inter-tidal/beach fauna (including associated effects on seabirds) and possible effects on archaeology.	Location, dimensions of seawalls.	Seawalls are high and large by definition: smothering would be comprehensive at the site where seawall is placed.
Increased wind-blown sediment into the sea from tailings dumps/slimes dams.	Scouring of reefs (abrasion by sand near-bed).	Abrasion and irritation of flora/fauna on the reef.	Local sand transport rate.	Not well defined.
	Deposition of discharged sediments on reef or sea-bed.	Smothering of fauna/flora and associated reduction in light, nutrients and oxygen: clogging of feeding apparatus; reduction in initial recruitment/choice of settlement and post-settlement survival.	Thickness, area and duration of sediment deposition.	Sub-millimetre sediment deposition lasting hours to days = low, neutral impact Sediment deposition centimetres to metres, lasting years to decades = high impact.

Source of sediment	Effect	Possible mechanism/s of impact	Associated indicator/s	Threshold of impact
	High fine sediment concentrations in suspension.	Reduced feeding and associated knock-on effects. Clogging gills of fish/lobster. Reduction in light penetration – resulting in reduced growth of flora, kelp.	Concentration of sediment in suspension (and associated duration).	100 mg/l, for more than a few hours to days.

Table 2.2(b): Near-shore mining platforms: Sources of sediment, effects of the sediment discharge, associated mechanisms of impact, the associated indicators of these mechanisms, and thresholds of these indicators above which impacts occur.

Source of sediment	Effect	Mechanism of impact	Associated indicator	Threshold of impact
Discharge of mine tailings into the sea or inter-tidal zone.	Scouring of reefs (abrasion by sand near-bed).	Abrasion and irritation of flora/fauna on the reef.	Local sand transport rate.	Not well defined.
	Deposition of discharged sediments on reef or sea-bed.	Smothering of fauna/flora and associated reduction in light, nutrients and oxygen: clogging of feeding apparatus; reduction in initial recruitment/choice of settlement and post-settlement survival.	Thickness, area and duration of sediment deposition.	Sub-millimetre sediment deposition lasting hours to days = low, neutral impact. Sediment deposition centimetres to metres, lasting years to decades = high impact.
	High fine sediment concentrations in suspension.	Reduced feeding and associated knock-on effects. Clogging gills of fish/lobster. Reduction in light penetration – resulting in reduced growth of flora, kelp.	Concentration of sediment in suspension (and associated duration).	100 mg/l, for more than a few hours to days.

Table 2.2(c): Offshore ship-based mining: Sources of sediment, effects of the sediment discharge, associated mechanisms of impact, the associated indicators of these mechanisms, and thresholds of these indicators above which impacts occur.

Source of sediment	Effect	Mechanism of impact	Associated indicator	Threshold of impact
Discharge of mine tailings into the sea.	Scouring of reefs (abrasion by sand near-bed).	Abrasion and irritation of flora/fauna on the reef	Local sand transport rate.	Not well defined.
	Deposition of discharged sediments on reef or sea-bed.	Smothering of fauna/flora and associated reduction in light, nutrients and oxygen: clogging of feeding apparatus; reduction in initial recruitment/choice of settlement and post-settlement survival.	Thickness, area and duration of sediment deposition.	Sub-millimetre sediment deposition lasting hours to days = low, neutral impact. Sediment deposition centimetres to metres, lasting years to decades = high impact.
	High fine sediment concentrations in suspension.	Reduced feeding and associated knock-on effects. Clogging gills of fish/lobster. Reduction in light penetration – resulting in reduced growth of flora, kelp.	Concentration of sediment in suspension (and associated duration).	100 mg/l, for more than a few hours to days.

Table 2.2(d): Marine dredging: Sources of sediment, effects of the sediment discharge, associated mechanisms of impact, the associated indicators of these mechanisms, and thresholds of these indicators above which impacts occur.

Issue of concern	Effect	Mechanism of impact	Associated indicator	Threshold of impact
Dredger overspill of fines	Scouring of reefs (abrasion by sand near-bed).	Abrasion and irritation of flora/fauna on the reef.	Local sand transport rate.	Not well defined.
	Deposition of discharged sediments on reef or sea-bed.	Smothering of fauna/flora & associated reduction in light, nutrients and oxygen: clogging of feeding apparatus; reduction in initial recruitment/choice of settlement and post-settlement survival.	Thickness, area and duration of sediment deposition.	Sub-millimetre sediment deposition lasting hours to days = low, neutral impact. Sediment deposition centimetres to metres, lasting years to decades = high impact.
	High fine sediment concentrations in suspension.	Reduced feeding and associated knock-on effects. Clogging gills of fish/lobster. Reduction in light penetration – resulting in reduced growth of flora, kelp.	Concentration of sediment in suspension (and associated duration).	100 mg/l, for more than a few hours to days.

The indicators (of the severity of impact mechanisms, e.g. suspended particulate concentration) listed in the above tables can be measured or predicted by means of models of coastal processes. Once thresholds of these indicators have been defined above which impact to biota would occur (e.g., say, sediment concentrations above 100 mg/l for a period of a week) then impacts and cumulative impacts on biota can be assessed. The definition of thresholds may be continually improved as information becomes available.

3. DEMONSTRATION AREA SELECTION AND MODEL DESCRIPTION

3.1 INTRODUCTION

Having defined various indicators of impact mechanisms, measurements and predictions of these indicators are required. These measured and predicted indicators can be compared to impact thresholds (where available) to determine where and when impact occurs. However, the capability and capacity do not exist to measure and/or model coastal areas of the entire project area for this study. Therefore a number of modelling sites (or "demonstration areas") representative of conditions in the BCLME were selected. A description of the selection process follows. Thereafter, a description of the computational models employed is provided.

3.2 DEMONSTRATION AREA SELECTION

3.2.1 Criteria for selection

Within the project area extending approximately from the Olifants River to Spencer Bay just north of Lüderitz (Figure 1.1), the criteria which were considered for selection are as follows:

3.2.1.1 Data and model availability

Key criteria in selection of demonstration areas are the availability of data (for validation of models and for impact assessment) and the existence of validated sediment transport models. Drawing on existing data and model resources enables a more comprehensive assessment of cumulative impacts within the budget of this project. This could be achieved because effort is invested in running existing models and analysing existing data to assess impacts, rather than spending effort on setting up new models and collecting data for validation of these models.

3.2.1.2 Wind and wave climate

Wind and waves are primarily responsible for the transport and dispersion of discharged sediments in the near-shore region. Therefore it is important to take account of representative regimes of these environmental forcing parameters in the project area in selecting demonstration areas. Comparisons of wave data from VOS (Voluntary Observing

Ships) (Table 3.1) indicated subtle variations from south to north. The data indicated that the region north of the Olifants River (see Figure 1.1) from 30 to 32 degrees latitude experiences slightly higher waves, but from the same direction as those further north at 30 to 28 degrees latitude (i.e. the region approximately offshore of Port Nolloth and Oranjemund – Figure 1.1). However, an increase in extreme wave heights (i.e. for waves occurring 1% and 5% of the time) and a more southerly wave direction offshore was indicated between Oranjemund and the Elizabeth Bay/Lüderitz area (Latitude 28 to 26 degrees), from observed data (CSIR, 2000).

Table 3.1: Annual percentage exceedance of wave height, from VOS (Voluntary Observing Ships) data

Area	Latitude (degrees)	Percentage exceedance of wave height				Dominant wave direction
		50	10	5	1	
North of Olifants River	30 to 32	2.5	4.2	4.8	6.3	South to south-south-west
Offshore Port Nolloth and Oranjemund	28 to 30	2.2	3.8	4.3	5.4	South to south-south-west
North of Oranjemund to Elizabeth Bay/ Lüderitz	26 to 28	2.2	4.0	4.5	6.1	South

While wave data manifested relatively subtle differences between the various regions, coastal wind data indicated a more marked difference. Table 3.2 derived from measured data (CSIR, 2000) shows that wind speeds are similar at Kleinzee and Oranjemund. However, wind speeds are significantly higher at Elizabeth Bay. Subtle changes in dominant wind direction are also evident.

This trend of increased wind speed in the region of Elizabeth Bay is also evident in wind data derived from a global atmospheric numerical model operated by the National Centre for Environmental Prediction (NCEP) in the USA. Model data just south of Port Nolloth were found to have significantly lower wind speeds (winds under 4 m/s occur 7% less, winds under 8 m/s occur 14% less) than winds about 70 km south of Elizabeth Bay. Subtle changes in dominant wind direction were also evident from these global atmospheric numerical model data (CSIR, 2002a).

Table 3.2: Annual percentage exceedance wind speeds from measurements at Kleinzee, Oranjemund and Elizabeth Bay (CSIR, 2000).

Location	Percentage exceedance of wind speed				Dominant wind
	50	10	5	1	
Kleinzee	4.8	9.9	11.3	13.5	South to south-south-west
Oranjemund	4.6	8.8	10.3	13.2	South-south-east
Elizabeth Bay	8.0	13.6	15.2	17.7	South

The significant differences in wind speed regime will have a large impact on the transport of fine sediment in suspension, as these winds drive near-shore currents (sensitivity to wind speed is confirmed in Section 9). Coastal aeolian transport of sand is also dependent on wind speed. Therefore it is important, in selection of demonstration areas, that both the very strong winds of the northern area (towards Elizabeth Bay/Lüderitz) and the relatively weaker winds of the southern area (Mining Area 1 near Oranjemund, and further south) are represented.

3.2.1.3 Coastline configuration

The local configuration of the coast plays a role in how discharged sediments are distributed. For example, discharged sand tends to accumulate in bays, while on open linear coasts sand is distributed alongshore by wave-driven currents for tens of kilometres. The distribution of fine sediment is also affected by the configuration of the coastline, as this affects near-shore tidal- and wind-driven flows. Ideally, demonstration areas selected should be representative of the various coastal geomorphological types/coastal configuration on the diamond mining coastline, i.e.:

- Open, linear sandy shores (e.g. as near Oranjemund);
- Rocky coast incorporating bays (e.g. Alexander Bay, Elizabeth Bay region);
- A combination of beaches and rocky shores, e.g. Chameis Bay and the region to the north (the “Pocket Beach” mine area).

3.2.1.4 Types of mining and natural sediment input

It was deemed important that the demonstration areas selected should represent all of the different types of large-scale mining, i.e.:

- Coastal mining;
- Near-shore mining platforms;

- Offshore ship-based mining;
- Marine dredging.

In order to facilitate comparison of mine-generated sediments with natural sediment inputs, areas of significant natural sediment input should also be considered, e.g. the Orange River.

3.2.1.5 Lobster interaction

As this project is focused on the impact of sediment discharges on the West Coast rock lobster (*Jasus lalandi*), the focus should be on areas where known sediment inputs (present and future) can overlap with commercial rock lobster resources, and where sub-tidal and inter-tidal reef areas and kelp beds occur.

The commercial rock lobster fishery in Namibia is centred on Lüderitz. The fishing area ranges from Kerbe Huk, 60 km north of the Orange River, to Sylvia Hill, 130 km north of Lüderitz (Figure 3.1). Thus the fishing area extends beyond the northern boundary of the project area. The commercial fishing season is from November to April. At present the Namibian rock lobster fleet consists of ~25 vessels (D. Bester, MFMR, pers. comm.).

Fishing is conducted with traps set in 10-40 m depth from wooden deck boats. Traps are usually set in the late afternoon and allowed to soak overnight before being retrieved the following morning. The deck boats may carry a fleet of small dinghies that may be deployed in shallow water under calm conditions (Barkai and Bergh, 1996). It is thus primarily an inshore fishery, although rock lobsters have been caught by traps and bottom trawl in deeper water.

Kerbe Huk is the most important fishing ground south of Lüderitz, although the areas around Plumpudding Island and Chameis Bay (Figure 3.1) are also occasionally targeted. Of the total rock lobster fleet of ~25 vessels, between 10 and 15 large boats (20 m in length; D. Bester, MFMR, pers. comm.) may fish in the Kerbe Huk area during the commercial season. This is a region where coastal sediment input (present and future) may interact with commercial rock lobster resources.

Although the commercial fishing season opens in early November, during the first two months of the season fishing is restricted to the southern lobster grounds. Rock lobster fishing south of Lüderitz is thus primarily limited to a relatively short period of time. Only in years when fishers struggle to fill their quotas will they continue fishing on the southern grounds, particularly in the Kerbe Huk area, into January or February. Exceptions to this annual fishing pattern do, however, occur. For example, during the 2003/2004 season most of the quota was fished in the Kerbe Huk area, with the season in the south being extended to May due to poor catches from the grounds north of Lüderitz.

Despite the extended distance from Lüderitz and steadily declining catches from the region, these southern fishing grounds remain important to the commercial industry. Lobsters caught in the south are on average larger than those from the northern fishing areas, and consequently the live product has a higher value.

The northern lobster areas which overlap with the mining areas have reduced stocks and low quotas compared with the major fishing areas further south.

In South Africa the extent of rock lobster fishing is considerable. Commercial catches of rock lobster in the area around Port Nolloth and Hondeklip Bay are confined to shallower water (<30 m), with almost all the catch being taken in <15 m depth. Lobster fishing is conducted with hoop nets from a fleet of small dinghies/bakkies. The majority of these work directly from the shore within a few nautical miles of the harbours, with only 30% of the total numbers of bakkies participating in the fishery being deployed from larger deck boats. These larger boats may occasionally set rock lobster traps out to 50 m depth. As a result, lobster fishing tends to be concentrated close to the shore within a few nautical miles of Port Nolloth and Hondeklip Bay. The lobster industry is an important source of income for West Coast fishermen.

3.2.2 Selected demonstration areas

The demonstration areas selected for this project were as follows:

- The Orange River mouth area;
- Mining Area 1 (Extending from the Orange River mouth to 100 km north);
- Chameis Bay region;
- Bogenfels region;
- Elizabeth Bay.

These sites are indicated in Figure 1.1. Table 3.3 provides a brief assessment of the degree to which the criteria discussed above were met. From this assessment it can be seen that the selected sites generally satisfy the specified criteria and represent a wide range of conditions representative of the diamond mining area of the BCLME. A shortcoming of the selected sites is limited representation in South Africa (apart from at the international boundary). This exclusion is primarily the result of limited available data on South African mine sediment inputs. This omission was not deemed to be severe, since mine sediment input to the marine environment in South Africa is limited. South African coastal mining operations discard fine sediment tailings (i.e. the largest component of coastal mining sediment input) in slimes dams, rather than directly into the sea. Sediment input to the project area in South Africa primarily takes the form of eroded sand from seawalls constructed on the shore or in the surf. However, this seawall sediment input occurs on a minor scale when compared to seawall mining in Namibia.

3.3 DESCRIPTION OF MODELS

At each of the selected demonstration areas a suite of computational models was set up and validated in order to address the objectives of this project. A description of the models employed follows.

3.3.1 Wave modelling

Prediction of the transformation of waves from offshore to the beach was required, as the near-shore waves play a significant role in the transport and dispersion of discharged material (both fine and coarse sediment).

3.3.1.1 Processes to be modelled

The following processes had to be accounted for to transform the deepwater wave conditions to the local wave conditions at the various demonstration areas:

- Wave refraction due to bathymetry;
- Depth-induced wave breaking;
- Depth-induced wave shoaling;
- The effect of sea-bed friction on wave propagation.

3.3.1.2 Description of wave model

The third-generation wave generation and refraction model SWAN (Simulating Waves Near-shore) was applied (Booij *et al.*, 1999). SWAN was run within the Delft3D-WAVE environment (WL|Delft Hydraulics, 2000), which provides a convenient interface for pre- and post-processing, and for including wave-current interactions by linking the current field on the hydrodynamic grid to the wave grid.

The SWAN model is based on the discrete spectral action balance equation and is fully spectral (in all directions and frequency), implying that short-crested random wave fields propagating simultaneously from widely different sources can be accommodated, e.g. a swell with superimposed wind sea. SWAN computes the evolution of random, short-crested waves in coastal regions with deep, intermediate and shallow water, and with ambient currents.

The SWAN model accounts for refractive propagation due to currents and affected by water depth and represents the processes of wave generation by wind, dissipation by white-capping, bottom friction and depth-limited wave breaking and non-linear wave-wave interactions (quadruplets and triads) explicitly. Wave blocking by currents is also explicitly represented in the model.

Table 3.3: Assessment of demonstration area criteria

Demonstration Area	Data available?	Model/s available?	Wind + wave regime		Coastline configuration			Type of mining				Interaction with lobster?
			Southern (Oranjemund and south)	Northern (Lüderitz area)	Open sandy	Rocky	Combination	Coastal	Near-shore platforms	Offshore vessel	Marine dredging	
Orange River	√		√		√			√	√			√[1]
Mining Area 1	√	√	√		√			√	√			√[1]
Chameis Bay	√	√	In between				√				√	√[2]
Bogenfels	√	√	In between				√	√				√[3]
Elizabeth Bay	√	√		√		√		√		√		√[2]

[1] At both these sites, interaction of deposited sediment with lobster fishing at Kerbe Huk is possible.

[2] Although only identified as “seldom fished areas” (Figure 3.1), these areas do have rocky reef and kelp bed environments which could be important for lobster breeding.

[3] Although not identified as a lobster fishing area at all (Figure 3.1), this area has rocky reef and kelp bed environments which could be relevant for lobster breeding.

3.3.2 Hydrodynamic modelling

Prediction of flows resulting from winds, waves and (in some instances) tides is important. These flows were needed to predict the transport and dispersion of fine sediment discharged by mines.

3.3.2.1 Processes to be modelled

Tides

Although tides on the West Coast have a low tidal phase lag and therefore do not generate strong tidal currents along open shorelines, some tidal currents are likely to be experienced within semi-enclosed bays. At sites where tidal currents are considered relevant to predictions of sediment transport and dispersion, tides were included in the modelling by means of water-level variations applied to the model boundaries.

Winds

The effect of winds is clearly discernable in measured currents on the West Coast. The effect of wind was therefore included in the hydrodynamic models. Wind set-up and Coriolis tilt effects on the water levels at the model boundaries were also taken into account.

Waves

Waves are the dominant forcing mechanism for currents in the surf zone. In addition wave action causes bed shear stresses (which in turn tend to re-suspend fine sediment) in depths of up to 50 m. Both of these processes are included in the hydrodynamic simulations by means of the coupling to the wave simulations as achieved with the SWAN model.

Salinity and temperature

Salinity and temperature were modelled where considered necessary, i.e. where thermocline dynamics should be explicitly included in the simulations.

3.3.2.2 Description of model

The modelling of the hydrodynamics was undertaken using the DELFT3D-FLOW model (WL|Delft Hydraulics, 1999a).

The hydrodynamic model, which solves the time-dependent shallow-water equations in two or three dimensions, is designed to simulate tidally-driven and wind-driven flows in shallow seas, coastal areas, estuaries, rivers and lakes.

The model includes formulations and equations that take into account:

- tidal forcing;
- wind shear stress on the water surface;
- wave-driven flows;
- the effect of the earth's rotation (Coriolis force);
- free surface gradients (barotropic effects);
- bed shear stress at the seabed;
- drying and flooding on tidal flats;
- turbulence-induced mass and momentum fluxes (k-ε turbulence closure model).

The wave forcing is obtained from the radiation stresses and volume fluxes computed by the wave refraction model. Enhanced bed stresses due to wave effects were incorporated in the model using the friction formulation of Fredsøe (1984).

The system of equations in Delft3D-FLOW includes the horizontal momentum equations and the continuity equation, the equation of state and the advection-diffusion equation for heat, salt and other conservative tracers which are solved using the Alternating Direct Implicit scheme. The computation grid employed was an irregularly spaced, orthogonal, curvilinear grid in the horizontal and a sigma coordinate grid in the vertical.

The model equations and their numerical implementation are described in detail in the DELFT3D-FLOW user manual (WL|Delft Hydraulics, 1999a); simplified versions are provided in Appendix A.

3.3.3 Fine sediment behaviour modelling

3.3.3.1 Processes to be modelled

The focus in this section is on the fate of the fine sediment fraction (< 63 µm), which will tend to stay in suspension in the water column and can thus potentially be distributed over a large area by the waves and currents. The coarser sand fraction (> 63 µm) will tend to remain on and near the beach; the effect of this was modelled using a shoreline model in combination with empirical theories.

After discharge into the surf zone and/or the near-shore area, the fate of the fine sediments is determined by the following processes:

- Advection due to currents;
- Dispersion due to turbulence in both the horizontal and vertical directions;
- Settling of the particles towards the sea-bed;
- Deposition onto the sea-bed when the bed shear stresses are sufficiently low;
- Resuspension from the sea-bed when the bed shear stresses increase.

3.3.3.2 Model description

The DELFT3D-WAQ sediment transport model (WL|Delft Hydraulics, 1999b) was used to model the advection-dispersion-settling-deposition-resuspension behaviour of the fine sediment particles discharged from mining operations. This model solves the advection-diffusion equation, and includes source and sink terms representing deposition and resuspension. The model equations are provided in Appendix B.

3.3.4 Shoreline Evolution

The primary effect of coarse sediment/sand discharged on the shoreline is accretion of the beach (and near-beach region) both at the discharge position and, through rapid lateral transport of material, along the beach on either side of the discharge position. In order to predict deposition of coarse material, as manifested by the consequent accretion of the shoreline in response to such discharges, a shoreline model was employed.

3.3.4.1 Processes to be modelled

The following primary processes were represented in the model:

- Wave refraction due to bathymetry;
- Depth-induced wave breaking;
- Depth-induced wave shoaling;
- Longshore currents generated as a result of wave breaking oblique to the shoreline;
- Longshore sediment transport induced by wave breaking and longshore currents;
- Shoreline evolution as a result of sediment discharges and alongshore variations in longshore sediment transport.

3.3.4.2 Model description

To simulate the evolution of the shoreline, the UNIBEST CL+6.00 computational model (WL|Delft Hydraulics, 1999c) was used. The model consists of two modules. The first module transforms offshore wave conditions to the coast (employing linear refraction) and computes wave-induced longshore current and consequent sediment transport. The second module simulates the changes in the coastline in response to the longshore sediment transport gradient along the coastline. This transport gradient is the result of variations in the wave-driven transport, which are a function of the local shoreline orientation. This second module allows for structures (e.g. headlands) and sediment sources (e.g. undersize sediment discharges) or sinks to be incorporated.

In shoreline modelling, it is assumed that the entire near-shore profile (from the high-water mark to a depth of 12 to 16 m) moves laterally (with the extent of movement being equivalent to the shoreline movement) during accretion or erosion. This is generally true on a time scale of months to years, but may not be representative of short-term changes (e.g. the short-term exchange of sediment between the top and bottom of the profile). Thus, the shoreline model is generally applicable to assess general trends on a time-scale of months to years. For shorter time-scale variations, reliance is placed on measurements of the near-shore profile.

4. MODEL SET UP AND VALIDATION

4.1 INTRODUCTION

In this study, computational models are set up to:

- investigate effects and the cumulative effects of mine sediment discharges;
- investigate sensitivity of predicted sediment transport and dispersion to data limitations;
- investigate possible tailings discharge strategies.

In order to achieve these objectives successfully, the integrity of the models must be established. This integrity is established by means of model calibration (i.e. making subtle and reasonable adjustments to model parameters, where necessary, to ensure good representation of measured conditions) and validation (i.e. critical comparison of model results with measured data to assess model integrity).

This section of the report discusses the set-up and the validation of a number of computational models. Models which represent the transport, dispersion, settling and deposition of fine sediment in the region of the Orange River Mouth (including the mining area extending about 65 km to the north-west and about 50 km to the south-east), Chameis Bay region and Elizabeth Bay are described first. Models representing the transport and deposition of coarse sediment/sand in Mining Area 1, Bogenfels, and at Elizabeth Bay are subsequently described.

4.2 ORANGE RIVER MOUTH REGION: FINE SEDIMENT

4.2.1 Introduction

As discussed in Section 5 below, the Orange River is by far the most significant natural source of sediment to the project area. Simulation of flood sediment discharges and the transport, dispersion, settling, deposition and resuspension of these sediments is a priority, since an understanding of this will facilitate comparison with mine sediment discharges.

Correct representation of a major flood discharge, such as the 1988 flood, is limited by the model's ability to accurately represent Coriolis forcing, stratification and associated baroclinic flow, sediment settling and sediment resuspension (these sediment processes are relatively unknown at elevated concentrations). Data limitations, particularly the lack of (a) wave direction data and (b) limited model validation data (e.g. current measurements) will also limit model validation. Despite these limitations, a model assessment of the effect of natural flood sediment discharges, and comparison with the effect of mine sediment discharges, will be valuable.

The approach taken was to calibrate the model as best as could be achieved to represent available measurements in the form of salinities, satellite images of the plume and approximate descriptive information on flood delta deposition. Subsequent to this, the sensitivity of model predictions (of sediment concentrations and deposition) to key parameters was tested.

The DELFT3D suite of numerical models was employed to simulate flow and sediment dynamics. Details of model set-up are provided in Appendix D. Figure 4.1 illustrates the model grid employed for the modelling of flows and sediment dynamics.

4.2.2 Model inputs

Bathymetry

Bathymetry data consisted of a combination of:

- South African Navy hydrographic charts 1) Chameis Bay to Orange River and 2) Orange River to White Point;
- South African Navy electronic data for the near-shore and offshore area of the Orange River to the Holgat River;
- CSIR surveys of the near-shore (1995), mid-shore (1999) and a combination survey of the offshore and detailed near-shore (2002); and
- NAMDEB ALS beach survey data (2002).

All data were projected onto a common projection (Clark 1880 spheroid and SALO 17 projection – this is the system employed by the mine) and then further adapted to model co-ordinates. The conversion was as follows:

$$X_{model} = (80\ 000 - Y_{SALo17}) + 200\ 000$$

$$Y_{model} = (3\ 300\ 000 - X_{SALo17}) + 200\ 000$$

In addition, all measured depths were referenced to mean sea level (MSL), which is approximately 0.9 m above chart datum. Figure 4.2 shows the bathymetry of the model in the Orange River mouth region.

Waves

The offshore wave data were extracted from measurements conducted in 100 m water depth offshore from Port Nolloth (29.29°S and 16.81°E). The coverage period spanned the period 01/01/1988 to 30/06/1988. However, the data exclude wave direction. In order to add direction information, a relationship between wave height and direction was established for available directional measurements and applied to the 1988 omnidirectional data set. The directional measurements used for this analysis were conducted by Shell International Exploration and Production at the Kudu Gas Field site (courtesy of Tullow Oil). These directional measurements were conducted between 08/03/1998 and 13/04/1999 at a location approximately 180 km west of the Orange River mouth (at 28° 37'36" S and 14°34'59"). These measurements are henceforth referred to as the Kudu wave measurements. Appendix C provides details of a process which resulted in the synthesis of 71 representative wave conditions. As confidence in the calculated wave direction is relatively low (as shown in Appendix C, the relationship derived has an R^2 value of only 0.37), the sensitivity of this parameter was subsequently tested (described in Section 9).

Waves were transformed to the near-shore region by means of the SWAN model.

Wind

Wind data (speed and direction) were extracted from meteorological measurements conducted at the Nymphea station, 84 m above sea level on board an oil rig (at 29.89°S 16.29°E) situated approximately 140 km south of the Orange River Mouth, and 75 km perpendicularly offshore. The extracted data spanned the period from 01/01/1988 to 31/12/1988.

The two main concerns of the data were 1) the distance between the oil rig and the shore, and 2) the height at which measurements were conducted.

1) South-westerly winds are typical of the west of southern Africa due to the combination of the South Atlantic high-pressure system, the pressure field over the southern African subcontinent and the mid-latitude cyclones passing south of South Africa (Van Ballegooyen, 1995). However, periodically a reversal of wind direction occurs due to coastal lows. The coastal lows are cyclonic systems which originate close to Lüderitz and move south along the coastline. They occur in response to the ridging of the high-pressure system over the South Atlantic, which is in the order of 4- to 12-day cycles. The concern was that the meteorological measurements were taken too far offshore to record the signals (wind reversals) of the coastal lows. However, semi-quantitative comparisons with synoptic charts from the same time period (South African Weather Bureau, 1988) indicated that the wind data obtained were representative of near-shore wind conditions. To furthermore quantify the effect of any inaccuracies, sensitivity to wind conditions is tested in Section 9.

2) The DELFT3D model requires as input the wind speed and direction equivalent of 10 m above water level. Therefore the wind data extracted from the Nymphea station had to be converted to this elevation. The following equation was used (American Petroleum Institute, 1991):

$$V(z_R) = V(z_M) / (z_M/z_R)^{0.125}$$

$V(z_R)$ - wind speed at reference level (10 m above sea level)
$V(z_M)$ - wind speed at measured level (84 m above sea level)
z_M - height above sea level at measured level (84 m)
z_R - height above sea level at reference level (10 m)

Tides

Experience has shown that tidal currents on this open coast are negligible compared to wind- and wave-driven flows. Tidal currents are therefore ignored in this model.

River discharge

Measurements of the river discharge rate (m^3/s) and suspended sediment concentration (g/l) are provided in Bremner *et al.* (1990). Measurements, starting 10h30 on 29/02/1988 and ending 14h40 on 30/05/1988 were measured at the Ernst Oppenheimer Bridge irregularly from between 5 times a day to once every third day. The data are depicted in Appendix D.

4.2.3 Model validation

Limited data available for model validation included surface salinity measurements, satellite images and estimates of sediment accumulation on the delta.

Comparison with salinity data

Reference was made to hourly surface salinity measurements conducted during a cruise track (on board the *RS Benguela*) through the river plume on 12/13 March 1988. Figure 4.3 is a snapshot of the simulated salinity at the surface (with flow vectors) for the area of the Orange River mouth on 13/03/1988, and includes, as little circles, the point measurements of salinity derived from the RS Benguela cruise data (Shillington *et al.*, 1990) in the appropriate contour colour. The predicted surface salinities compare reasonably well with measurements opposite and north of the Orange River mouth, as indicated in Table 4.1, which indicate salinities (and also corresponding surface flows) to be well-represented by the model in this region.

Table 4.1: Comparison of predicted with measured surface salinities (13 March 1988) in the region of the Orange River mouth. Measurements were made approximately 3 km to 13 km offshore

Site	Measured salinity (ppt)	Predicted salinity range (ppt)
~15 km south of mouth	21.8	10-22
Offshore of the mouth	19.3	15-20
~25 km north of the mouth	23.8	22-24
~50 km north of the mouth	31.9	28-30

However, predicted salinities to the south were less successful. In the region from 40 km south of the mouth extending as far south as Hondeklip Bay salinities were considerably over-predicted. Where the predicted salinities were close to that of sea water (35 ppt), measurements indicated salinities from 23 to 30 ppt. This may have been a result of the Coriolis forcing not being correctly predicted in the model. Wave-driven currents at the time may also have been incorrect (as wave directions were based on a derived relationship – see Appendix C – and not on measured directions). The viscosity applied in the model may also have had an influence. Sensitivity of model results to wave direction and viscosity is further tested in Chapter 9.

In sum, the validation results suggest that hydrodynamics resulting from wave- and wind-driven currents which cause a northward flow (as shown by the accurate prediction of salinities) are reasonably well predicted, while flows to the south as affected by the Coriolis forcing are not well predicted.

Comparison with satellite images

The predicted dimensions of the sediment plume from flood sediment discharge were compared to satellite images. Since the relationship between what is visible on the satellite image and the predicted sediment concentration is not clearly defined, this evaluation is deemed to be qualitative. The available satellite images obtained from Shillington *et al.* (1990) are dated 8 March (NOAA 9), 14 March (LANDSAT 5), 19 March (NOAA 9) and 30 March (LANDSAT 5).

Figure 4.4 illustrates the NOAA 9 image from 8 March 1988, taken in the visible band. The red indicates high suspended sediment concentrations, while the green indicates low concentrations. The anticyclonic (anticlockwise) plume (deemed to result from Coriolis forcing) is clearly evident. The simulated plume for the same period is shown in Figure 4.5. If it is considered that concentrations over 10 mg/l would be visible (previous work on ground truthing of aerial images in Elizabeth Bay suggest this to be the case – CSIR, 1998c), the plumes in the predicted and measured images are apparently of similar scale. Limited evidence of an anticlockwise trend is evident in the simulated data.

The NOAA 9 satellite image of 19 March 1988 is shown in Figure 4.6. This plume has a westerly to west-north-westerly orientation and is about 46 km long. The corresponding simulated suspended sediment plume of 19 March 21:00 is shown in Figure 4.7. In this case, the simulated plume does not correspond very well with the image. The orientation (south-westerly) and size (approximately 38 km in length) are not totally correct. However, a day later in the simulation, the plume exhibits dimensions and an orientation similar to that of the satellite image in Figure 4.6. Figure 4.8 shows the simulated sediment plume for 20 March 09:00. The plume is approximately 45 km in length and has an orientation tending more to the west than the plume in Figure 4.7. Improved correlation of the simulated result with the measured result a day later may indicate a time-lag within the model.

The comparison of the above and other simulated sediment plumes with the satellite images from Shillington *et al.* (1990), including the above, has been summarised in Table 4.2 in terms of scale and general plume orientation. In general, the approximate scale of plumes and general orientation seem to be reasonably well predicted. Thus it can be expected that the model will predict the general orientation and approximate scale of floods tested in the model.

Table 4.2: Summary of the comparison between satellite images from Shillington *et al*. (1990) and simulated suspended sediment plumes.

Date	Satellite	'Measured'		'Simulated'	
		Orientation	**Scale**	**Orientation**	**Scale**
8 March 1988	NOAA9	Curved plume towards SW	Approximately 45 km diameter	Towards SW, slight curve evident	42 km diameter
14 March 1988	LANDSAT 5	Circular plume to the SW, pincer-shaped protrusions	Approximately 12 km diameter	Oblong bulge to SW, evidence of protrusions in plume	Maximum diameter 18 km
19 March 1988	NOAA9	Elongated plume towards W	Approximately 46 km in length offshore	Towards SW	38 km in length
30 March 1988	LANDSAT 5	Broad plume facing SW, single filament protruding NW	Approximately 22 km width 8 km offshore	Close to land, extending N	28 km diameter

Comparison with reported delta deposition

Bremner *et al.* (1990) discuss the sedimentological aspects of the flood of 1988. The authors discuss a mean sea floor rise of approximately 1 m on the ephemeral delta adjacent to the river mouth by 19 April 1988. The area was approximated to be 138 hectares (1.38 km^2). Figure 4.9 depicts the simulated depositional thickness of 19 April 1988. The deposition of 1 m was predicted. However, the area of deposition is roughly an order of magnitude larger than stated in the literature. This result indicates that any area of deposition near the river mouth predicted by means of the model must be evaluated cautiously.

The above result may be due to the model's limitation regarding the 'mud flow' (i.e. at very high concentrations, settlement behaviour of fine material is vastly modified). As the model cannot simulate the effects of high sediment concentrations on fluid properties, the input had to be modified in terms of conditions critical to deposition and resuspension to allow for the deposition thickness indicated in the literature. The respective increases in critical shear stresses for deposition and resuspension may have been exaggerated. As there is considerable uncertainty in both the predicted and literature-reported deposition, it is worthwhile to assess the effect of less deposition on predicted results. To achieve this, a model sensitivity test was conducted (Section 9).

Synthesis

In sum, some but not all of the validation results indicate a totally reliable prediction of fine sediment transport, dispersion, settling, deposition and resuspension from Orange River flood discharge. Based on these results, it is estimated that predictions of sediment concentrations and deposition throughout the model domain are not geographically precise and are only within order of magnitude accuracy. Sensitivity testing (Section 9) will inform limitations in data and/or modelling processes.

4.3 CHAMEIS BAY: FINE SEDIMENT

4.3.1 Introduction

During January and February 2005 Namdeb and De Beers Marine Namibia conducted a marine dredging trial at Chameis Bay. During this operation a contractor trailing suction hopper dredger stripped the sea-bed marine sediments at two panels, the first in Chameis Bay (Panel 1) and the second approximately 6 km to the north opposite Chameis Head (Panel 3), near Pocket Beach Site 2 (Figure 4.10).

The dredger discharged each load through a pipeline (termed the “sinker line”) to mined-out areas termed “paddocks” situated onshore (Figure 4.11). As a result of this operation, water discharged from dredging overflowed from these paddocks (usually by means of pipes placed in the seawall) back into the sea (Figure 4.12).

The dredged material in the paddocks as well as material mined on-land in the region (at Pocket Beach Sites 2, 3&4) was processed by means of a mobile treatment plant. Undersize material (“slimes” - material finer than 1.4 mm) from the processing is discharged to the inter-tidal zone (upper beach) at Site 2 (location of this plant discharge - see Figure 4.10). Oversized material (material coarser than 16 mm) was discharged back into mined-out paddocks. Plant operations (and associated sediment discharges) commenced in March 2004. It is anticipated that plant operation will continue until December 2006.

During the marine dredging and subsequent processing, fine material will enter the sea from three sources:

(a) From the overspill of excess water during the filling of the dredger's hopper with each load;
(b) From water overflowing from the paddocks as a result of the dredger pumping material (and large volumes of water) ashore. However, it was found that as long as this is managed with care, negligible sediment is discharged back into the sea from this source (CSIR, 2005c);
(c) In the undersize material that is discharged onto the beach from the plant, during the processing of the dredged material.

Modelling, by means of the DELFT3D suite of models, was conducted to investigate sediment transport, dispersion, settling, deposition and resuspension as a result of the dredger overspill and plant discharge sediment sources.

4.3.2 Model Inputs

Bathymetry

Figure 4.13 illustrates the offshore bathymetry and Figure 4.14 illustrates a zoomed-in view of bathymetry in Chameis Bay. This bathymetry data employed in the modelling were obtained from the following:

- *Offshore:* Depth points were digitised from hydrographic charts (SAN111 and SAN112);
- *Mid-depth:* Detailed bathymetric information was supplied by De Beers Marine Namibia;
- *Near-shore and surfzone:* Data measured by CSIR in the region were used. Beyond this measured area no detailed bathymetry measurements were available and selected points were digitised from the hydrographic charts. In addition, the 5 m depth contour was estimated from aerial photographs. Interpolation was used to fill in areas where no data were available;
- *Shoreline:* The location of the shoreline was provided by De Beers Marine Namibia;
- *Panther Reef:* Located approximately 1.2 km north of Panther Head, the position of this reef was obtained from hydrographic charts and correlated to the observed

position on aerial photographs. The position of the reef was not covered by the detailed mid-water bathymetric data.

The modelling coordinate system was based on WGS84 UTM Zone 33 South. For numerical reasons the coordinate system used in all the fine sediment modelling was converted as follows:

$$X_{model} = X_{UTM33S}$$

$$Y_{model} = Y_{UTM33S} - 6000\,000 \text{ m}$$

Tides

The open boundaries are located along the three offshore edges of the model, i.e. the southern, western and northern boundaries. At these open boundaries a water-level time-series was specified which is based on the predicted tide for the region. The changes in tidal constituents between Lüderitz Bay and Port Nolloth were used to make allowance for the changes in phase of the tidal constituents along the open boundaries of the model. The tide was specified at intervals of five minutes.

Waves

The offshore wave conditions, measured at Namdeb's TriAxis buoy situated about 80 km to the south east (at 28°34'38" S, 16°07'48" E) during the instrument deployment period, were decimated from over 700 data points (hourly measurements of wave height, period and direction) to 135 conditions (on average a condition every 6.9 hours) that preserved the characteristics of the offshore wave time-series. These conditions (significant wave height, peak wave period and wave direction) are illustrated in Figure 4.15.

Wind

The winds as measured at the site were employed. However, the wind speeds were increased by a factor of 10 % to account for the fact that the wind speeds were measured on the beach. Onshore wind speeds are generally 10% – 15% lower than the speeds in the open ocean. Time-series of the measured wind speed and wind direction are shown in Figure 4.15.

4.3.3 Model Validation

Wave model validation

Wave conditions were transformed from offshore to the shoreline by means of the SWAN model. Figure 4.16 illustrates predicted wave field for a typical offshore condition.

The simulated wave conditions predicted at the positions of the 25 m and 10 m SEAPAC wave measurement instruments (Figure 4.17) were compared to the conditions measured at these instruments. Figure 4.18 shows the comparison between simulated and measured wave height at the 25 m and 10 m SEAPAC instrument positions. Agreement between measured and simulated conditions is good. Therefore, wave dissipation and wave-generated currents, and the associated fine sediment behaviour which occurs as a result of these waves should be reasonably well predicted.

Hydrodynamic model validation

The calibration procedure was undertaken for the period during which wind, wave and current measurements (as described above) were available, namely 23 January to 1 March 2005. The calibration took place by comparing the measured and modelled currents.

A comparison of the modelled and measured currents at the 25 m SEAPAC location (Figure 4.17) is shown in Figure 4.19. The current speeds in both the model and measurements range between 0 m/s and 0.4 m/s. For most of the simulation time, the model represented the measured variation in current speeds well. However, the modelled currents show less diurnal variability than the measurements. The model represents the current directions reasonably well, but with a slight deviation, i.e. the measured directions indicate a north-north-westerly to northerly movement of the currents (on average) at this position, while the modelled current directions indicate a north-westerly to north-north-westerly movement of the currents (on average). In general, the modelled currents are considered sufficiently accurate for the prediction of fine sediment behaviour as a result of these currents.

Suspended sediment transport model validation

Comparison of predicted with measured concentrations was limited by the fact that the dredger discharge was represented by a single point discharge, while in reality the discharge from the dredger was highly mobile. In addition, the model does not incorporate any natural “background” sediment concentrations. The predicted concentrations were generally found to be higher or lower (often by about 10-20 mg/l) than measured data (CSIR, 2005c).

However, the approximate magnitude and location of elevated concentrations were reasonably well predicted.

As waves and hydrodynamics were reasonably well predicted, it is expected that the general orientation and approximate magnitude of concentrations in fine sediment plumes and of deposition on the sea-bed (which is dependent on the hydrodynamics) were also reasonably well predicted. The accuracy of predicted sediment concentration results as indicated above will inform an interpretation of any predictions, i.e. the *general area* and *approximate concentrations* (within roughly ± 20 mg/l) of suspended sediment should be correct in the predictions.

4.4 ELIZABETH BAY: FINE SEDIMENT

4.4.1 Introduction

At Elizabeth Bay, situated about 25 km south of Lüderitz on the Namibian coast, mining operations commenced in July 1991. Between that date and December 2001 about 9 200 000 million m^3 of sediment were discharged by means of a pipeline into the inter-tidal zone at various positions along Elizabeth Bay beach. While most of the discharged material consisted of sand, less than 1% consisted of fine material (size < 63 microns). The exception was in 2001, when 5-8% of the discharged sediment consisted of fine material.

After a mine plant upgrade, a massive increase in discharge volumes was anticipated. For this reason a modelling exercise to assess the fate of fine sediments (by means of Delft3D models) was conducted.

4.4.2 Model Input

Bathymetry

A detailed bathymetry of the model domain was compiled by combining the following data sets:

- SA Navy hydrographic chart (SAN110)- Spencer Bay to Elizabeth Bay;
- SA Navy hydrographic chart (SAN111) - Elizabeth Bay to Chamais Bay;
- The bathymetric survey performed by CSIR (February 1995);
- The bathymetric survey performed by CSIR (June, 2001);

- Detailed bathymetry of the Channel Panel area was provided by De Beers Marine Namibia.

The x-y coordinate system used in the model is based on the LO 17 coordinate system. A linear transformation is applied to provide model coordinates (x_{model}, y_{model}), which are positive and increase from South to North and from West to East. The transformation used is:

$$x_{model} = 100\ 000 - y_{lo17}$$

$$y_{model} = 3\ 500\ 000 - x_{lo17}.$$

Figure 4.20 illustrates the total model domain and offshore bathymetry. Figure 4.21 provides a zoomed-in view of bathymetry in Elizabeth Bay.

Waves

Near-shore wave data from 7 to 26 May 1997 were available from measurements in 20 m depth off Elizabeth Bay.

Wind

The wind data applied in the simulations are those measured with hourly intervals at the Elizabeth Bay monitoring site.

4.4.3 Model validation

Waves

In the absence of simultaneous deep water and near-shore wave measurements, an independent calibration of the wave model was not possible. The SWAN model has, however, been found to give reliable results for Southern African conditions when the default parameters are selected (CSIR, 2002e). The only available near-shore data comprised wave heights, periods and directions measured offshore of Elizabeth Bay in 18 m water depth at 30-minute intervals between 7 and 26 May 1997.

The SWAN model was used to estimate the equivalent deepwater wave conditions occurring during this period. These deepwater conditions were then applied on the offshore boundaries and the model used to compute the wave conditions throughout the model domain.

Wave conditions were computed at 12-hour intervals throughout the model simulation period. Although not an independent calibration, comparing the original measured wave conditions in 20 m water depth to the modelled values at the same location provides a check on the modelling procedure. These results are plotted in Figure 4.22, which shows that the measured wave heights are generally recovered in the model simulations. Figure 4.22 also shows the corresponding deep-water wave condition applied on the model boundary, in a considerable reduction in wave height, and the increase in wave direction by up to 40º in the case of the southerly wave directions is evident.

Currents

A comparison of the model-predicted and measured currents (from an instrument situated just beyond Elizabeth point in 20 m water depth) is shown in Figure 4.23. The current speeds in both the model and from measurements are generally low (less than 0.15 m/s). The most significant discrepancies between the model results and the measurements occurred on 18 May, as well as from 25 - 27 May. The latter period was characterised by a storm condition with a large swell and strong northerly winds, the phasing of which was not accurately reproduced in the model. The event on 18 May occurred under calm conditions and is thus most likely explained by a remotely generated disturbance. In general, the modelled currents are within 0.05 m/s of the measured values. This is considered sufficiently accurate for an assessment of the general behaviour of fine sediment.

No validation of predicted concentrations was conducted. Based on results in other areas (e.g. Chameis Bay) and on previous validation conducted at Elizabeth Bay (CSIR, 1998c), it is expected that the location of the predicted concentration will be approximately correct, while the magnitude of the predicted concentration is likely to be within roughly ±10 to ±20 mg/l.

4.5 SOUTHERN NAMIBIA/MINING AREA 1: SAND

4.5.1 Introduction

A shoreline model was established (CSIR, 2002b) to investigate the fate of coarse sediment and corresponding accretion of the beach in response to potential sediment discharge of several million cubic metres of sediment from dredging operations, primarily between 5 km and 15 km north of the Orange River. This model was subsequently extended to investigate the wave-driven transport of coarse sediment across the Orange River mouth and to the south (CSIR, 2003a). The results from this modelling, and a northward extension of this model (developed within the present study), will be valuable in providing an assessment of the fate and potential impact of coarse sediment discharged into the near-shore environment.

The domain of this shoreline modelling is from the Orange River to a point about 65 km to the north (i.e. in the region of mine coordinate K75, between No. 1 Plant and No. 2 Plant). In this region roughly 381 million tons of sediment have been discharged since commencement of large-scale coastal mining in the area (details: Section 5), while further discharge of several million m^3 of sediment is likely to occur in future.

4.5.2 Model inputs

Waves

Offshore wave conditions were obtained from the 1988/1989 Kudu offshore wave dataset, measured approximately 180 km west of the Orange River mouth. A representative offshore wave climate (i.e. 33 wave conditions defined by wave height, period, direction and duration of occurrence) was derived from this year of measurements (details, Appendix E) and transformation of this offshore climate to the near-beach region was achieved by means of the SWAN wave refraction model. Figure 4.24 illustrates a predicted wave field for a typical storm-wave condition at the site. The colours and arrows indicate subtle changes in wave height and direction respectively, from south to north. Wave conditions for each of the 33 offshore conditions were extracted along the 10 m depth contour from the SWAN modelling results. The wave height was found to vary only slightly in the alongshore direction. However, variations of a few degrees in wave direction were observed. These height and direction changes are the result of features in the offshore seabed topography affecting the refraction of the waves.

Wave height and direction are the primary drivers of longshore transport. Therefore, alongshore variations in either of these parameters will affect the sediment transport and shoreline orientation. To ensure that such alongshore changes are represented in the shoreline model, longshore transport conditions were calculated at 31 selected positions along the study shoreline, employing the UNIBEST_CL shoreline model (Description in

3.3.4.2). In the shoreline model, transport conditions are interpolated between these locations.

Near-shore Bathymetry

Representative beach and near-shore profiles were input at the 31 selected positions mentioned above. Data for these were obtained from the CSIR bathymetric survey (conducted in May 2002) and an ALS (aerial survey by means of laser) beach survey (conducted February 2002).

Sediment

During existing and proposed dredging operations it is mainly the very large volume of discharged material that will be subject to longshore transport. Sampling indicated an average median grain size 460 µm (CSIR, 1999). This grain size is used in the model simulations.

Mine discharge data

During the period April 1997 to July 2002, approximately 31 million tons of material was discharged to the beach by the dredge through 13 discharge positions. The monthly discharge volumes from a major dredging operation as well as from three mine plants (No 3 Plant, No 4 Plant and PTF Plant) as provided by Namdeb are presented in Appendix F, together with the approximate positions of the discharge pipes (and shifts in position of the dredge tailings discharge). These discharges were employed in the validation of the model.

4.5.3 Model validation

Beach surveys cover the period from the commencement of dredging operations in April 1997 to July 2002 (although data coverage in 2000 and 2001 is poor). Together with the records of discharge volumes, these data were used to calibrate the model. Figures 4.25 and 4.26 show comparisons between measured shorelines (+2m MSL contour as interpolated from beach profile surveys) and predicted shorelines. (The rotated and distorted scale provide a more critical comparison of measured and predicted shorelines.)

On average, differences between measured and predicted shorelines are within ±15 m to ±25 m. Isolated deviations between measured and predicted shorelines of about 50 m occurred. These deviations were deemed to be due to short-term changes in grain size discharged and/or short-term changes in wave conditions (and associated changes in the beach and near-shore profile) that deviated from the climate-driven conditions simulated in the model. From modelling experience in the region, the quoted deviation between predicted and measured data (±15 m to ±25 m with isolated larger deviations up to 50 m), the validation as above is expected to translate to a similar error between actual and predicted shorelines for the first 2-3 years of predictions.

A test of the shoreline model was conduct to assess this estimated accuracy. The model as described above was run from July 2002 with no alterations. The mine sediment discharges from the Beachcomber dredger, PTF Plant, No 4 Plant and No. 3 Plant were incorporated as provided by Namdeb (these inputs are described in Sections 5 and 7.) Measured and predicted shorelines of 24 May 2005 were generally within ±25 m of each other (beyond the validation area, to the north of No. 4 Plant, a difference of up to ±40 m was found). This result confirms the model to be as accurate as expected for the first 2-3 years after calibration. However, this accuracy is expected to decrease somewhat into the future. An accuracy of about ±50 m is probably realistic for predictions from 5-15 years into the future (e.g. ±50 m accuracy was estimated for a 12-year period in CSIR, 2002b).

Data for validation of the model was sparse for the area to the north of this well-validated model region. Figures 4.27, 4.28 and 4.29 illustrate comparison of predicted and measured shorelines in 1998, 1999 and 2004 respectively, along the extensive sandy beach to the north. Predicted shorelines are generally within ±30 to ±40 m of measured shorelines, with some isolated exceptions. While a similar accuracy can be expected in the following 2-3 years, predictions into the future are (as indicated above) likely to be less accurate. The accuracy achieved in this latter validation exercise is considered to be as good as can be expected, since the measured data are relatively crude: these are measured by means of a helicopter flying over the high-water mark (not always clearly defined) and measuring with a differential GPS, while the predictions represent the +2 m contour.

4.6 CHAMEIS REGION: SAND

4.6.1 Introduction

The shoreline model was employed to predict:

- future accretion of the beach at Chameis Pocket Beach Site 2 (Figure 4.30);
- behaviour of the shoreline after mining ends;

- the quantity of sand transported along the coast to the north and to the south of Site 2; and
- the associated accretion of these coastlines.

These potential effects will occur on a beach which was virtually unaffected by mining until 2004.

4.6.2 Model inputs

Waves

A set of 63 offshore wave conditions was employed in this study, as was compiled previously for this region (CSIR, 2004b). These selected conditions, derived from a year of measurements from Kudu gas field (courtesy of Tullow Oil), allow representation of the net annual longshore transport. The SWAN model was employed in order to predict the transformation of waves from offshore to the wave-breaking region. The set-up for SWAN was similar to that employed for the fine sediment dynamics model (Section 4.3). Wave height, direction and period information were extracted from the SWAN results at the 10 m MSL depth contour opposite Site 2. This information was input to the UNIBEST_CL model at six positions alongshore.

Nearshore Bathymetry

Typical beach and near-shore profiles were extracted from the near-shore bathymetric survey data of 2000 (CSIR, 2001) and employed at the six alongshore positions mentioned above. The bathymetric survey indicated that the (natural, undisturbed) near-shore bathymetry varies along the beach. Opposite the southern end of Site 2, the 10 m depth contour is located almost 800 m offshore, while opposite the centre and northern part of the beach it is less than half of this distance offshore.

Sediment

The sediment input in the UNIBEST_CL shoreline model is based on beach sediment sampling results. The average median grain size of this material is 391 microns.

4.6.3 Model validation

The shoreline model was first calibrated to represent the long-term stability of the pre-mining Site 2 beach shoreline (measured shoreline data from 1995 and 2000 indicates this shoreline to be stable, apart from minor seasonal fluctuations). Shorelines measured at the adjacent Sites 3 and 4 beach also indicate a quasi-stable shoreline, with seasonal on/offshore variations of up to 30 m. It is reasonable to assume that similar fluctuations could occur at Site 2.

Figure 4.31 shows a comparison of the measured pre-mining shorelines with the predicted shoreline before mining. Over a 5-year period the model shoreline is predicted to be stable, with a constant net northward longshore transport of 400 000 m^3/year. Thus the long-term stability of the Site 2 shoreline is well represented.

Figure 4.32 shows a comparison of the predicted with the measured shorelines of 7 September 2005, by which time overburden stripping (and associated seawall construction) at Site 2 had ceased, but plant discharge was still occurring. The comparison between model-simulated and measured shorelines is generally within 10 m, except at the southern part of the site where the difference is in the order of 20 m. Thus, the model demonstrates reasonable accuracy in predicting shoreline change.

4.7 BOGENFELS REGION: SAND

4.7.1 Introduction

A shoreline model was established to investigate the fate of coarse sediment and accretion of the beach as a result of proposed discharge of several million tons of sediment from a dredging operation at a mining site situated about 170 km north of the Orange River, in the Pocket Beach mining area north of Mining Area 1. Figure 4.33 provides an image of the model domain (and associated bathymetry). The modelling employed a time-series of wave conditions (rather than a climate of wave conditions as employed in the models described above). While more computationally intensive, this approach resulted in more accurate computation of sand transport at model boundaries, an essential component of this particular model. The results from this modelling are valuable in providing an assessment of the impact of the discharge of coarse sediment into the near-shore environment.

4.7.2 Model inputs

Waves

Wave conditions used were taken from the Kudu offshore wave dataset. This time-series of half-hourly measurements had been previously decimated (CSIR, 2002c) to reduce computational time during wave refraction simulations. The decimated data set of 311 conditions was transformed to the near-beach region by means of the SWAN wave refraction model (CSIR, 2002d). Figure 4.34 illustrates the predicted wave field for a typical wave condition. Wave conditions along the 10m depth contour were extracted from each of the results of this SWAN wave refraction modelling study. The alongshore wave conditions manifested limited change in direction and height from the south to the north of the site. Longshore transport conditions were calculated at 16 selected positions along the study shoreline, employing the UNIBEST_CL shoreline model (Description 3.3.4.2). As mentioned, transport conditions are interpolated between these locations in the shoreline model.

Near-shore Bathymetry

Bathymetry measurements conducted by the CSIR in May 2002 were available for the near-shore region, while the beach configuration was obtained from beach topography measurements conducted by Namdeb in February 2002. To resolve the lack of measured data between the 5 m depth contour and the shoreline (this area was not measured due to breaking waves), the bathymetry in this region was estimated, based on comprehensive profile data with similar barred profile characteristics, surveyed close to Oranjemund.

Sediment

Sampling of the upper (inter-tidal) beach and across the surf zone (conducted by divers) provided native grain sizes shown in Table 4.3. In the table, D_x is the diameter for which x percent of the sample, by weight, is smaller.

Table 4.3: Grain size of native material

Description	D_{84} size (µm)	D_{50} size (µm)	D_{16} size (µm)	Sorting coefficient
Native material	723	518	368	0.539

4.7.3 Model validation

Figure 4.35 indicates the average shoreline position over a 5-year period, as predicted by the shoreline model, compared to the average of four shorelines from beach and aerial laser surveys conducted in the period of 2000 to 2002. Figure 4.36 depicts the most north-easterly extent of the shoreline (i.e. the maximum erosion of the shoreline) predicted by the model during a 5-year period, compared to the most north-easterly of the four measured shorelines. Similarly, Figure 4.37 depicts the most south-westerly extent of the shoreline (i.e. the maximum accretion of the shoreline) predicted by the model during a 5-year period, compared to the most south-westerly of the four measured shorelines. These results indicate the predicted shoreline to represent the sediment transport regime and the quasi-stable (i.e. remaining within a defined on/offshore margin) condition of the shoreline as measured, for an extended period. In isolation, this result does not necessarily guarantee accurate predictions of large shoreline excursions as a result of major mine sediment discharges. However, knowledge of the expected of behaviour from a similar dredging operation in similar conditions (CSIR, 2002b) improved confidence in shoreline evolution predictions. Based on these former results, together with results of tests of model sensitivity to input parameters, model accuracy is estimated to be ±20% to ±25% of shoreline accretion (resulting from deposition of sand). For example, a prediction of 100 m is expected to have an accuracy of ±20 m to ±25 m.

4.8 ELIZABETH BAY: SAND

Figure 4.38 illustrates the model domain (i.e. extending along the smooth curved shoreline of the bay from the base of Elizabeth point to the easterly rocky shore) for the prediction shoreline change resulting from the transport and deposition of fine sediment. A description of model inputs and validation follows.

4.8.1 Model inputs

Wave conditions

Kudu offshore wave data were applied in a wave refraction study to obtain near-shore conditions that could be input to the shoreline model. The 63 wave conditions applied in the refraction simulations are presented in Appendix G.

Wave height and direction, as derived from a refraction analysis, were evaluated along a line approximately parallel to the shoreline, between the 4 m and 7 m depth contours. To represent the alongshore variability in wave conditions in the shoreline model, points were identified along the shoreline: the wave height, period and direction for each condition at each of the points were imported into the model.

Profiles

At each of the selected points of wave input (mentioned above), the beach and near-shore profile was extracted from 2001 measured bathymetry.

Sediment

The sediment characteristics were defined for each section, taking into consideration the mine discharge grain size and the beach grain size. The D_{50} and D_{90} values that were used for the calculation of longshore transport ranged from 300 to 1100 μm and from 780 to 1450 μm respectively.

4.8.1.1 Model validation

Shoreline evolution from 1997 to 2004 was predicted, employing the sediment discharges (as per Appendix H) at a single point on the beach (Discharge point 11.4, as indicated in Figure 4.38).

The shoreline simulated by the model was compared to shorelines from measured data. Figures 4.38 and 4.39 depict the comparisons between the measured shoreline of February 1998 and August 2003, and the corresponding simulated shorelines respectively. On average the difference between measured and simulated shorelines was ±25 m, ranging between ±10 and ±35 m. Such discrepancies are deemed to be the result of localised and short term effects of accretion and erosion due to storms, short-term changes in grain sizes and/or day-to-day fluctuations in the mine discharge rate. It is expected that a similar level of accuracy would be expected when predicting 2-3 years into the future. However, for predictions further into the future, less accuracy would be expected. Based on experience in the region, an accuracy of within ±40 m for predictions extending from 5 to 15 years into the future is estimated.

5. SEDIMENT INPUTS

5.1 INTRODUCTION

Information on both natural and mine-induced sediment inputs to the near-shore zone are paramount to this project, as per the following key questions posed in the project terms of reference:

> *What quantities of suspended sediment are transported into the <40m depth zone by rivers, wind and coastal currents? How does this compare with the quantity of sediment re-mobilised/discharged by land-based and near-shore mining activities and what are the relative particle-size distributions of these various sediment inputs?*

This chapter provides available information on fluvial, aeolian and marine natural sediment input rates to the project area, as well as available information on the particle-size distributions of these inputs. In addition, available information on mine sediment inputs rates to the project area and associated particle-size distributions are provided.

5.2 NATURAL SEDIMENT INPUTS

5.2.1 River discharge

5.2.1.1 Rates

Large volumes of sediment are delivered to the sea in the event of floods. This is especially the case in semi-arid and arid environments, characteristic of the project area. Flash flooding in the non-perennial rivers crossing the Namib transport large quantities of terrigenous sediment to the river mouths, even though quite infrequently (Krapf *et al*., 2003).

South African rivers south of the Orange

Only two of the rivers in the project area are perennial: the Olifants and the Orange Rivers. (Figure 5.1 shows the location of river mouths of these rivers and the non-perennial rivers situated between them in South Africa.) The non-perennial rivers experience surface flow only every few years, making measurement of data on such run-off and sediment yield difficult. Therefore data regarding the non-perennial rivers are scarce.

The *Olifants River*, 260 km long, has an estimated mean annual run-off of the entire catchment of 12.2 million m^3/yr, but this potential fresh-water input to the sea decreases significantly downstream due to the construction of the Bulshoek and Clanwilliam dams, built in 1919 and 1932 respectively (CSIR, 1984). A conservative (maximum) estimate of catchment sediment yield (excluding dams) indicates a possible 4.25 million tons/annum (see Table 5.1 which provides estimates of sediment discharge from catchments, excluding dams. However, according to Perry (1988), the estimates in Table 5.1 are “maximum relative values” and are therefore not considered very accurate). A recent, relatively crude estimate suggests present sediment input from the Olifants River to the marine environment (with the dams included) to be significantly less than the potential input, i.e. in the region of 9000 tons/annum (Taljaard *et al.*, 2005).

Table 5.1: Estimated “maximum” yield of sediment from the catchment for South African rivers in the project area from Perry (1988).

River	Maximum sediment discharge * (x 10^6 tons/yr)
Olifants	4.25
Sout	0.13
Brak	0.07
Groen	0.27
Bitter	0.07
Spoeg	0.11
Swartlintjies	0.14
Buffels	0.58
Holgat	0.13
Orange	119.39
Total	125.14

* These data were estimated from Rooseboom (1975). Confidence in the data is not considered to be high as the results were rather vaguely indicated to be “relative maximum” values. Neither of the terms “relative” or “maximum” are made clear in Perry (1988).

Between 60 and 180 km north of the Olifants River are six small rivers: the Sout (length 62 km), the *Brak* (length 41 km), the *Groen* (length 67 km), the *Bitter* (length 70 km), the *Spoeg* (length 95 km) and the *Swartlintjies* (65 km). These rivers have very erratic flow and reach the sea only during flood events. For example, the Groen River has a flow frequency of once in every five years (CSIR, 1981a). The erratic flow of these small systems results in relatively small sediment inputs: even the conservative/"maximum relative" values indicated in Table 5.1 are not very high.

One hundred and fifty kilometres south of the Orange River is the *Buffels River*, 149 km long. This stream has very erratic flow and only reaches the sea during flood events, every 3 to 5 years. Reasons for low flow occurrence include the position of the catchment in a low-rainfall area and the existence of two large geological aquifers absorbing much of the river flow. The "maximum" sediment discharge indicated in Table 5.1 is 0.58 million tons/annum. Indications are that this will be significantly reduced due to the Floriskraal Dam upstream: an estimate of annual sedimentation in this dam (Rooseboom, 1978) suggests that virtually all of the river discharge is trapped in the dam.

The *Holgat* River (length 80 km) is situated about 50 km south of the Orange River. Flow in this river occurs only occasionally. In 1981 it was indicated to have flowed only about 50 years prior. Nevertheless, Table 5.1 indicates an annual average sediment discharge of 0.13 million tons/annum.

The Orange River

The *Orange River* is approximately 2 173 km long and has a catchment area of 891 780 km^2. It is classified as one of the world's major rivers as its mean annual runoff exceeds 10 km^3 (i.e. $10x10^9$ m^3). During non-flood times (normal flow) the mean annual runoff of the river catchment is approximately 11 000 million m^3 per year.

Table 5.2 indicates estimated Orange River sediment input averages for various periods (from Bremner *et al.,* 1990). The value of 119 million tons/year indicated for the period prior to 1921 is considered to be a conservative estimate of low accuracy (Perry, 1988). Nevertheless, if the values in Table 5.1 are considered in a relative sense, the Orange River would, under natural conditions, deliver 95% of sediment discharge between the Olifants River and Namibia. Rooseboom and Maas (1974) and Rooseboom and von Harmse (1979) indicated that between 1929 and 1969 the Orange River delivered, on average, 60.4 million tons of sediment per year. However, there was a great degree of variability in the data, which ranged from 8.2 to 325.8 million tons per year. The mean discharge of sediment declined from about 80-90 million tons per year in the early 1930s to 30-40 million tons per year in the 1960s. This was mainly ascribed to poor land management in the 1930s, leading to excessive erosion (Rooseboom and Maas, 1974). An annual sediment yield of less than

17 million tons/yr has been indicated since the 1980s (Bremner *et al.,* 1990). River flow is erratic and responds to summer rains in the interior (Bremner *et al.*, 1990).

Table 5.2: A list of the sediment discharges of the Orange River since before 1921, calculated of over discreet periods up to the 1980s (after Bremner *et al.*, 1990)

Period	Sediment discharge ($x 10^6$ tons/yr)
Pre- 1921	119
1929-1934	89
1934-1943	56
1943-1952	52
1952-1960	46
1960-1969	34
1980's	<17

It is logical that the Orange River sediment input would have decreased over the years, with increased demands for water. Dams have played a major role in reduction of sediment discharge in recent times, particularly the construction of the Gariep Dam (formerly named the Hendrik Verwoerd Dam) and the Vanderkloof Dam (formerly named the PK le Roux Dam) in 1972 and 1977 respectively. Mean annual runoff (MAR) reaching the Orange River mouth has been reduced to about 43% of the natural MAR as a result of dams (CSIR, 2003a).

Estimates of the natural sediment discharge rate of the Orange River are complicated by the effects of bad agricultural practice and by damming of the river. The best period to estimate the sediment discharge representative of natural conditions is probably from 1940 to 1960, since this period follows the period of bad agricultural practice, but occurs before construction of the major dams. The estimated average annual sediment input in this time was in the region of 46 to 52 million tons/annum (Table 5.2).

Most sediment discharge occurs in the form of floods. If a flood is defined as an event when monthly flow is twice the average monthly runoff, then about 36 events can be identified for the period 1921 to 1971, based on simulated runoff data (Perry, 1988). Therefore a flood would be expected about once every 1.4 years on average. The nature of sediment input to the project area is strongly influenced by major floods. For example, during the flood of 1988 the sediment discharge during the flood ($64.2x10^6$ tons) exceeded the annual sediment discharge of the 1980s by about four times.

The floods (again defined by a monthly flow of twice the average monthly runoff) in a system such as the Orange River are of relatively long duration compared to most rivers in the region. Available data indicate most floods to be longer than one month, with some floods lasting as long as 5 months (Swart *et al*., 1990).

Namibian Rivers

North of the Orange River are a number of ephemeral rivers. These rivers flow sporadically and very rarely reach the sea, as most are hindered by dunes of the Namib Desert. The only river that could be identified by name in the project area north of the Orange River was the Koichab River, situated east of Lüderitz. This river appears (Lancaster, 1989) to end in the Koichab Pan, which is situated over 50 km inland. Stengel (1964) confirms that of all rivers between Walvis Bay and Oranjemund, none flow visibly into the Atlantic Ocean, although they may reach the ocean via groundwater seepage.

An assessment of rivers north of the project area (Appendix I provides some details) highlights the occurrence massive episodic input of sand from desert rivers. However, northward longshore currents will prevent this sand from entering the project area as defined.

5.2.1.2 Grain Sizes

The main silt load in the Olifants River system is carried by the Doring River (tributary), which drains areas of relatively soft tillites and shales, and is uninhibited by any major dams. The Olifants River proper carries very little silt and the two large dams on this river act as silt traps (CSIR, 1984). The Olifants exhibits a variation in grain size along the lower reaches of the river course. 13 km upstream of the mouth, medium sand (429 µm) dominates; 7 km upstream fine sand (221 µm) dominates in the upper estuary; medium sand (358 µm) dominates the lower estuary 0.75 km upstream of the river mouth, which is an indication of increased marine influence (CSIR, 1984). Some of this sand would be transported into the sea during floods, together with the silt load from the Doring tributary.

Both Spoeg and Groen Rivers exhibit fine silt along their river beds. However, this fine silt is overlain with sand closer to the river mouths (CSIR, 1981a; CSIR, 1981b). The Buffels River exhibits fine to medium sand (125 to 500 µm) with fine silt (7.8 to 15.6 µm) in places along its river course, but the typical fluvial sediment is coarse sand, 500 to 1000 µm (CSIR 1981c). South of the river mouth, on the beach and spit, grain sizes are in the order of 333 µm (fine to medium sand). This information suggests that a range of sediment sizes from fine silt to coarse sand could be discharged episodically from these small rivers.

Table 5.3 contains averages of the fractions of sand, silt and clay in suspension measured near the Orange River mouth for the duration of the 1988 flood (derived from Bremner *et al*., 1990). The table also indicates the maximum and minimum percentages of sand, silt and clay during the flood, demonstrating considerable variability in the content of suspended sediment.

Table 5.3: Summary of grain size fractionation of sediment discharge from the Orange River during the 1988 flood

Type of sediment	Size [µm]	Average percentage of sediment content	Minimum percentage recorded	Maximum percentage recorded
Sand	125 to 2000	16	3.4	49.0
Silt	3.9 to 62.5	31	12.8	48.9
Clay	< 3.9	53	24.3	69.9

Analysis of suspended sediment sampled upstream under low flow conditions provides some indication of the detailed grain-size distribution (Table 5.4). These data confirm existence of a low sand content. A relatively high content of silt was typical of the period prior to major dam construction: historical data show that the silt fraction dominated until the 1970s, after which the clay fraction began to dominate due to the trapping of the coarser fractions by dams (Bremner *et al.*, 1990).

Table 5.4: Size distribution of Orange River sample at Upington. Percentages estimated from Rogers (1977)

Percentage sand in size band:			Percentage Silt	Percentage Clay
246 - 420 µm	147 to 246 µm	50* to 147 µm		
3	5	10	60	22

* close to the 63 µm, which distinguishes between sand and silt.

As mentioned, sediment data for rivers north of the Orange River are scarce. The only indication is that, in general, the Namibian rivers to the south are more coarse sand- to gravel-dominated, while to the north the rivers are more sand-dominated (Krapf *et al.*, 2003).

5.2.2 Aeolian transport of sediments

5.2.2.1 Input rates

Background

Only particles less than 80 µm in diameter tend to be **suspended** in the atmosphere to be rapidly transported by wind (Bagnold, 1941). This grain size is close to that defining fine sediment (i.e. silt and clay with particles <63 microns).

On the other hand, coarser sand grains tend to move primarily by means of **saltation** (the “bounding motion of sand grains” through air, involving a series of impacts with the ground surface). These sands tend to have sizes of 150 to 300 µm (Bagnold, 1941). The assessment of aeolian sediment inputs to the project area takes both the sand and suspended fine material fractions into account.

This distinction between suspended and saltating grains is important since it affects the type and extent of sediment transport into the defined marine project area. Sand can enter the near-shore area of the marine environment only from the beach, near ground level, and will require a local source relatively close by. On the other hand, fine sediment suspended by strong winds may enter the marine environment over an extensive area, and may originate from a source some distance inland.

Sand sinks from prevailing winds

The coastline of the project area is influenced by moderate to strong winds primarily from the south-south-westerly to south-south-easterly directions (for example, Figure 5.2 shows wind conditions at three sites in the project area), driven by the South Atlantic High-Pressure System. Considering the shoreline orientation in the project area (generally south-south-east/north-north-west, but south-east/north-west between Oranjemund and Chameis Bay) in relation to the wind climate, predominantly onshore and cross-shore transport would be expected in the project area (based on indicative winds at the sites as shown in Figure 5.2).

Between the Olifants and the Orange Rivers, a number of dune fields indicate significant aeolian sand transport at isolated sites. These dune fields are situated at the mouths of the Bitter, Spoeg, Swartlintjies and Holgat Rivers (Tinley, 1985; CSIR, 1981b; CSIR, 1981d; CSIR, 1981e; CSIR, 1981f). In addition, extensive dunes are evident just south of Port Nolloth (Readers Digest, 1984). At all the river mouths indicated above, dunes occur which extend northward in response to prevailing winds. The presence of these dunes and their northward migration away from the sea indicate an aeolian sand sink to the project area.

North of the Orange River, in southern Namibia, major aeolian sand transport corridors (manifested by barchan dune trains) originate in wave-sheltered areas. These wave-sheltered areas generally take the form of log-spiral and south-facing bays. It is in these bays that fine sand, which is driven northward by waves on more exposed coasts, tends to deposit. This sand then serves as a source to inland dune corridors. Three major dune corridors which originate from log-spiral and south-facing embayments are currently active – these originate at Chameis Bay, Bakers Bay and at Prinzenbucht (Corbett, 1989), as can be seen in Figure 5.3. A fourth, smaller aeolian transport corridor originates in the vicinity of Van Reenen Bay. In between these isolated, wave-sheltered fine-sand sources, the shoreline is exposed to persistent high wave action (CSIR, 1998a; CSIR, 2002a). This wave action causes winnowing out of fine sand on the inter-tidal beach (i.e. finer sand is transported seawards of the inter-tidal beach). The result of this winnowing is evident in the medium to coarse inter-tidal beach sand size (mostly greater than 350 μm, i.e. less than 1.5 phi) on exposed beaches between the Orange River and Elizabeth Bay (Rogers, 1977; CSIR, 1979; CSIR, 2001; CSIR, 2002b). This coarse beach sand serves only as a limited source for aeolian transport as it would be mobilised only during very strong winds.

From Lüderitz to the northern extent of the project area (Spencer Bay), the Namib Sand Sea, an extensive dune system, is situated close to the coast, at times resulting in an exchange of sediment with the near-shore zone.

Table 5.5 provides available estimates of sediment transport rates (these are net rates in the dominant wind direction) in the project area and includes, at least in part, the three major corridors mentioned above (Chameis Bay, Bakers Bay and Prinzenbucht).

Table 5.5: Summary of available aeolian transports in the project area. The location of these areas is shown in Figure 5.3

Area	Annual volumetric transport [m^3/yr]	Annual volumetric transport rate [m^3/m/yr]	Reference
Chameis Bay Region (Mine Site 1)	50 000	67	CSIR (2001)
Chameis Bay Region (Mine Site 2)	80 000		CSIR (2001)
Chameis Bay region (Mine Site 3 & 4)	140 000	230	CSIR (2001)
Bakers Bay	80 000	67	CSIR (2002d)
Bogenfels	<10 000	3.7	Corbett (1989) CSIR (2002d)
Bogenfels (4 km eastwards, in corridor from Bakers Bay)		51	Corbett (1989)
Elizabeth Bay (originates at Princenbucht)	350 000	50-200	CSIR (1988) Lancaster (1989)

From the above it is clear that aeolian sediment transport functions primarily as a sand sink to the project area. This sand sink is driven by the prevailing southerly winds.

Aeolian sand source

Occasional offshore winds could serve as a source of sediment at times. During autumn and winter catabatic north-easterly bergwinds occur. These strong offshore winds can exceed 14 metres per second (about 50km/hr), producing sandstorms that can cause a significant input of sand (and fine material) to the near-shore environment (Lane and Carter, 1999).

For the case of sheltered beaches (e.g. in bays such as those indicated in Table 5.5), while occasional seaward transport may occur during bergwinds, the massive sand losses during prevailing winds clearly dominate, as evident from the discussion on the sand sinks above.

However, on the exposed reflective beaches of southern Namibia, other effects may prevail. Basic calculations of aeolian sediment transport and of offshore sand movement from the upper beach were made (details, Appendix J). The calculations suggest that:

- The magnitude of sediment transport (whether directed onshore or offshore) at the exposed beaches in the project area is relatively small;
- The magnitude and direction of net transport is affected by both the relative grain sizes of the inter-tidal beach and of the back-beach (i.e. the region landward of the coastline which may serve as a sediment source);
- The magnitude and direction of net aeolian sand transport is affected by moisture and salt on the beach face;
- Where a net input to the marine environment does occur, calculations suggest this to be in the order of a few ten thousand cubic metres per year per 100 km of coast. Thus the net input for the project area (excluding the sheltered bays, where net loss from the marine environment occurs) is probably in the order of a few hundred thousand tons in total.

However, these findings are preliminary and should be validated by means of (a) more extensive measurements of grain sizes at shore sand sources as well as on the inter-tidal beach face, and (b) associated measurements of wind-blown sand transport.

Fine sediment input

While the above section deals with sand transport, it appears that considerable fine sediment input can occur as well. Images such as the satellite images of Figure 5.4 captured by satellite in May 1979 (Payne and Crawford, 1989) and Figure 5.5 (Mendelsohn *et al*., 2002) depict the aeolian transport of fine sediment, which in some areas may extend as far as 200 km offshore (i.e. seaward of the Orange River mouth).

From satellite imagery, Whitaker (1984) observed seven offshore dust plumes in 1978, 12 in 1979, 5 in 1982 and 8 in 1983. The plumes were oriented from north-east onshore to south-west offshore, crossing the Namib Sand Sea south of Walvis Bay and also crossing the Skeleton Coast as far north as Cape Frio. An examination of LANDSAT satellite images showed that most of the plumes emanated from erosion by winter bergwinds deflating summer-rainfall flood deposits on the coastal plain, west of river valleys that funnelled the bergwinds of winter onto the desiccated flood-deposits.

Sediment grains over 80 μm would not be transported over the sea (because of the required mechanism of saltation for larger grains (Bagnold, 1941), which requires a solid base, the images most likely represent fine material only). It has been indicated that this source of input of sediment into the Benguela region probably constitutes a significant input of sediment to the region (Shannon and Anderson, 1982). An input of up to about 50 million m^3 was suggested to be possible for the entire ocean area affected. However, no ground truthing of the quantity of sediment deposited has been obtained. Furthermore, only a fraction of this area would constitute the project area as defined for this study (less than 40 m depth).

It is unlikely that the fine sediment would remain within the wave-dominated environment in depths of less than 40 m for any extended period, as will be demonstrated by modelling (discussed in Section 6). The likelihood that fine material would be rapidly mobilised is further confirmed by calculations of conditions for mobilisation (initiation of motion) of sediments on the sea-bed, based on Lenhoff (1982). Employing the Lenhoff initiation of motion relationship indicates that sediment grains of 80 μm will be mobilised by wave-generated flows for 98% of prevailing wave conditions, in depths equal to and less than 40 m. Considering that sediments of 80 μm and much finer will enter the near-shore region from bergwind action, these calculations demonstrate that such fine grains will be mobilised under most conditions, until transported to calmer waters beyond a depth of 40 m.

5.2.2.2 Grain sizes

Data on aeolian sand grain sizes in the South African section of the project area are not available at this time. However, data on mean beach sand suggest grain sizes in the region of 200 to 350 μm in the region from the Orange mouth to 140 km south.

Table 5.6 provides an indication of sand grain sizes available (at and near the beach) to be transported by wind at isolated sites on the southern Namibian coastline. Sampling near the Orange River indicates consistently coarse sand on the back-beach (D_{50} = 451 microns), while a similar sand size is found at the back-beach some 120 km further north (at Chameis Pocket Beach Site 3&4). Such large sand sizes will not result in high transport rates. However, finer sand (D_{50}=340 microns) was found from inter-tidal beach sampling 120 m north of Orange mouth. This sand size may justify the higher aeolian transport rate estimate in the region of Chameis Pocket Beach Site 3 & 4 (Table 5.5)

Further north (at about 170 km north-west of the Orange River mouth) at Bogenfels, beach sand and sand sampled up to a few hundred metres inland were generally very coarse (although there is evidence of a fine pan sand below the surface) and transport of this sand would be minor (CSIR, 2002d).

In general, the occurrence of coarse upper beach sand as occurs on the exposed beaches from the Orange River to some 170 km north (Table 5.6) is confirmed in Rogers (1977), where mean sand sizes (apart from those sampled in the region of sheltered bays) are primarily in the top fraction of medium sand (250 to 500 μm), as well as coarse (500 to 1000 μm) and very coarse (1000 to 2000 μm) sizes.

Within sheltered bays (e.g. Chameis Bay, Bakers Bay) beach sand sizes are much smaller (indicated by data in Rogers, 1977). Corbett (1989) indicates mean sand sizes in the region of 200 to 300 μm in the sheltered regions of Bakers Bay, with a rapid increase (to over 1000 μm) on the exposed beach to the north. Sand sizes from traps situated in the aeolian transport corridor inland of Bakers Bay indicated a similar typical mean size in the region of 200 to 300 μm.

Further north within the project area, mean beach sand size is smaller (Rogers, 1977), i.e. mostly in the fine sand range (125 to 250 μm). An example is Elizabeth Bay, where fine sand was sampled on the natural beach (Table 5.6). This fine sand is readily mobilised by the strong southerly winds in this region, resulting in high transport rates (as indicated in Table 5.5).

Table 5.6: Grain size distributions (in µm) of beach and near-beach sand at various sites along the Namibian shoreline

Site	D5	D16	D50	D84	D95	Exposure to high waves	Comments	Reference
15 km NW of Orange Mouth (G68-G90) – back-beach sampling	130	214	451	947	1267	n/a	Minor transport expected	CSIR (1998b)
Approx 120 km NW of Orange Mouth (Pocket Beaches Sites 3 & 4) – back-beach sampling	120	247	476	923	1410	n/a	Minor transport expected	CSIR (2001)
Approx 120 km NW of Orange Mouth (Pocket Beaches Sites 3 & 4) – inter-tidal Beach	200	250	340	460	570	Moderately exposed	Moderate transport is likely	CSIR (2001)
Approx 170 km NW of the Orange Mouth – back-beach material to be dredged	148	204	503	1229	1619	n/a	No significant transport likely	CSIR (2005a)
Approx 170 km NW of the Orange Mouth – inter-tidal beach	411	603	967	1362	1695	Very exposed	Very limited transport likely	CSIR (2005a)
Elizabeth Bay – inter-tidal beach.	137	153	177	187	201	Sheltered	High transport rate expected.	CSIR (1988)

Airborne fine material (dust), such as that mobilised during bergwinds, would probably be finer than 80 microns (i.e. primarily in the "silt/clay" range), according to Bagnold (1941). This was more or less confirmed by the observations of Whitaker (1984), who found about 80% of the terrigenous grains in the form of mica flakes, and minor amounts of gypsum, which is common in the salt pans of the Namib Desert. Only a small fraction of fine quartz grains was found, in the 63 to 125 µm size category.

5.2.3 Coastal currents

5.2.3.1 Input rates

Without doubt the most significant of any current-induced input of sand (coarse sediment) to the near-shore region (<40 m depth) will be from near-beach wave-driven flows. Through such flows, sediment will most probably enter the project area in the south and will exit the project area in the north. The rates of this sediment input and sediment sink will probably range from a few hundred thousand m^3/year to about a million m^3/year, based on longshore sediment transport calculations conducted at various sites in the region (CSIR, 2002b; CSIR, 2002d; CSIR, 2005a; CSIR, 2005b). Large variations in longshore transport from year to year are expected.

Imbalances in longshore currents and corresponding longshore transport in the project area could cause natural long-term erosion or accretion trends. However, no such natural trends have been discerned (discussed in Section 7). Perhaps more relevant will be the rapid deposition of sand as a result of storms. High waves will cause erosion of the beach. Estimates of sand volumes eroded from the upper beach (employing a calibrated storm erosion model – CSIR, 2002b) indicate that on exposed coasts (such as just north of the Orange River) volumes of roughly 50 m^3 to 100 m^3 per linear metre of beach can be eroded during extreme storms. These eroded volumes can double if the shoreline is substantially artificially accreted, such as through mining activity. The eroded material is carried offshore by undertow and rip currents and tends to deposit in the near-shore zone. Profile measurements indicate that significant deposition (predictions indicate this to be from some 10 cm to some two metres in thickness) can occur in depths of up to 14-18 m. This constitutes a significant source of sediment to the shallow near-shore zone which would deposit in a time period of hours to days. Such sediment deposited would be removed by wave action during calm periods, a process which would take a long time (generally in the order of months to years for major storm deposition). This sediment is generally returned shoreward in calm conditions.

In addition to sand input, wind-driven, tide-driven and ocean currents will transport fine sediments in suspension both into and out of the shallow (less than 40 m depth) regions of the project area. Modelling studies (Section 6 and 7) and calculations of sediment mobility in the wave-dominated shallow region indicate a tendency for fine sediment to deposit offshore. Thus, unless the coastal currents are supplied by a source (such as rivers, as already identified above), it is more likely that such currents will serve as a fine sediment sink to the project area.

5.2.3.2 Grain sizes

As indicated above, the most significant sand input to the project area would be through erosion of beaches by storm waves and deposition of this material in the near-shore zone. The beach material eroded would range from fine to coarse sand (reference is made to available information on beach sand sizes as discussed in 5.2.2.2).

No detailed information on sediment sizes input to the project area by ambient currents (i.e. other than those supplied by aeolian and fluvial sources) is available.

5.2.4 Synthesis of information on natural sediment inputs

River discharge

About 95% of the fluvial sediment discharged into the project area is from the Orange River. This Orange River sediment discharge was estimated to be as high as 119 million tons/year maximum (prior to 1921) reducing to less than 17 million m^3 in recent years. Under natural conditions, considerable sediment input came from the Olifants River (4.3 million tons/year maximum). However, the sediment input is presently negligible because of dams on this river. Apart from the Olifants and Orange River sources, some river sediment input to the project area would have come from episodic flow of the rivers in South Africa. Occasional major episodic sand input occurs north of the project area. However, no significant fluvial sand source has been identified in the Namibian part of the project area. This is not surprising, since rivers in southern Namibia do not flow visibly into the Atlantic Ocean (Stengel, 1964).

About 15% of the Orange River sediment discharge is indicated to be sand. Most of this sand is fine, as indicated from sampling at Upington and from sampling of sand deposited on the delta (Rogers, 1977, confirmed by recent sampling: pers comm. J Rogers). Considering this sand input only, 15% of 17 million tons (maximum estimated present sediment discharge) implies an annual average (at present) of less than 2.55 million tons – which translates to about 1.4 million m^3. As the sand is fine, not all of this will contribute to shoreline accretion and the longshore transport corridor. Therefore, this estimate of 1.4 million m^3 of sand per year seems reasonable, since it is similar to the estimated longshore transport of sand (calculations indicate about 1.2 million m^3/year).

Applying the same sand percentage (15%) to early estimates (pre-1921) of flood discharge (Table 5.2), a major sand input as high as 10 million m^3 is the result. This estimate does not agree with longshore transport estimates as above. This suggests that the sand percentage may have been lower at that time, or that the annual discharge was overestimated. A third possibility is that major accretion occurred at that time. However, no evidence of such accretion was found.

The fraction of fine sediment input from the Orange River is much larger than that of sand. The silt and clay content are estimated to be 31% and 53% respectively, as indicated by sampling from the 1988 flood (Bremner *et al.*, 1990). Considering the range of possible sediment inputs over time (Table 5.2), this implies that fine sediment input has ranged from an annual average of about 95.2 million tons/year in the early 1900s to 13.6 million tons/year in recent times.

Aeolian transport

Input of sediment to the project area by means of aeolian transport is on a smaller scale than fluvial transport. In fact, it appears that aeolian transport of sand primarily serves as a sand sink to the project area. Only occasional offshore bergwinds can cause some fine sand input to the project area (this fine sand may ultimately be transported by waves to the wave-sheltered bays, where it can be transported inland). However, consideration of relative sand sizes of beaches and sand sources landward of these beaches suggests that most sand blown into the sea will be returned during onshore winds.

Mobile sand tends to be fine. Sand sampled in aeolian corridors, where most transport occurs (Corbett, 1989), tended to be within the range of windblown sand sizes as proposed by Bagnold (1941).

Major dust clouds observed in satellite images suggest a large input of fine sediment, some of which is indicated to be very fine sand. While a first-order estimate of several million tons of sediment input during a large bergwind event (Shannon and Anderson, 1982) has been made, this estimate considers plumes extending as far as 200 km offshore. As the project area (to 40 m depth) extends only a few kilometres offshore (generally less than 10 km) the fine sediment input to this area would be considerably less than the total estimated for the entire BCLME. Furthermore, calculations and modelling (Section 6) indicate fine sediment to be highly mobile, which means that it would settle only during rare calm events. As a result, fine sediment it is likely to be mobilised and transported out of the project area by currents fairly rapidly.

Coastal currents

Coastal currents may play a role in supplying sand to the project area, particularly at the southern boundary. However, it is likely that this sand input is roughly balanced by similar loss of sand at the northern boundary of the project area. If that were not the case, one would expect an imbalance to manifest itself in the form of either shoreline erosion or accretion. No obvious shoreline change has been determined.

In addition to transporting sand, currents transport fine sediments in suspension both into and out of the shallow (less than 40 m depth) regions of the project area. Modelling studies (Section 6) and calculations of sediment mobility in the wave-dominated shallow region indicate a tendency for fine sediment to deposit offshore. Therefore, unless sediments borne by coastal currents are replenished by a source (such as rivers, as already identified above), it is more likely that such currents will serve as a fine sediment sink to the project area.

Furthermore, as will be shown in Section 6, the primary role of currents is not the supply of sediments, but rather the transport and redistribution of sediments within the project area.

5.3 MINE SEDIMENT INPUTS

5.3.1 Rates

Table 5.7 provides information on past sediment inputs into the inter-tidal zone in southern Namibia, from land-based diamond mining operations. The data were compiled from various reports (CSIR, 1996a; CSIR, 1996b; CSIR, 2002; CSIR, 2005a) together with data supplied by mining companies. Several sources of sediment input are indicated in the table, as follows:

- Seawalls. Sand seawalls constructed both on the original shoreline and seaward of the original shoreline erode, causing a significant sand supply to the near-shore zone. The volumes of sediment input to the project area (from erosion) are derived from figures provided by Namdeb Diamond Corporation. In some places it is known that seawalls existed; however, no volumes were available. In such instances estimates of volumes eroded were made (indicated in italics in Table 5.7);

- Plant tailings discharges (labelled “Plant” in the table). Volumes were supplied by Namdeb Diamond Corporation;
- Dredger tailings, resulting from the onshore dredging activities about 14 km north-west of the Orange River mouth (mine location G68-G90);
- Screening plants (termed “Screen” in the table). In early stages of mining, tailings were dumped partially in the inter-tidal zone. For the period prior to 1979, it was assumed that 10% of these tailings were eroded and served as input to the near-shore zone (CSIR, 1996a). Only this 10% of the volumes dumped is indicated for this early period. In addition, recent wet infield screening results in tailings discharged directly to the inter-tidal zone – this input is recorded in the table;
- Discharges of sediment resulting from marine dredging in the Chameis Bay region.

Figure 5.6 illustrates cumulative sediment input (from seawall mining, plant discharges and dredger tailings) to the near-shore region in southern Namibia. About 404 million tons of sediment were discharged by early 2005.

Significant future sediment inputs are possible: estimated discharges to 2012 are provided in Table 5.8. This table is by no means complete and only represents some possible future sediment inputs. The following should be noted:

- The WOMS (Wet Overburden Mining System) dredger tailings discharge is likely to continue (at the same rate as presently in progress just north of the Orange River) to mid-2015 (CSIR, 2005a);
- No. 3 Plant, No. 4 Plant and PTF tailings have been estimated up to 2012 (CSIR, 2005a). It is uncertain what is anticipated beyond this time;
- Marine dredged tailings will continue beyond 2007 if this project is found to be successful. It is conceivable that the rate will increase by 2 to 3 times after 2010 and continue for several years (du Preez, Namdeb Diamond Corp, pers. Comm.). It is assumed for now that the project is successful and will continue at the same rate to at least 2012;
- The Pocket Beaches Site 11 and 12 dredger tailings are based on an assumed dredging start date of 1 April 2006 (CSIR, 2005a);
- Elizabeth Bay discharge (CSIR, 2002) is estimated to continue at the same rate until mid-2013.

Table 5.7 lists all sediment discharges between the years 1968 and 2005 between Oranjemund and Elizabeth Bay. The table has been split in to 4 sections:

1. Discharges from 1968 to 1990 for mine reference positions G0 to U40;
2. Discharges from 1968 to 1990 for mine reference positions U40 to Elizabeth Bay;
3. Discharges from 1991 to 2005 for mine reference positions G0 to U40;
4. Discharges from 1991 to 2005 for mine reference positions U40 to Elizabeth Bay.

Table 5.7: Mine sediment discharges (tons)/…

Table 5.7: Mine sediment discharges (in tonnes). (Years 1968 to 1990; Mine position references G0-G2 to U37-U40)

Sediment discharge type	Approx. distance from Orange Mouth (km)	Mine position reference	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Seawall	6.7	G0-G2																							
Seawall	7.0	G3-region																						587257	832165
Plant	7.7	PTF																					433589	1004207	1118959
Seawall	8.5	G13-G25																						746514	94864
Screen	9.6	G30/G32					69219	83704	90729	26527															
Seawall	10.4	G40-G44																							
Seawall	10.8	G44-G47																							
Seawall	11.1	G47-G50																							
Seawall	11.4	G50-G54					360000	360000	360000	360000															
Seawall	11.8	G54-G57					360000	360000	360000	360000															
Seawall	12.1	G57-G60					183600	183600																	
Seawall	12.4	G60-G63					183600	183600																	
Seawall	12.7	G63-G67					183600	183600																	
Seawall	13.1	G67-G71					183600	183600																	
Seawall	13.9	G75-G80																						1474970	694908
Dredger	14.3	G68-G90																							
Seawall	15.4	G90-G93					693000	693000																	
Plant	15.8	4 Plant					3270001	2959999	2680000	2740000	2599999	2973931	2858377	2790571	2843654	2626072	2606081	1830076	1131516	1061669	2699417	2748911	2749504	3095824	2898772
Plant	15.8	Recovery tailings treatment																			17854	38338	24650	20521	11700
Seawall	15.7	G93-G96						693000	693000																
Seawall	16.0	G96-G99							1134000	1134000															
Seawall	16.3	G99-G104								1512000	1512000														
Seawall	16.8	G104-G107									736200														
Seawall	17.0	G107-G110										736200													
Seawall	17.3	G110-G113											736200												
Seawall	17.7	G113-G116												736200											
Seawall	17.9	G116-G119												736200											
Screen	18.5	G122					104225	110000	113242	101682	90040	31772													
Seawall	18.5	G122-G125													736200										
Seawall	18.9	G125-G128														736200									
Seawall	19.2	G128-G131														736200									
Seawall	19.4	G131-G134															736200								
Seawall	19.7	G134-G139															736200								
Seawall	20.2	U0-U3																1939563	5517963						
Screen	20.5	U0/U2					46173	8199											6810	75980	74074	71012	61224	54680	27196
Seawall	20.6	U3-U4																		716539					
Seawall	20.8	U5-U6																		3051272					
Seawall	21.0	U7-U8																		1456526	673677				
Seawall	21.2	U9-U10																			844038				
Seawall	21.4	U11-U12																			2769309				
Seawall	21.6	U13-U14																			1653651				
Seawall	21.8	U15-U16																			608661				
Seawall	22.0	U17-U18																			789075	3452211			
Seawall	22.2	U19-U20																				1003995			
Screen	22.3	U20					40189	80207	99621	91603	77597	15071													
Seawall	22.4	U21-U22																				2116677	2526098		
Seawall	22.6	U23-U24																					2843359	538632	
Seawall	22.8	U25-U26																						2721240	2024896
Plant	22.9	3 Plant										1860000	2310000	208500	208500	104250	0	0	0	0	0	144530	2364590	2522744	2627022
Seawall	22.9	U26-U30																							62735
Seawall	23.3	U30-U34																							
Seawall	23.7	U34-U37																							
Seawall	24.0	U37-U40																							

Table 5.7-continued: Mine sediment discharges (in tonnes). (Years 1968 to 1990; Mine position references U40-U43 to Elizabeth Bay)

Sediment discharge type	Approx. distance from Orange Mouth (km)	Mine position reference	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Seawall	24.3	U40-U43																							
Screen	24.6	U42					111499	153993	149673	147252	118679	103535	58606								9412	49080	40192	34226	39798
Seawall	25.3	U50-U54																						199091	
Seawall	25.7	U54-U58																							425479
Seawall	26.1	U58-U60																							
Seawall	26.3	U60-U65																							
Seawall	27.3	U70-U73																							616500
Seawall	27.6	U73-U75																							
Seawall	27.8	U75-U77																							
Seawall	28.0	U77-U81																							
Seawall	28.4	U80-U86																							
Screen	29-36	Wet Infield screeing																							
Seawall	29.8	U95-U97																						121727	926964
Seawall	30.0	U97-U99																							
Seawall	30.3	U99-U106																							
Screen	30.5	U104					18211																		
							1821																		
Seawall	33.8	U138-U141																						870046	214027
Screen	34.3	U142					86310	80611	94517	93830	91989	84689	52297								22959	37141	31992	24682	24682
Seawall	35.9	U155-U160																						731088	528736
Seawall	36.4	U160-U185																							
Seawall	40.3	M18																							655030
Seawall	42.4	M33																							
Seawall	43.4	M47																						716649	248993
Seawall	45.2	M62																				756			5492
Seawall	49.6	M107																							
Seawall	50.1	M115																							
Plant	53.1	2 Plant								1110000	1510000	1700000	2380000	1910000	1910000	1910000	0	0	0	0	0	2266780	2253560	2161466	2293946
Seawall	54.1	M154																							
Seawall	54.6	M159																							
Seawall	56.6	M175																				267874			
Seawall	57.6	M186																							
Seawall	57.6	M189																							
Seawall	58.3	K3																							
Seawall	60.3	K26																							
Seawall	66.0	K84																							
Plant	79.0	1 Plant	776180	776180	776180	776180	1530000	1570000	1490000	1320000	1300000	1390000	1340000	1269398	1295699	1268626	1184434	706391	618710	1138538	1300334	1197265	281804	464769	200851
Plant	approx 98.6	Chameis																							
Seawall	98.7	C4																						16114	
Seawall	100.2	C18																							
Seawall	101.5	C33																						1879	
Seawall	102.3	C42																						6880	
Seawall	103.8	C54																						36427	
Seawall	104.6	C64																							
Seawall	105.5	C70																							
Seawall	106.6	C86																						810	
Plant	approx. 120	Pocket Beaches Site 2																							
Dredging	approx. 120-130	Chameis Bay Region																							
Plant	approx. 240	Elizabeth Bay																							

Table 5.7-continued: Mine sediment discharges (years 1991 to 2005; mine position references G0-G2 to U37-U40) and the total sediment discharge between 1968 and 2005.

Sediment discharge type	Approx. distance from Orange Mouth (km)	Mine position reference	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005.33	TOTAL
Seawall	6.7	G0-G2			136249													136249
Seawall	7.0	G3-region	2779900	2118911	1556924	313231	1564074	1137341										10889804
Plant	7.7	PTF	955982	961376	1001932	1053962	1096203	1053753	1304523	1587233	1704553	1660252	1010956	1236361	1139230	1425818	422689	20171577
Seawall	8.5	G13-G25	394198	29693	141298	819736	1139400											3365703
Screen	9.6	G30/G32					1000000											1270179
Seawall	10.4	G40-G44				828000	1440000											2268000
Seawall	10.8	G44-G47			1289696													1289696
Seawall	11.1	G47-G50		463169	771698	535160	447646											2217672
Seawall	11.4	G50-G54																1440000
Seawall	11.8	G54-G57																1440000
Seawall	12.1	G57-G60																367200
Seawall	12.4	G60-G63																367200
Seawall	12.7	G63-G67																367200
Seawall	13.1	G67-G71																367200
Seawall	13.9	G75-G80	26359					189734										2385972
Dredger	14.3	G68-G90							3782040	5741583	5723046	6239341	6301537	8056431	4788932	5824439	495554	46952903
Seawall	15.4	G90-G93																1386000
Plant	15.8	4 Plant	2826889	3992587	1576226	1506722	953743	1031999	815557	1019356	830999	766525	558643	844465	846009	871699	106540	67712332
Plant	15.8	Recovery tailings treatment	6684	1522	159	1953	1866	15716	13585	2041	0	0	0	7515	6464	8506		179073
Seawall	15.7	G93-G96																1386000
Seawall	16.0	G96-G99																2268000
Seawall	16.3	G99-G104																3024000
Seawall	16.8	G104-G107																736200
Seawall	17.0	G107-G110																736200
Seawall	17.3	G110-G113																736200
Seawall	17.7	G113-G116																736200
Seawall	17.9	G116-G119																736200
Screen	18.5	G122																550962
Seawall	18.5	G122-G125																736200
Seawall	18.9	G125-G128																736200
Seawall	19.2	G128-G131																736200
Seawall	19.4	G131-G134																736200
Seawall	19.7	G134-G139																736200
Seawall	20.2	U0-U3																7457526
Screen	20.5	U0/U2																425348
Seawall	20.6	U3-U4																716539
Seawall	20.8	U5-U6																3051272
Seawall	21.0	U7-U8																2130203
Seawall	21.2	U9-U10																844038
Seawall	21.4	U11-U12																2769309
Seawall	21.6	U13-U14																1653651
Seawall	21.8	U15-U16																608661
Seawall	22.0	U17-U18																4241286
Seawall	22.2	U19-U20																1003995
Screen	22.3	U20																404288
Seawall	22.4	U21-U22																4641775
Seawall	22.6	U23-U24																3381991
Seawall	22.8	U25-U26																4746136
Plant	22.9	3 Plant	2955308	2880949	2168498	2573155	2716516	2735693	2096642	2297462	1876657	1821553	1758312	2586184	2631515	2442568	706473	46597622
Seawall	22.9	U26-U30	1317600															1380335
Seawall	23.3	U30-U34	792218															792218
Seawall	23.7	U34-U37	453100															453100
Seawall	24.0	U37-U40	22099	206843														228942

Table 5.7-continued: Mine sediment discharges (years 1991 to 2005; mine position references U40-U43 to Elizabeth Bay) and the total sediment discharge between 1968 and 2005.

Sediment discharge type	Approx. distance from Orange Mouth (km)	Mine position reference	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005.33	TOTAL
Seaw all	24.3	U40-U43		693124	155174													**848299**
Screen	24.6	U42	2500	13091	11718	10015	7852	1035										**1062155**
Seaw all	25.3	U50-U54	1317600	1317600														**2834291**
Seaw all	25.7	U54-U58	1317600	1317600														**3060679**
Seaw all	26.1	U58-U60	608809															**608809**
Seaw all	26.3	U60-U65		361391	4165	456340	603450	484321										**1909667**
Seaw all	27.3	U70-U73	897473	1317600														**2831573**
Seaw all	27.6	U73-U75	328923															**328923**
Seaw all	27.8	U75-U77	130750	22329														**153079**
Seaw all	28.0	U77-U81		443898	174969	13019												**631886**
Seaw all	28.4	U80-U86			331025	701161	425412	161577										**1619176**
Screen	29-36	Wet Infield screeing											558829	1090086	834266	2822240		**5305421**
Seaw all	29.8	U95-U97	482508	1317600														**2848799**
Seaw all	30.0	U97-U99	281599	367528														**649127**
Seaw all	30.3	U99-U106			403069	950544	1055093	358623										**2767329**
Screen	30.5	U104																**18211**
Seaw all	33.8	U138-U141		166333														**1250406**
Screen	34.3	U142	5950	3915	3888	2695	3436	3505	2663									**751752**
Seaw all	35.9	U155-U160	650588	343190	1067			410186										**2664855**
Seaw all	36.4	U160-U185		745031	389297	649548	790011	122004										**2695891**
Seaw all	40.3	M18	587201	267228														**1509459**
Seaw all	42.4	M33		602042	923699	852499	385886	138200										**2902326**
Seaw all	43.4	M47																**965642**
Seaw all	45.2	M62	399624	1512		854												**408238**
Seaw all	49.6	M107				182306	35711											**218017**
Seaw all	50.1	M115					622357	234209										**856566**
Plant	53.1	2 Plant	2519150	2321696	1851787	1985036	1671693	1872234	1930914	1332740	1230635	1186921	337333	341997	332649	494903		**40815439**
Seaw all	54.1	M154	5120	241146	592843													**839109**
Seaw all	54.6	M159			396034													**396034**
Seaw all	56.6	M175																**267874**
Seaw all	57.6	M186	2970															**2970**
Seaw all	57.6	M189	11232															**11232**
Seaw all	58.3	K3			83060													**83060**
Seaw all	60.3	K26	43053															**43053**
Seaw all	66.0	K84					185250	7248										**192498**
Plant	79.0	1 Plant														313200		**24284738**
Plant	approx 98.6	Chameis	360972	372920	279473	292776	269496	288039	282425	62006	11046							**2219153**
Seaw all	98.7	C4	118554	131884			16016	52942										**335510**
Seaw all	100.2	C18			41428	250805	156											**292389**
Seaw all	101.5	C33	7924				35860	329										**45992**
Seaw all	102.3	C42		124582	712													**132174**
Seaw all	103.8	C54	374605	331632	350803	2761	6345											**1102573**
Seaw all	104.6	C64			76304	280835	72362											**429501**
Seaw all	105.5	C70			*7923*	*306381*	*497062*	*161736*										***973102***
Seaw all	106.6	C86		359130	64501	40060	2732											**467233**
Plant	approx. 120	Pocket Beaches Site 2														834937	337104	**1172041**
Dredging	approx. 120-130	Chameis Bay Region															7443	**7443**
Plant	approx. 240	Elizabeth Bay	1101314	3068415	1462966	1449364	1519160	1380785	1385474	1389112	1346171	1171129	1273719	1261609	1267159	1637795	523915	**21238087**

Table 5.8: Future sediment discharges (tons)

Sediment discharge type	Dredger (WOMS)	Plant	Plant	Plant	Marine dredged tailings	Dredger tailings	Plant
Approx. Distance from Orange Mouth (km)	**4 to 13**	**7.7**	**15.8**	**22.9**	**29.0**	**Approx 170**	**Approx. 240**
Mine Position Ref	**G-16 to G68**	**PTF**	**4 Plant**	**3 Plant**	**U90**	**Pocket Beaches 11&12**	**Elizabeth Bay**
YEAR							
2005 (from April)		921659	897129	1205333			2875000
2006	7900000	1375000	1491600	629000	1345500	8000000	3054688
2007	10500000	1375000	1491600	950000	1495000	3700000	3234375
2008	10500000	1375000	1491600	950000	1495000		3234375
2009	10500000	1375000	1491600	950000	1495000		3234375
2010	10500000	1375000	1491600	950000	1495000		3234375
2011	10500000	1375000	1491600	950000	1495000		3234375
2012	10500000	1375000	1491600	691750	1495000		3234375
TOTAL:	70900000	10546659	11338329	7276083	10315500	11700000	25335938

From Table 5.8 it is estimated that in the next 7 years the sediment discharge volume would be almost 147 million tons. This is equivalent to the discharged volume over the last 12.5 years. Thus, the rate of sediment input relative to the last 12.5 years will be almost doubled.

Limited data on discharges from mining vessels operating within the project area (<40 m depth) have been obtained. Most of the available information only provides some idea of the location of mining operations. Just south of Lüderitz (Figure 1.1), in the region shown in Figure 5.7, boat-based and shore-based small-scale mining has occurred, together with contractor “mid-water” mining (i.e. 30-80 m depth). Between 1999 and 2001, limited sampling operations took place in the region south of Halifax Island. In total, limited mining has been conducted in this area.

A little further south (just north of Elizabeth Bay – Figure 1.1), some boat-based and shore-based diver mining has occurred in the Zweispitz area (Figure 5.8). Limited sampling operations were conducted by De Beers Marine from 1999 to 2001 near Peninsular Extension, and in the Peninsular and Channel areas (Figure 5.8). In the channel area a total 71883 m^2 has been mined (C. August, De Beers Marine Geologist, pers. comm., 1995). Limited mid-water mining was conducted by Transhex in 2002 and 2003 (approximate location outlined in the Channel area in Figure 5.8). De Beers Marine also conducted limited mining landward of the Channel sites (approx. location Figure 5.8) in 2004. Available information indicates that an area of 13 116 m^2 was mined about 5 km to the south-west of Elizabeth Bay, in about 60 m water depth. Estimates of mining rates of De Beers Marine vessels range from 136 to 580 tons/hour (this range of estimated rates is for crawler and drill vessels). Mining in the proximity of Elizabeth Bay, where sediment is discharged from a plant, raises questions of the possible cumulative effect of simultaneous plant and vessel discharges. This is explored in Section 8.

Further south, mid-water mining (30 m to 80 m depth) was conducted by Transhex in the Blackrock and Bogenfels area (i.e. opposite and north of Bogenfels – Figures 1.1 and 5.9) on an irregular basis up to 2004. Contractor mining company YAM operated approximately in the area shown in Figure 5.9, from the early 1990s to 2002. De Beers Marine Namibia conducted limited sampling operations between Blackrock and Bogenfels.

In the region at and just north of Chameis Bay (location, Figure 1.1), limited boat-based diver operations have been conducted in less than 15 m depth. In addition, near-shore vessel mining occurred in the 1960s. More recently, dredger mining of Panels 1 and 3 (Figure 5.10) occurred – the estimated sediment input from the vessel was relatively minor (about 7400 tons - Table 5.7).

In the Kerbe Huk area (Figure 5.11) just north of Namdeb's No. 2 Plant (about 53 km north-west of the Orange River mouth), inshore boat-based diver operations have been conducted. This region is an established rock lobster fishing area.

In these various vessel mining regions the identification of future target areas (shown in Figures 5.7 to 5.11) indicates a likelihood of continuation of these operations.

No other data on sediment discharges are currently available. In South Africa it is known that mining with coastal seawalls has occurred and is currently practised. At present small-scale seawall mining is conducted just north of the Olifants River (e.g. Figure 5.12). Significant seawall operations have been and are being conducted near Alexander Bay. For example, a seawall mining operation was conducted on the rocky coast a few kilometres south of the Orange River (CSIR, 1996c; CSIR, 1997), at some time around 1996/1997. A volume of sand in the region of 180 to 360 tons/hour was supplied to a seawall in an operation lasting roughly 2 years. The total sand input was probably in the region of 3 to 6 million tons. The scale of these operations is not as major as that executed in southern Namibia. This is further mitigated by the discharging practice: since South African mines are not permitted to discharge tailings into the sea, tailings are discharged into slimes dams.

5.3.2 Grain sizes

Most of the sediment discharges in the region are comprised of sand. However, a small percentage of fine material occurs. Details are as follows:

- Seawalls in South Africa are generally constructed from beach sand and/or coarser materials, such as cobbles or large rock fragments (e.g. Figure 5.12). It is unlikely that a large fines content occurs from seawall erosion;
- Seawalls in Namibia have been generally constructed from coarse overburden sand. Fine sediment originating from seawall erosion is probably negligible;
- Information on grain-size distributions of discharge material from the PTF Plant, No. 4 Plant and No. 3 Plant (CSIR, 1996a and CSIR, 1998b) indicates about 1% fine

material. No information is available on the grain sizes of No. 2 Plant and No. 1 Plant;

- A fine sediment percentage of 1% was indicated for the WOMS dredger discharge (CSIR, 2003a);
- The percentage fine material for the Beachcomber discharge is not known. However, a lack of significant fine sediment plumes observed at the discharge in seven sets of aerial photographs between 1997 and 2000 suggests this to be very small;
- 85% of the relatively small amount of sediment discharged from dredging operations is fine, as indicated from a series of samples (CSIR, 2005c). The grain-size distribution of this material is depicted in Figure 5.13;
- 14% of the plant tailings discharged at Pocket Beach Site 2 that originated from land-based mining (Pocket Beach Site 2) in the region was fine (85% sand and 1% was gravel), as indicated from limited sampling (CSIR, 2005c). The grain-size distribution of this fine sediment is illustrated in Figure 5.13;
- At most, 2% of the plant tailings discharged at Pocket Beach Site 2 that originated from the sea-bed (as a result of shallow marine dredging operations) was fine, as indicated from limited sea-bed sampling (CSIR, 2005c);
- Dredger tailings at Pocket Beach Site 11 & 12 is indicated to have a small fraction of fine sediment (2% of the material is finer than 125 microns – some of this may be finer than 63 microns). Plant discharge content at this site is not known;
- At Elizabeth Bay the most up-to-date information indicates a fine sediment content of up to 5% (CSIR, 2004).

Thus, it is evident that, apart from the marine dredger discharge, by far most of the material discharged is sand. Table 5.9 below provides the grain-size distributions of the sand content of the various tailings and dredging discharges. It is important to note the following:

- Data from the PTF Plant, No. 4 Plant and No. 3 Plant indicated that medium to coarse sand was discharged at these plants. The data suggest that a minor fine sand and silt/clay content occurs. However, experience has shown that accretion opposite these plants is less than expected for sediment of the sizes indicated in Table 5.9 (CSIR, 1996a; CSIR, 1998b; CSIR, 2000a; CSIR, 2002b). This suggests that the sediment has a finer distribution than that measured (Table 5.9). Plumes observed near plant discharges also suggest that a significant percentage of fine sediment occurs;

- The dredging discharge data for the *Beachcomber* vessel were derived from detailed sampling of a series of 21 boreholes;
- The WOMS dredger discharge is derived from a single representative sample (CSIR, 2002b);
- The grain-size distribution indicated in Table 5.9 for the Chameis Bay dredging is only for the overspill of the sand fraction (which was 15% of the overspilled material on average);
- The "land" material discharged at Pocket Beach Site 2 originated from land-based mining in the region. This material had 85% sand (14% was fine sediment and 1% was gravel);
- The "sea" material discharged at Site 2 originated from the sea-bed (as a result of shallow marine dredging operations). This distribution was estimated from a sample obtained on the sea-bed;
- The grain-size distribution of the anticipated discharge at Pocket Beaches Site 11 & 12 is from a representative sample from boreholes in the region to be dredged;
- The grain-size distribution of material discharged from the plant at Elizabeth Bay shows average discharged grain sizes from a series of samples taken annually from 2000 to 2004. Plotting the median grain size over a longer period (Figure 5.14) demonstrates a general increase in grain size from 1993 to 2001, after which a steady grain size of about 300 μm on average has been discharged.

No specific grain size data are available on sediment input from seawall construction and maintenance. Samples of overburden material from which seawalls are constructed provide some idea of this. Samples of overburden material at the Beachcomber Dredger (G68 to G90), the WOMS region, and at Site 11 & 12 (the coastal region) indicate this material to be coarse (Table 5.9). The grain size of overburden material at Pocket Beach Site 3 & 4 is similarly relatively coarse (D_{50}= 476 microns).

Data on the grain sizes of tailings material from vessel mining are very limited. For the De Beers Marine vessel mining operation south-west of Elizabeth Bay (location Figure 5.8) in

2004, available data indicated 50% of the bed material at the site to be comprised of mud, silt and sand, 30% of the material to be from 2 mm to 14 mm size, and 20% greater than 14 mm.

In future it is possible that more fine material will be discharged. The existing plants and additional future land-based dredging operations are expected to yield a small percentage of fines (similar to the present). However, marine dredging will yield a large quantity of fine material. Of an annual input of about 1.5 million tons of marine dredged tailings (Table 5.8), it is estimated that about half will be fine material.

Table 5.9: Grain size statistics (in μm) of plant and dredge sands discharged

Source of material	Date	D5	D16	D50	D84	D95	Reference	Comments
PTF Plant	26/02/1997	185	321	706	1469	1826	CSIR (1998b)	
3 Plant	Jan 1996	203	317	726	1418	1725	CSIR (1998b)	
3 Plant	26/02/1997		107	235	494	776	CSIR (1998b)	Insufficient sample data to estimate the D5
4 Plant	Jan 1996		163	353	1089	1515	CSIR (1998b)	Insufficient sample data to estimate the D5
4 Plant	26/02/1997	168	358	955	1658	1955	CSIR (1998b)	
Beachcomber Dredging (G68-G90)	April 1998	131	212	447	945	1267	CSIR (1998b)	Detailed sampling from 21 boreholes
WOMS	Aug 2002	121	234	710	1306	>2000	CSIR (2002b)	Sample included gravel fraction
Chamies Bay Dredging	Jan 2005	77	87	107	139	180	CSIR(2005c)	Sand represents 15% of the overspill
Plant at Site 2 (land)	Jan 2005	158	250	422	823	1191	CSIR(2005c)	Material mined on land at Site 2
Plant at Site 2 (sea)	March 2005	111	173	601	882	1109	CSIR(2005c)	Most of the discharge is sand (only 2% fines estimated)
Pocket Beaches 11 & 12		148	204	503	1229	1516	CSIR (2005a)	Sample included gravel fraction. Material from the coastal region at Site 11 & 12
Elizabeth Bay plant	2000	155	257	628	1143	1413	CSIR (2001a)	
Elizabeth Bay plant	2001	194	224	334	753	1026	CSIR (2002f)	
Elizabeth Bay plant	2002	122	183	300	551	778	CSIR (2003b)	
Elizabeth Bay plant	2003	119	167	280	482	757	CSIR (2004a)	
Elizabeth Bay plant	2004	128	193	357	584	793	CSIR (2005d)	

5.3.3 Synthesis

According to available data (restricted largely to Namibian coastal mining), 404 million tons of sediment have been discharged into the marine environment between 1968 and the present. About 63% of this material has been discharged between the Orange River mouth and 23 km north of the Orange River mouth (up to No. 3 Plant). About 32% of the material has been discharged between this point 23 km north of the Orange and Chameis Bay. About 5% of the total has been discharged at Elizabeth Bay.

The total sediment input is comprised of the various components indicated in Table 5.10.

Table 5.10: Sediment input from coastal mining in Namibia

Type of discharge	Amount discharged (million tons)	Percentage of total
Seawalls	122.6	30.3
Plant tailings	224.4	55.6
Dredger tailings	46.9	11.6
Discharges from screening	9.7	2.4
Total	**403.7**	**100**

In future the rate of sediment input will change, primarily as a result of both on-land and marine dredging. The rate is anticipated to approximately double in the next few years, and this rate could increase more depending on the success of marine dredging. Most of the discharge is anticipated in the region just north of the Orange River (WOMS in Table 5.8), while other areas of focused discharge will be U90 (about 29 km north-west of the Orange River mouth), Pocket Beach Sites 11 & 12 (near Bogenfels) and Elizabeth Bay.

To date most of the material has been medium to coarse sand. Fine material has comprised at most one or two percent of the total material discharged. More fine material is anticipated in future, particularly as a result of marine dredging. About 5% of the total discharge for the next seven years is anticipated to be fine sediment.

5.4 COMPARISON OF NATURAL VERSUS MINE SEDIMENT INPUTS

5.4.1 Rate of sediment discharged

From the above it is clear that in the early 1900s sediment discharge from the Orange River was about an order of magnitude greater than other sediment inputs to the project area. In recent decades the Orange River sediment input has been less, ranging from an average of 34 million tons/year (1960 to 1969) to an average of less than 17 million tons (1980s). Based on these values, it is likely that 400 to 800 million tons was discharged from 1968 to April 2005.

In comparison, 404 million tons was estimated from available mining data in the same period, indicating the volumes from the two sources to be of the same order of magnitude. However, it must be borne in mind that discharge from the Orange River is not entirely “natural”– as a result of damming and water abstraction, and as a result of poor agricultural practice in the 1930s. Perhaps the best estimate of “natural” Orange River sediment discharge is for the period after the bad agricultural practices of the 1930s, but prior to significant damming in the 1970s. For this period the annual average discharge ranged from 34 to 52 million tons/year. If this discharge rate had persisted during the mining period of 1968 to 2005 (i.e. if no damming, abstraction or catchment erosion had occurred), a total river input in the order of 1600 million tons could have occurred naturally. This is roughly four times the total mining discharge.

The rate of sediment discharge differs for mines and in nature. While mine sediment discharges tend to have a relatively constant rate, natural, flood sediment discharges tend to be large and somewhat more intermittent. Floods (defined as more than twice the monthly average flow) occur about once every 1.4 years. A major flood such as that of 1988 can discharge as much as four times the annual average discharge volume in a matter of a few months (most floods last over a month, with the longest floods lasting for up to 5 months).

While millions of tons of windblown fine sediment has been estimated for the total BCLME, only a fraction of this would be delivered to and would remain in the <40 m depth region, (This material would be rapidly mobilised and transported into deeper water.) From calculations made at a number of sites, sand input to the project area is also estimated to be minor.

5.4.2 Composition

Natural sediment input to the project area tends to be fine. About 84% of sediment from the Orange River is indicated to be fine material. Fine windblown sediment input, primarily from bergwinds, is suggested to be extensive (while net sand input from wind is estimated to be relatively limited). On the other hand, available data indicate that 98% to 99% of the sediment discharged from mining is medium to coarse sand. A small increase in the percentage fines, to about 5% of the total mine discharge, is expected in future, primarily as a result of proposed deep-water marine mining.

6. THE FATE OF FINE SEDIMENT

6.1 INTRODUCTION

As has been explained (in Section 1), processes associated with the dynamics of fine sediment (<63 micron) are different from processes associated with coarse sediment (>63 micron). This chapter focuses on the dynamics of fine sediment only. The following key questions (as posed in the project terms of reference) are addressed:

*How far, and in which directions, are **fine** sediments (input to the near-shore region either naturally or from mine discharges) transported and by what mechanisms, and where in the near-shore zone are they deposited?*

*What is the extent and duration of the natural deposition of unconsolidated **fine** sediments on near-shore reefs and how does this compare with the potential smothering of reefs as a consequence of discharged and mobilised sediments?*

In order to address the latter question, the configuration of near-shore reefs is required. This information is available for southern Namibia only and is shown in Figures 6.1 and 6.2.

6.2 ORANGE RIVER REGION

6.2.1 Background

Historical sediment input

The Orange River is the greatest source of fine sediment to the project area, since it represents 95% of the total fluvial sediment input to the project area, and approximately 85% of this fluvial sediment input is fine (details of the Orange River sediment input: Section 5). The extent of wind-blown fine sediment in the Orange River region is not well defined, but is deemed to be orders of magnitude less that of the Orange River.

Fate of sediment

Whereas coarse sediments (sand and gravel) are carried northward by strong littoral drift (wave-driven currents), Bremner *et al.* (1990) indicate that fine sediment (silt and clay) discharged at the Orange River is entrained in a southward-moving, inshore, counter-current known as the De Decker Current (Bremner *et al.,* 1990). Wind-driven flows are sure to play a major as well (as is evident from various model simulations which follow).

During the Orange River flood a significant southward flow, driven by the strong Orange River flow in combination with the Coriolis force, was found to occur in the absence of strong winds (Shillington *et al.*, 1990). However, at times when winds are dominant and river flow is not extreme, wind-driven flows are expected to dominate.

Deposition of fine sediment on the delta was investigated during and after the major 1988 flood. In May 1988 (well after the flood peak had subsided), mud deposited by the flood was found in the near-shore region from 20 m to 40 m depth to have a thickness of up to 100 mm (Bremner *et al.*, 1990), while deposition of up to 50 mm was observed in a region (situated below a turbid mud plume) shallower than 20 m depth.

Impacts to date

The impact of fine sediment in suspension from the major 1988 Orange River flood was relatively limited on the open coast. Branch *et al.* (1990) indicated that, although turbidity reduced light penetration over wide areas, this turbidity was an unlikely cause of mortalities, even of plants, since survival of kelp was high in deeper waters. Branch *et al.* (1990) also indicate that no accumulation of silt or smothering of organisms was seen at any time during the early stages of the flood. However, it was found in the same study that sediment was trapped by mats of algae (which had temporarily formed as a result of the fresh flood water) – this sediment subsequently proved detrimental to limpets.

6.2.2 Modelling scenarios

Scenario 1: Flood of 1988

Data input for this scenario is discussed in detail in Section 4.2.2. This section describes the massive flows and associated sediment input to the marine environment, combined with late summer/early autumn environmental conditions.

Scenario 2: 1 in 20-year flood

Wave data

This scenario assumed relatively high southerly wave conditions, as could be experienced (and have previously been recorded) in summer. Appropriate wave data were extracted from the offshore Kudu wave data for the period 8 March to 5 April 1998 and the dates adapted to the period of river discharge data. The 36 wave conditions used in this scenario are presented in Appendix K.

Wind data

The period for wind data had to coincide with the period of selected wave data. Therefore, data were obtained which originated from a global atmospheric numerical model operated by the National Centre for Environmental Prediction (NCEP) in the USA. The period extracted was from 7 March 1998 to 6 April 1998, and the dates were again adapted for the period of river discharge.

Tides

As for the flood of 1988 scenario, tides were excluded.

River discharge data

A flood hydrograph of a 1 in 20-year flood constructed by Ninham Shand was selected as river input. The flood occurred during the period 6 February 1996 to 24 March 1996. A salinity of zero was assumed for the flood waters.

The rate of sediment discharge was inferred from distributions of flow versus discharge as presented in Bremner *et al.* (1990). As the sediment modelling requires the percentages of three separate size fractions of fine sediment, the relative percentages provided by Bremner *et al.* (1990) were applied to the data points available in the river hydrograph data. The dates, discharges and sediment concentrations of the flood are tabulated in Appendix L.

6.2.3 Description of results

Flood of 1988

An animation of this simulation is provided on the attached compact disk (CD) – the animation is in the “Orange” directory and is named *1988_flood.avi* (instructions provided with the CD to view this). Figure 6.3 and Figure 6.4 show the results of the flood of 1988 simulation for the bottom and surface water layers respectively, in terms of maximum turbidity and the time that specified concentration thresholds were exceeded. It should be noted that the concentrations depicted in these model results exclude any natural or background concentrations.

Evident from plots of suspended sediment concentration, and the description of the model validation (Section 4.2.3), is the large area covered by the plume (defined here by concentrations greater than 1 mg/l) resulting from the flood. Plume dimensions of up to 50 km offshore are predicted. In this instance, the flood magnitude and the volume of water entering the ocean drive the process that causes the spreading of the plume. River water is essentially fresh and generally warmer relative to sea water; therefore the water is less dense and buoyant upon entering the ocean. The result is that fresh water occupies the upper layers, causing stratification in the area of the river mouth. The effect of the stratification is similar to forming a smooth layer upon which the fresh water flows with ease from the river mouth. Constant forcing from high river flow drives the fresh water offshore. This water slowly mixes with sea water to result in an increase in salinity with distance from the river mouth.

Differences between upper and lower layers can be seen when comparing Figures 6.3 and 6.4. The differences occur primarily due to settling of fine sediment, but the effects of stratification may also play a role.

The scale of the volume of fresh water during the 1988 flood was large enough to yield to the effects of the Coriolis force. Hence, as the river water enters the ocean, at high flow rates, the jet of water is deflected to the left (in accordance with Coriolis forcing). Therefore, the plume exhibits an anti-cyclonic shape, spiralling in an anti-clockwise shape towards the south. This results in high suspended sediment concentrations south of the river mouth. In the bottom and surface layers concentrations between 100 and 200 mg/l, and 20 to 50 mg/l, respectively, can be found up to 40 km southwards. This predicted movement to the south is predicted to reduce at times, due to reduction of river flow or forcing of flow to the north by wave or wind forcing.

Apart from the Coriolis- and wind-influenced plume formed by the river discharge, large volumes of sediment are transported to the north by dominantly north-bound longshore transport. This occurs primarily in the near-shore zone up to a few hundred metres from the shore, but is powerful enough to transport much of the discharged river sediment northwards. As a result of this longshore transport, high concentrations (> 1000 mg/l) are predicted to remain inshore of the 40 m depth contour in the bottom layer and extend almost to the northern end of the model domain (i.e. over 80 km to the north-north-west). In the upper layer concentrations greater than 100 mg/l are predicted landward of the 20 m depth contour, while concentrations of up to 500 mg/l are predicted at the 40 m depth contour.

Figure 6.5 shows the results of the flood of 1988 simulation, in terms of maximum deposition and times for which the deposition thicknesses of 0.05, 0.2 and 1 mm were exceeded. It should be noted that the deposition depicted in these model results excludes any natural or background deposition which existed prior to the flood. In accordance with the literature, as described in Section 4.2.3 on model validation, a pro-delta (deposition forming the foundation of the delta-forming processes) is predicted in the immediate area of the river mouth. Deposition of more than 5 mm is predicted over a large extent of the model domain, mainly beyond the 40 m depth contour, except in the area adjacent to the river mouth, where it is more localised. South of the river mouth, deposition of greater than 5 mm is predicted up to 40 km away from the river mouth. Deposition in this southern region is also predicted only seaward of the 40 m depth contour. Finally, it is interesting to note that deposition is predicted to extend to close to the rocky reef areas. But these areas are not predicted to be smothered with sediment for any sustained period. This suggests that the extent of predicted deposition correlates reasonably well with the extent of historically deposited sediment.

As mentioned above, discharged river sediment is predominantly driven northwards. After the flood simulation, it was calculated that 73% of total discharged sediment remained within the model domain (an area of 48 km x 174 km – see Figure 4.1). This percentage includes sediment in suspension and sediment deposited on the seafloor. This indicates that the volume of fine sediment discharged was so large that prevailing flows could not transport most of the material beyond the model domain in the two-month modelling period. The retention of fine material on the sea-bed (as indicated in Figure 6.5) is supported by evidence of deposited mud offshore of the Orange River (Bremner *et al.,* 1990).

1 in 20-year flood

An animation of this simulation is provided on the attached compact disk – the animation is in the “Orange” directory and is named *1in20yr_flood.avi*. When compared to the results of the flood of 1988, it is clear that processes driving suspended sediment plume dynamics are different for the 1 in 20-year flood. Figures 6.6 and 6.7 illustrating predicted suspended sediment statistics for the bottom and surface layers respectively, show that sediment is primarily driven northwards by wind and the relatively high summer waves. In addition, the jet effect (i.e. the effect of high momentum of a large mass of water), as displayed with the flood of 1988 simulation, is no longer prevalent. Concentrations greater than 1 mg/l are predicted as far 30 km offshore in the bottom layer and extend to the northern end of the model domain. The plume is predicted to reach up to 20 km southwards, with rapid tapering of concentrations indicating that extension of the plume far south rarely occurs.

In the upper layers similar patterns exist, but predicted concentrations do not reach as far offshore as for the bottom layers.

Deposition during the simulation (Figure 6.8) was not as extreme as with the flood of 1988. Patches of deposition greater than 5 mm, up to 20 km in length, are predicted just north of the river mouth, between Uubvlei and No. 2 Plant, and near the northern model boundary. No deposition is predicted to the south of the river mouth. Deposition is predicted to occur beyond the 40 m depth contour and rarely landward of the 20 m contour. As for the 1988 flood case, predicted deposition extends to close to the rocky reef areas. But these areas are not predicted to be smothered with sediment for any sustained period. This suggests that the extent of predicted deposition correlates with the extent of historically deposited sediment.

In this simulation, 26% of the total sediment input into the model remained in the model domain of 58 km x 174 km (Figure 4.1) at the end of simulation. This is a marked reduction compared to the flood of 1988, reflecting the efficiency of physical conditions (particularly the summer southerly wind and waves) playing a prevalent role in transporting sediment to the north and out of the model bounds.

6.2.4 Effects/impacts

In terms of effects and impacts, only the bottom layers will be discussed. The reason for this is that a primary focus of this study is the impact of elevated sediment concentrations (which are highest near the sea-bed) and of deposition on rocky reef habitats (and therefore on rock lobster).

It is important to note with all exceedance of threshold values that the percentage exceedance represents a fraction of the total simulation time. This total exceedance time (defined as a percentage of total simulation time) at any point in the model domain is generally made up of several events.

Concentrations

For the 1988 flood case, exceedance of the 100 mg/l concentration threshold is predicted up to 40 km offshore in the region south of the Uubvlei Plant. However, this offshore extent of elevated concentrations is predicted to reduce to the north (Figure 6.3). Inshore of the 40 m depth contour, exceedance of the 100 mg/l threshold value (as discussed to be indicative of impact in Section 2.3.4) is predicted for over 40 % of the total simulation time (approximately 25 days). Inshore of the 20 m depth contour exceedance of 100 mg/l is predicted for more than 80% of the time (50 days). The times of predicted exceedance of elevated concentrations reduce towards the northern model boundary, with exceedance of 100 mg/l at the boundary predicted to be less than 1% of the time (less than one day). Based only on an assessment of impact defined by the exceedance of the 100 mg/l threshold for more than ”hours to days”, an extensive area of impact on biota, extending a few kilometres offshore and over 70 km alongshore, would be expected.

Figure 6.6 shows predicted maximum turbidity and the predicted time exceeding the 10, 50 and 100 mg/l concentrations in the bottom layer for the 1 in 20-year flood. Exceedance of the 100 mg/l is generally predicted landward of the 40 m depth contour, with the concentration being exceeded for longer periods (longer than 50% of simulation time, approximately 24 days) landward of the 20 m depth contour. Time of predicted exceedance of elevated concentrations does reduce somewhat towards the north. Based only on an assessment of impact defined by the 100 mg/l for more than “hours to days”, a considerable area of impact on biota, extending kilometres offshore and over 70 km alongshore, may be expected.

Deposition

Figures 6.5 and 6.8 display the time when deposition exceeds 0.05, 0.2 and 1.0 mm and the maximum deposition ever reached during the flood of 1988 and 1 in 20-year flood simulations respectively.

In both scenarios, predicted maximum deposition beyond the 40 m depth contour is considerable and persists for long time periods. Shoreward of the 40 m depth contour, predicted exceedance of 1.0 mm of deposition reduces to less than 10 to 20% (approximately 12-24 days). The exception is the case of the 1988 flood, where the delta formed just seaward of the river mouth by the flood will have a significant impact due to the thickness of deposition and the period of deposition (>90%, which is approximately 57 days).

Exceedance of 1 mm deposition appears to be increased in the areas of rocks and reef (delineated on the plots with grey/silver) for the 1:20 year flood case. Generally, deposition thicknesses are predicted to persist for longer periods in the reef area. Close to the northern model boundary, an isolated spot occurs where 1.0 mm of deposition is exceeded for between 10 and 50% of simulation time (approximately 5 to 24 days).

In summary, the 1988 flood simulation indicates some major (several cm thickness) and persistent deposition. While impact would be expected, only a limited part of the deposition is predicted to occur on rocky reefs. For both floods tested, the deposition on rocky reef is neither defined as low/neutral ("sub-millimetre for hours to days" – Table 2.2) or as high impact ("cm to metres for years to decades"), but is somewhere in between these extremes.

Finally, comparing the 2 floods, it appears that the lesser flood (1:20 year) has more impact in terms of deposition and the greater 1988 flood more impact in terms of suspended sediment concentrations.

6.3 SOUTHERN NAMIBIA MINING AREA

6.3.1 Background

Historical sediment input

The southern mining area (loosely defined here as the region from the Orange River mouth to about 100 km to the north-west) has had the highest input rate of mine sediments of any region. This commenced in earnest in the late 1960s to early 1970s. The discharge has primarily taken the form of coarse sediment. Fine sediment content of plant and dredging discharges in the order of 1% and less has been indicated from limited sampling (Section 5).

Fate of sediment

Fine sediments from plant and coastal dredging are discharged into the inter-tidal zone. From here, swash wave action (particularly at high water) carries sediments into the surf zone. Turbulence associated with breaking waves keeps fine sediments in suspension and prevents any deposition in this zone. Wave-driven longshore currents transport the suspended fine sediments alongshore. In the southern mining area, these currents are largely northbound.

Fine sediment is also ejected by rip currents to beyond the surf zone into deeper water, where it is subject to transport by currents, primarily those generated by wind. As the winds are predominantly from the southerly sector, predominantly northbound transport of fine sediments would be expected.

Impacts to date

No impacts from fine sediment discharged from mining in the southern area have been found from limited assessments (e.g. CSIR, 2003a). It is likely that when the rates of fine sediment are compared to historical sediment input from the Orange River, they will be relatively minute. Therefore associated impacts in this region are probably not meaningful. This issue will be explored further by means of modelling.

6.3.2 Modelling Scenarios

The 'Future' Scenario

While fine sediment inputs in the southern area have apparently not been major to date, future potential fine sediment discharges from processing of mine-dredged sediment may be considerable. To simulate the fate and behaviour of potential future mine sediment discharge in the southern mining area, the model set-up used for simulations of the Orange River was employed. In this scenario the simulation period and coastal hydrodynamic conditions corresponding to the 1 in 20-year flood scenario (Section 6.2.2) were used.

Five mine discharges were simulated: PTF Plant, WOMS (discharge of fine sediment from dredging situated between the Orange River and No. 4 Plant), No. 4 Plant, No. 3 Plant and

Uubvlei Plant. The coordinates and rates of discharges are tabulated below. These were derived from data on planned discharges, as provided by Namdeb. Most recent data indicate the fines discharge at Uubvlei (from processing of marine dredged material) to be approximately correct: roughly 700 000 tons of fine material is to be discharged in 2007. However, a potentially large increase may occur if marine dredging proves successful.

Table 6.1: Locations and rate of fine sediment discharge of the five mine discharge sites included in the future scenario of the Southern Area.

Discharge Site	tons/year
WOMS	120 000
PTF Plant	14 000
No. 3 Plant	20 000
No. 4 Plant	9 000
Uubvlei Plant	735 000

6.3.3 Description of results

As for the above (Orange River) case, only the bottom layers will be discussed. This is because the primary focus of this study is the impact of elevated sediment concentrations and of deposition on rocky reef habitats (and therefore on rock lobster). In any event, the surface and bottom sediment concentrations are similar for this simulation (see Figures 6.9 and 6.10).

An animation of this simulation is provided on the attached compact disk – the animation is in the "Orange" directory and is named *Mine_discharge_only.avi* (instructions for viewing are provided with the disk). Figure 6.9 shows predicted suspended solids concentrations, for the bottom layer, of the future mine discharge scenario. It is reiterated that the concentrations depicted in these results exclude any natural or background concentrations. From the 'Max turbidity reached' plot it is evident that in the area adjacent to the three most southern discharge points (PTF, No. 4 Plant and No. 3 Plant) concentrations are relatively lower, as expected due to low discharge rates. Adjacent to Uubvlei concentrations are higher and extend further offshore (by over 10 km). Beyond the 40 m depth contour, concentrations do not exceed 20 mg/l. However, concentrations greater than 100 mg/l occur inshore of the 20 m depth contour. The plume extends south of Uubvlei by approximately 10 km, but maximum concentrations occurring in this area are low. On the other hand, the plume extends to the north of Uubvlei by roughly 60 km (i.e. at least to the model boundary).

Deposition is predicted to occur in more or less the same area as the suspended sediment plumes (see Figure 6.11) with maximums reaching 0.2 mm between the Uubvlei discharge site and Kerbe Huk. It is reiterated that the deposition depicted in these model results exclude any natural or background deposition that existed prior to mine discharges. An isolated area of deposition between 0.05 mm and 0.1 mm thick is predicted near the model boundary.

At the end of simulation, only 5% of total sediment input was predicted to remain within the model domain (58 km x 174 km – see Figure 4.1). This may be a result of discharge being within the surf zone and suspended sediment, therefore being subject to rapid longshore transport in the surf zone, towards and beyond the model boundary.

6.3.4 Effects/impacts

Concentrations

Concentrations greater than 100 mg/l are predicted to be exceeded along an area about 20 km long in the region of the Uubvlei discharge location. The greater part of this area of exceedance of 100 mg/l is for less than 20% of simulation time (i.e. approximately 10 days in total), while an area 1.5 km alongshore and 200 m offshore adjacent to the Uubvlei site is predicted to experience 100 mg/l concentrations for more than 50 % of the time (about 25 days). From these results it may be concluded that the 100 mg/l threshold is exceeded in a confined area (1.5 km by 200 m) for more than “hours to days” at times. Impact can be considered to occur in this area.

Deposition

Predicted deposition thicknesses were not large and the overall time that deposition persisted was low. Deposition of more than 0.05 mm persisted for less than 10% (5 days) of simulation time. At the model boundaries, the small area of deposition greater than 0.05 mm persists to between 20% and 30% (10 to 14.5 days). This particular area falls directly over a rock/reef area. However, as deposition occurs for a limited period and is much less than

1 mm in extent, no impact is anticipated (low/neutral impact defined by "sub-millimetre deposition lasting hours to days" – Table 2.2). For the rest of the model domain, predicted deposition on rocks is limited. Therefore, deposition impact due to the future mine discharges is deemed to be low/neutral from the discharges anticipated.

6.4 CHAMEIS BAY

6.4.1 Background

Historical sediment input

Apart from vessel-based near-shore marine mining operations from 1962 to 1965 by Marine Diamond Corporation and subsequently by De Beers until 1971, the Chameis Bay region was relatively undisturbed until 2004.

Fate of sediments

Fine sediments from vessel discharges from these early operations would probably have been transported northward as a result of prevailing winds and northbound longshore transport.

Impacts to date

Judging by the rapid mobilisation of fine sediment, the rapid dilution of sediment concentrations and the rapid transport of this fine sediment to the north and offshore (as evident from recent measurements and modelling – CSIR, 2005c), it is unlikely that any meaningful impact occurred from the discharge of fine sediment from previous vessel mining in the region.

6.4.2 Modelling Scenarios

In 2004 mining of Pocket Beach Site 2 commenced. Trial dredger mining commenced in early 2005, and mining of Pocket Beach Sites 3 & 4 commenced recently (due to be completed at the end of 2006).

Scenario 1: Plant discharge only

This scenario simulated the fate and behaviour of fine sediment discharged from a treatment plant alone into the inter-tidal zone. Section 4.3 describes the model set-up and environmental input, while sediment discharge rates from the plant are given in Appendix M.

Scenario 2: Dredge overspill only

The second scenario excluded mine discharge into the inter-tidal zone and included dredge overspill due to dredging operations only. As with the above, model set-up and environmental data input were described in Section 4.3, while sediment discharge rates have been included in Appendix N.

6.4.3 Results

As in Section 6.2.3, only the bottom layers will be presented (these are relevant to potential effects on rocky reef habitat, and are in any event very similar to surface concentrations for this Chameis Bay case).

Plant discharge only

An animation of this simulation is provided on the attached compact disk – the animation is in the "Chamies" directory and is named *Plant_discharge_only.avi* (instructions for viewing are provided with the disk). Figures 6.12 and 6.13 depict the results of the simulation of land-based discharge in the Chameis Bay region (at Mining Site 2). It is reiterated that the concentrations depicted in these model results exclude any natural or background concentrations. The configuration of maximum turbidity predicted in the bottom layer, shown in Figure 6.12, indicates that a strong wind- and wave-driven alongshore transport drives suspended sediment to the north. A predicted extension of the plume footprint by approximately 5 km to the south is the result of episodic reversals in wind direction. Maximum concentrations of greater than 200 mg/l occur around the discharge site, but reduce with distance from the discharge position, such that concentrations greater than 10 mg/l do not reach Bakers Bay.

Maximum deposition of between 0.01 and 0.02 mm is predicted just west of Site3/4, beyond the 40 m depth contour (again noting that predicted deposition excludes natural or background deposition). The area of deposition is approximately 20 km in length and 5 km wide, with a tongue of deposition of thickness less than 0.001 mm extending further north.

Furthermore, small patches of deposition are predicted close inshore at and just north of the plant discharge site.

In this scenario 9% of sediment input into the system was predicted to remain within the model domain (an area of 109 km x 56 km - see Figure 4.13) at the end of simulation. This again attests to the strong northbound transport and dispersion of fine sediment in the near-shore zone.

Dredge overspill only

An animation of this simulation is provided on the attached compact disk – the animation is in the directory “Chameis” and is named *Dredger_discharge_only.avi* (instructions for viewing are provided with the disk). Figures 6.14 and 6.15 depict the results of the simulation of dredger overspill in Chameis Bay (again noting that predicted concentrations exclude any natural or background concentrations). Predicted concentration maxima occur in the areas of the dredge panels, and these decrease to the north. Concentrations are predicted to reach between 500 and 1000 mg/l in a very small area at the northern dredge panel, and between 100 and 200 mg/l in a small area at the more southern dredge panel. As for the plant discharge scenario, there is a small extension of the plume footprint to the south. However, in this dredging case the southward extension is more substantial due to the nature and position of the discharge. The predicted plume extends south of Panther Head and up to 7 km south of the southern-most dredge panel. Maximum concentrations between 1 mg/l and 5 mg/l are predicted to reach the shore, and maximum concentrations of less than 5 mg/l are predicted north of Bakers Bay.

Two main areas of deposition are predicted, both seaward of the 40 m depth contour: one area west of Site 3/4 and one area west of Panther Head (again noting that predicted deposition excludes any natural or background deposition). The northern deposition area has a similar configuration to that of the plant discharge scenario, with a length of approximately 20 km and a width of approximately 5 km. The maximum thickness of predicted deposition is no more than 0.05 mm. To the south, the maximum thickness predicted is not more than 0.005 mm.

Nearly half of the dredger-discharged material remained within the model domain (an area 109 km x 56 km) for this 10-day dredger sediment input scenario. This is probably due to the short period of modelling, and the relatively deep water conditions in the dredging area, resulting in slower transport of material than would occur by longshore transport in the near-beach zone (e.g. as occurs for plant-discharged material).

6.4.4 Impacts

Concentrations

Concentrations of 100 mg/l are predicted to be exceeded in small areas around the locations of discharge. For the plant discharge scenario, a small area close to the discharge location, 600 to 700 m in length (extending a few hundred metres offshore), shows exceedance of the 100 mg/l threshold concentration for 30 to 40% of the total simulation time (5 to 7 days). The time of exceedance of 100 mg/l would be more severe when considering the total period of discharge (almost two years). Thus, since the defined threshold of 100 mg/l is exceeded for longer than "hours to days" as indicated in Table 2.2, some localised impact would be expected.

For the dredge overspill scenario, at the northern dredge panel, 1 to 10% exceedance of 100 mg/l was predicted (less than half a day to less than 2 days) in an area approximately 400 m in length. Elevated concentrations at the southern site were less severe. These times of exceedance of the threshold of 100 mg/l, which are probably made up of several small events, suggest that no impact would have occurred.

Deposition

In terms of deposition and threshold values, predicted deposition in both scenarios never exceeds the impact threshold values – with maxima only reaching some 0.05 mm. Therefore, impact may be assumed to be negligible.

6.5 ELIZABETH BAY

6.5.1 Background

Historical sediment input

At Elizabeth Bay mining operations commenced in July 1991. From that time to April 2005, 21.2 million tons of sediment was discharged by means of a pipeline into the inter-tidal zone at various positions along Elizabeth Bay beach. From 1991 to 2000 material discharged consisted primarily of sand, with less than 1% of fine material (size <63 microns). However, in 2001 5-8% of the discharged material was comprised of fine material.

Since a mine upgrade, which was completed in 2004, total rate of sediment discharge has increased to date, while available information indicates a fine sediment content of this discharge of about 5% (CSIR, 2004).

Fate of sediments

Fine sediment discharged into the inter-tidal zone at Elizabeth Bay is mobilised by surf-zone currents and ejected seaward of the surf by rip currents. Prevailing strong southerly winds generally cause an anti-clockwise circulation in the bay. During calm periods, fine sediment tends to accumulate within the bay. These sediments are subsequently driven out of the bay to the north by typical wind-driven flows.

Impacts to date

A monitoring survey in 2004 (Pisces, 2004a) revealed that the deposition of fines from the Elizabeth Bay processing plant had (a) no effect on inter-tidal and sub-tidal communities at wave-exposed sites, had (b) detectable effects within semi-exposed sites and had (c) a significant impact on communities at sheltered localities, where fines accumulated because wave action was insufficient to disperse them. Reductions of grazers, proliferation of algae and increased dominance by filter feeders were recorded at the impacted sites within Elizabeth Bay.

A lower density of kelp was recorded at the fines-impacted sites within Elizabeth Bay than at reference sites to the north. This may be a consequence of increased turbidity at the sheltered sites in the bay (or due to inundation of the sub-tidal reef habitat by sediments as beach accretion continues).

The fine sediment discharge was found to have no detectable effects on the sex ratio, size or abundance of rock lobsters. However, it was indicated (Pisces, 2004a) that substantial inter-site variability (i.e. particularly variations between control and potentially impacted sites) made it difficult to regard the results as a definitive indication of no impact on the fishery.

6.5.2 Modelling Scenarios

Two scenarios were simulated to separately assess the effects of land-based (present and future) and vessel-based discharges (based on a past vessel operation). For both scenarios to be described below, identical environmental conditions were employed.

Four separate months were chosen that are representative of an annual climate (i.e. representative of typical wind and wave conditions), ensuring that concurrent directional wave data and local wind data were employed to drive the hydrodynamic model. The following months were selected:

- May 1997 (calibration period)
- August 1998
- November 1998
- December 1998

The simulation period for each water-quality scenario was derived by running the four simulation periods applied for the hydrodynamic modelling sequentially, with the initial conditions for each month obtained from the conditions at the end of the previous month. Each simulation therefore had a length of 4 x 30 = 120 days. In this way a typical sequence of events as observed from time-series measurements could be reproduced and the dynamic behaviour of the turbid plumes could be realistically simulated.

Wave data

The period between 7 and 26 May 1997 was the validation period during which near-shore wave measurements off Elizabeth Bay were available (see Section 4.4.3). Wave conditions for the remainder of May 1997 were obtained from data measured in 20 m depth off Oranjemund, with five hours travel time allowed for the swell to reach Elizabeth Bay.

Data for the August 1998, November 1998 and December 1998 were derived from the Kudu wave measurements. A five-hour travel time was allowed for the swell to reach Elizabeth Bay from the southern Kudu gas field site, and the total wave height was converted to the swell component using a derived relationship (CSIR, 2002). The resulting deepwater wave conditions applied at the model boundaries for these four months are plotted in Figures 6.16, 6.17, 6.18 and 6.19.

Tidal data

The open boundaries are located along the three offshore edges of the model, i.e. the Southern, Western and Northern boundaries. At these open boundaries a water-level time-series is specified which is based on the predicted tide. The 8 largest amplitude tidal constituents along the West Coast were applied to predict the tide (Rosenthal and Grant, 1989). The change in tidal constituents between Lüderitz Bay and Port Nolloth were used to make allowance for the changes in phase of the tidal constituents along the open boundaries of the model. The tide is specified with 10-minute intervals.

Each of the 4 periods simulated by the model include both Neap and Spring tides. The tide sea levels specified in the model for each of the four months simulated are shown in Figures 6.20 to 6.21.

Wind data

The wind data applied in the simulations are those measured with hourly intervals at the Elizabeth Bay monitoring site. These data sets, for the four selected months, are also shown in Figures 6.20 and 6.21.

Sediment discharges

Scenario 1: Land-based discharge only

From July 2005 to the end of mining, approximately 3.234 million t/year of total sediment input was estimated. Based on available information from Elizabeth Bay mine (CSIR, 2004) 5% of this material was assumed to be fine. Thus a fines discharge rate of 161 719 tons/year was simulated in Elizabeth Bay. The fine sediments discharge is split between two locations on the beach (Discharge points 11.4 and 14 – e.g. see Figure 6.22) in the ratio 1 : 2.5.

Scenario 2: Vessel discharge only

Scenario 2 consisted of discharge at the vessel discharge site only. Exact details of this mining operation were not available. Therefore, in order to obtain an idea of the effects of a vessel discharge, the rate applied was approximately that of the De Beers Marine drill vessel discharge rate, i.e. 1 191 360 tons/year but with a roughly estimated fines composition of 10%.

6.5.3 Results

Scenario 1: Land-based discharge only

An animation of this simulation is provided on the attached compact disk – the animation is in the directory "Ebay" and is named *Plant_discharge_only.avi* (instructions for viewing are provided with the disk).

The predicted suspended sediment concentrations and deposition in the bottom layer for this scenario are presented in Figures.6.22 and 6.23.

The predicted plume tends to remain within and close to the bay, with the highest concentrations occurring in the bay. This may be due to the sheltering effect of the bay causing discharged fine sediment to accumulate in the immediate area of the discharge sites. The maximum predicted suspended sediment concentration is between 200 mg/l and 500 mg/l at the discharge location. Offshore from Elizabeth Bay, but mostly onshore of the 20 m depth contour, the maximum predicted concentration is less than 20 mg/l. Such concentrations are predicted to extend northward, around the western-most point of the bay, Elizabeth Point, while concentrations less than 10 mg/l reach further north and concentrations between 1 mg/l and 5 mg/l extend to over 17 km north of Elizabeth Bay. The plume is predicted to extend no further than 2 to 3 km south of Possession Island.

Maximum deposition (between 0.3 and 0.4 mm) is predicted within the bay, just south-east of Elizabeth Point, over an area approximately 1 km in length. Further areas of deposition are predicted seaward of the bay, mid-way to Possession Island, and east of the island. Between 0.01 and 0.05 mm of deposition is predicted over much of the area west of the bay, beyond the 40 m depth contour. The maximum deposition in this western area is predicted to be less than 0.07 mm.

No deposition over 1 mm is predicted. Deposition greater than 0.2 mm does occur, but only for less than 10% of *total* simulation time (approximately 12 days). More than 0.05 mm of deposition occurs for similar periods of time. However, this occurs over a greater area: isolated patches of deposition (800 and 1000 m in length each) persisting for less than a *total* of 12 days.

Towards the end of simulation, the percentage of sediment remaining in the model domain was about 3% of the total sediment input (over a model domain of 81 km x 35 km – see Figure 4.20). The simulations indicate that almost all of the sediment is transported out of the model to the north. This fine sediment transport is driven mainly by wind, and also by longshore transport, as would be expected in the surf zone**.**

Scenario 2: Vessel discharge only

An animation of this simulation is provided on the attached compact disk – the animation is in the directory "Ebay" and is named *Vessel_discharge_only.avi* (instructions for viewing are provided with the disk).

The modelled turbidity and deposition in the bottom layer for this scenario are presented in Figures 6.24 and 6.25 respectively. It is highlighted that neither the predicted suspended solids/turbidity predictions nor the deposition predictions include natural, background levels.

Figure 6.24 shows that maximum turbidity is predicted not to exceed 10 mg/l, and the area experiencing suspended sediment occurs west of the bay, beyond the 40 m depth contour, but further north the plume (defined by a concentration over 1 mg/l) does reach inshore of the 20 m depth contour. The reason for the low concentrations is the relatively low energy of the area into which sediment is discharged. Relative calmness (in comparison to the surf-zone discharge in the bay) results in suspended sediment settling rapidly to the sea floor to deposit, intermittently, onto the sea-bed.

From Figure 6.25 it is evident that maximum deposition thicknesses of between 0.1 mm and 0.2 mm are reached in the area beyond the 40 m depth contour. The greater area of deposition experienced a thickness less than 0.05 mm. A maximum deposition thickness of 1 mm is reached directly at the vessel discharge site. However, the area over which this was predicted to occur is very small (and is not visible on the scale of Figure 6.25). Apart from this, no deposition over 1 mm is predicted. Deposition greater than 0.2 mm does occur for less than 10% of *total* simulation time (approximately 12 days) and beyond the 40 m depth. Deposition greater than 0.05 mm occurs for similar periods of time, but over a greater area. Between 10 and 20% of *total* simulation time (12 to 25 days) deposition exceeds 0.05 mm but, again, beyond the 40 m depth contour.

According to model statistics and output, towards the end of the simulation the percentage of material discharged that is predicted to remain within the model domain (81 km x 35 km) is about 2%. This is slightly less than the result for land-based discharge. The reason may be the aforementioned relatively low energy state of the area where vessel input was simulated, causing the dispersal and subsequent transport of the sediment out of the model.

6.5.4 Impacts

Concentrations

When compared to vessel discharge, the land-based discharge in Elizabeth Bay is likely to cause more impact in terms of the concentration impact threshold of 100 mg/l discussed in Section 2.3.4. The 100 mg/l concentration threshold is exceeded within the bay itself, in a localised area around the discharge site. Exceedance of 100 mg/l (for more than 1% of the time) is predicted to occur along a 2 km stretch, 400 to 500 m wide in the offshore direction. At Discharge Point 11.4 the 100 mg/l concentration is exceeded less than 50% of the simulation time (62 days). The time the 100 mg/l concentration is exceeded is greater at Discharge Point 14; more than 50% exceedance is restricted to within 300 m of the discharge site, with more than 90% exceedance (111 days) directly at the discharge site. Considering the extended period of high concentrations, some impact would be considered likely in this localised region of a few hundred metres around the discharge points.

On the other hand, the vessel discharge appears to have very limited impact, as predictions indicate that the 100 mg/l concentration is never exceeded. This is probably largely a result of model resolution, in that some very high concentrations would probably occur directly below the mining vessel. However, these would be limited to a very small area, i.e. finer than the model grid, which resolves effects in the order of tens of metres.

Deposition

In the areas of rock (grey/silver lines) deposition is predicted during the vessel discharge scenario, but rarely exceeds 0.2 mm (i.e. <1% of the time). Both the extent and the *total* time of deposition is low for both vessel and land-based discharge cases. Transient deposition (much less than 1% of the time) of greater than 1 mm is predicted to just below the vessel site and deposition over 1 mm is predicted not to occur for the land-based discharge case. As deposition over 1 mm is extremely localised and transient, deposition (for both scenarios) is estimated to cause negligible impact.

6.6 DISCUSSION

6.6.1 Fate of fine sediments

From model results it is evident that fine sediment is mobilised by wave action and is transported rapidly, generally by both wave- and wind-driven currents. The result of this rapid transport is that fine sediment that is discharged moves beyond the model domains extending tens of kilometers from discharge sites within periods of weeks to months.

For the mine discharge cases, over 90% of fine sediment discharged was predicted to exit model domains (areas of several tens of square km) within the periods modelled (ranging from weeks to months). The only exception was for dredging at Chameis Bay (in which about half of the sediment discharged from a dredger was predicted to remain in the model domain). However, the 10–day period of this model simulation was not considered sufficient time to transport the fine sediment beyond the model domain (model simulations for longer periods indicated over 90% of the dredger-discharged sediment to exit the model domain).

For the flood discharge cases, the rate of fine sediment discharge is orders of magnitude larger than mine fine sediment discharges (discussed in Section 5), with the result that the discharged sediment is predicted to be less rapidly expelled from the model domain. For example, for the 1988 flood case only 27% of sediment discharged was predicted to exit the model domain in a two-month period. For the 1:20-year flood case, a reduced discharge rate resulted in a predicted 74% of the fine material leaving the model domain in a period of almost seven weeks.

Most of the fine sediment is seen to exit model domains in the north in the form of low concentrations in a relatively narrow band adjacent to the shoreline. This transported sediment is likely to continue north until reaching areas that are relatively wave-sheltered, and that experience lower wind-driven flows (often taking the form of deeper areas). Deposition may occur in such areas, with possible subsequent remobilisation during extreme conditions.

6.6.2 Elevated concentrations

For the cases of mine fine sediment discharge, concentrations which could cause impact on biota (in terms of the 100 mg/l threshold defined in section 2.3.4) are generally limited to with a few hundred metres of the discharge position. This finding is corroborated by measurements both in the Chameis Bay Region (CSIR, 2005c) and at Elizabeth Bay (CSIR, 1998c). According to predictions, the most severe area of elevated, sustained high concentrations is an area of 1.5 km x 200 m offshore of Uubvlei discharge in the southern Namibia region, resulting from increased fine sediment discharge associated with marine deep-water dredging (the dredged material being discharged to land and subsequently processed, which involves a fine tailings discharge). However, all of the discharges that were investigated are situated such that elevated, sustained concentrations that may have an impact on biota do not significantly occur over rocky reef areas.

For the case of fine sediment discharges from floods, concentrations which could cause impact on biota (in terms of the 100 mg/l threshold defined in section 2.3.4) occur over a far more extensive area. For both flood cases such concentrations extend up to several kilometres offshore (particularly near the Orange River mouth) and up to 70 km alongshore. The extent of elevated, sustained concentrations is therefore one to two orders of magnitude higher than for the mine discharge cases. For both the 1988 and the 1:20-year flood modelled, elevated, sustained concentrations (e.g. concentrations over 100 mg/l totalling up to a month in a two-month period) that may have an impact on biota were predicted to occur at limited areas of rocky reef about 50 km north of the Orange River mouth.

6.6.3 Deposition

Natural

For the case of the simulated floods, deposition was considerable. Apart from extreme deposition on the pro-delta during the 1988 flood, deposition of more than 5 mm is predicted over an area some 100 km (in the alongshore direction) by about 30 km (in the on/offshore direction). This extent of deposition is predicted to occur mainly beyond the 40 m depth contour. For the 1:20-year flood, deposition is less but is still much larger than for any of the mine discharge cases.

The 1988 flood has some major (several cm thickness) and persistent deposition, as was corroborated by post-flood measurements (Dr J. Rogers, University of Cape Town, pers. comm.). While impact would be expected (according to defined impact thresholds – Table 2.2), only a limited part of the deposition occurs on rocky reefs. It is possible that these regions of deposition on unconsolidated sediments do not have an impact, as biota in these regions may be adapted to occasional flooding. For both floods tested, the deposition on rocky reef is neither defined as low/neutral (“sub-millimetre for hours to days” – Table 2.2) or as high impact ("centimetres to metres for years to decades"), but is somewhere in between these extremes.

Mine discharges

For all cases of mine sediment discharge, deposition is generally predicted to be an order of magnitude less than 1 mm, and is therefore much less than the defined impact threshold (Table 2.2). The only exception was very localised and transient deposition of just over 1 mm for a vessel discharge offshore of Elizabeth Bay. Where deposition is predicted, it tends to occur in water depths greater than 40 m, and does not tend to deposit (with meaningful thickness or for a meaningful duration) on the near-shore reefs within the study project area. Therefore, it is clear that mine discharges of fine sediment result in minimal deposition in comparison with natural flood deposition.

Accuracy

The results of flood modelling should be treated with some caution. Prediction of the behaviour of sediment settling, deposition and resuspension at elevated concentrations is not very accurate. This is manifested in the results of model validation, which indicated that predictions of sediment concentrations and deposition throughout the model domain are not necessarily geographically precise and are probably within an order of magnitude accuracy.

For the mine sediment discharge cases, accurate calibration of hydrodynamics and experience of the capablity to predict concentrations (CSIR, 1998c) suggest a reasonable level of accuracy (concentrations being predicted within roughly ±10 to ±20 mg/l).

7. THE FATE OF COARSE SEDIMENTS

7.1 INTRODUCTION

As has been explained, processes associated with the dynamics of fine sediment (<63 micron) are different from processes associated with coarse sediment (>63 micron). This chapter focuses on the dynamics of coarse sediment (i.e. primarily sand) only. The following key questions (as posed in the project terms of reference) are addressed:

How far, and in which directions, are ***coarse*** *sediments (input to the near-shore region either naturally occurring or from mine discharges) transported and by what mechanisms, and where in the near-shore zone are they deposited?*

What is the extent and duration of the natural deposition of unconsolidated ***coarse*** *sediments on near-shore reefs and how does this compare with the potential smothering of reefs as a consequence of discharged and mobilised sediments?*

7.2 NATURAL SEDIMENTS/ORANGE RIVER SAND INPUT

7.2.1 Background

Historical sediment input

From an assessment of sediment inputs (Section 5) it is clearly evident that the Orange River has been and probably still is the most significant source of sand/coarse sediment to the near-shore region. If it is assumed that 15% of the input from the Orange River is comprised of sand (as suggested by limited sampling data), historical input in the order of 5 to 8 million tons of sand (i.e. 15% of the values indicated in Table 5.2) would have occurred, on average, annually. More recently, this sand input rate has been reduced to less than 2.6 million tons/annum on average. These volumes of sand input are one or two orders of magnitude higher than the estimated input of aeolian sand for the project area (Section 5) (i.e. excluding aeolian sand sinks that occur in wave-sheltered regions)

Fate of sediment

Sand in the Orange River would be ejected out of the mouth during a flood. This sand would deposit in the near-shore region as flow velocities decrease. Currents would rework the sand up- and down-coast (i.e. north-west and south-east), and asymmetrical orbital currents would drive the sand onshore, where it becomes part of the near-beach sand system. At this stage the sand can be transported northwards by means of littoral drift, at an estimated rate of about 1.2 million m^3/year (i.e. this translates to about 2.2 million tons/year) just north of the Orange River mouth.

Insignificant sediment input to the shoreline in the region of the Orange River is anticipated from wave-driven sand transport originating from the south, along the rocky shore of Alexander Bay. The occurrence of minimal sediment transport along this coast is supported by observations of limited sand accumulation in the nearby Alexander Bay Harbour: in the period from April 1980 to December 1988 only 70 600 m^3 of sand was removed from the harbour, indicating an accumulation rate of only 8100 m^3/year (CSIR, 2003a).

If it is considered that sand is transported northward from the shoreline at the Orange River, it follows that the sand input from the Orange River is key to maintaining the stability of the neighbouring shoreline. In other words, without this persistent sand input, erosion would be expected. Figure 7.1 illustrates a time history of shoreline excursions (measured from aerial photographs) a few hundred metres north of the Orange River mouth. It must be recognised that these measurements are affected by photograph and measurement accuracy (estimated to be ±10 m) as well as short-term variations in the beach due to changes in wave conditions/sedimentary formations (these may be up to ±25-30 m). Also plotted on the figure is the estimated annual rate of sand input from the Orange River (assumed to be 15% of river discharge), and average annual rates of mine sediment input, to the region just north of the Orange River (within about 15 km of the river), for the 1970s, 1980s, 1990s and for the period 2000-2004.

From this analysis it is evident that a retreat of the shoreline of about 65 m from 1937 to 1964 is reasonably well correlated with a decrease in estimated sand input from the Orange River. Significant mine sediment input in the region (within a few kilometres) of the Orange River mouth commenced in the early seventies. It is significant that the magnitude of sediment input from mining is of the same order as that from the Orange River, and that this input has increased over the years since the 1970s (Figure 7.1). The cumulative effect of both the

Orange River and mine sediment input is evident when the Orange River and the neighbouring mine sediment inputs are added – the result is plotted in Figure 7.2. According to the figure, the shoreline seems generally to respond well to the combined sediment input rate (recognising the above-mentioned inaccuracies and short-term fluctuations in shoreline position – e.g. the accretion of the shoreline directly after 1964 is deemed to be a result of an incidental local effect rather than a response to sediment input). The exception to this observation is that there is no clear response to the high sediment inputs in recent years. This may be due to the discharge being located further north in recent years (i.e. it is situated some 12-14 km to the north-west) and the loss of some of the discharged material to the north of discharge operations, where a higher northerly transport occurs.

The above assessment suggests that sand discharged by the Orange River is important in maintaining the adjacent shoreline. As limited sand reaches the sandy shoreline from the south, the Orange River is the only logical source of supply to the high sand transport to the north. A rough analysis indicates that an annual sand discharge rate of about a million cubic metres (about 1.8 million tons) is required to maintain a stable shoreline in the region of the Orange River, which would otherwise erode. This estimate corresponds to calculations of north-bound longshore transport indicated to be in the region of a million cubic metres (about 1.8 million tons) annually. This northward transport of sediment from the Orange River is in turn approximately balanced by losses from the marine environment resulting from the landward aeolian transport of sand deposited on sheltered beaches much further north. Available information on aeolian transport (Table 5.5) indicates a northbound transport of 700 000 m^3/year. However, considering that this information excludes the aeolian transport corridor at Van Reenen's bay (not indicated in the table) as well as other minor aeolian sinks, a total aeolian sink in the order of a million m3/year (about 1.8 million tons) is deemed to be feasible.

Impacts to date

During storms, natural erosion of beaches would result in removal of sediment from the upper, inter-tidal beach and corresponding deposition further offshore (generally to depths of 15-20 m). This deposition could possibly impact on areas (particularly reefs) in the near-shore region.

During floods, deposition of sand in the near-shore region just offshore of the Orange River occurs (e.g. Bremner *et al.*, 1990). Any flood impact (e.g. on benthic fauna) would have been localised to this area.

7.2.2 Future effects

A potential impact of reduced sand supply from the Orange River would be retreat of the shoreline, as indicated by the shoreline analysis above. However, this effect has apparently been mitigated by mine sand discharges, which may in future cause accretion at the Orange River mouth (CSIR, 2003a). However, the composition and corresponding local effects of the mine sediment discharges must be carefully examined. This is dealt with in the following section.

7.3 SOUTHERN NAMIBIA MINING AREA

7.3.1 Background

Sediment input

Sediment input to this area was described in detail in Section 5. This is undoubtedly the area of most sediment input in the project area. In total, an estimated 381 million tons of sediment has been deposited in the region from the Orange River to a point 107 km north-west (just south of Chameis Bay) between 1968 and April 2005. As shown in Figure 7.3 (derived from the information in Table 5.7), most of this sediment was discharged within 30 km of the Orange River mouth.

Fate of sediment

Accretion

Most of this sediment contributes to accretion of the shoreline. Some of it is transported northwards by means of littoral drift. Figure 7.4 provides a distorted view of measured shorelines between the Orange River and 45 km to the north-west. It is clear from this plot that major accretion of the shoreline has occurred over the years, attaining a shoreline offset of almost 500 m in the region of No. 4 Plant. The area of accretion accumulated between 1971 and early 2004 is about 7.2 million m^2. Assuming that the build-out of sand extends to a depth of about 15 m (as evident from surveys) and occupies the upper beach to an elevation of about 5 m (above MSL), the area of 7.2 million m^2 translates to a volume of 7.2 million x 20 = 144 million m^3.

From 1971 to early 2004 about 292 million tons of sediment was discharged in this region: this can be translated to a volume of about 162 million m^3 of sand. Thus, about 89% of the sand discharged in this region is accounted for by accretion.

Figure 7.5 provides an estimate accretion in the No. 2 Plant area. The plot is constructed from a topographical map (1971) and two surveys of the high-water mark as conducted with a helicopter. An area of 840 000 m^2 of beach accretion is estimated for the period from 1971 to 1999. Assuming that the build-out of sand extends to a depth of about 15 m (as evident from surveys) and occupies the upper beach to an elevation of about 5 m (above MSL – as evident from surveys), the area of 0.84 million m^2 translates to a volume of 0.84 million x 20 = 16.8 million m^3.

From 1971 to early 1999 about 38 million tons of sediment was discharged in this region – primarily in the form of tailings from No. 2 Plant: this can be translated to a volume of about 21.1 million m^3 of sand. Thus, as was found for the southern area, about 80% of the sand discharged in this region is accounted for by accretion.

Apart from the southern region (Figure 7.4) and the No. 2 Plant region (Figure 7.5), the only other area where significant accretion could be discerned was in Chameis Bay. Figure 7.6 shows the shorelines of 1971 and 1999 respectively. Accretion within the wave-sheltered region of Chameis Bay is clearly evident. Although the 1999 measured shoreline as measured by helicopter and GPS is not very accurate, this accretion is also evident on aerial photographs. A rough estimate indicates the accreted beach area to be 114 000 m^2. Assuming accretion to a depth of 15 m and up to 5 m (above MSL) on the upper beach, an accreted volume of 2.3 million m^3 is estimated. This accretion would probably have occurred as a result of discharged sand to the south (e.g. from No. 1 Plant).

Limited information suggests that the beaches north of Chameis Bay are relatively stable. The configuration of the beach at Site 3 & 4 was compared to aerial photographs of 1978. From the measurement of some key distances (e.g. the position of the beach in relation to the near-shore North Rock, a near-shore island) no meaningful change could be discerned (CSIR, 2001). Shorelines from survey and orthophotograph data also indicate no significant trend at Site 2 for the period 1995 to 2005 (CSIR, 2005c). A worthwhile indication of whether accretion has occurred further north is the state of the shoreline at Sinclair Island. There is little doubt that in the wave-sheltered zone of this island, a tombolo has formed in the past, as indicated in Green (1950): ”One peculiar sight at Sinclair’s Island is the sand bridge stretching from the island to the mainland". Green (1950) indicates that this occurs "once in every two or three years, perhaps". It is likely that the bridge was only accessible during very low tides. Nevertheless, the intermittent formation of a tombolo indicates that the relationship between the beach position and the island dimensions (length parallel to the shoreline) are such that a small increase in sand supply and consequent build-up of sand on the beach would result in permanent tombolo formation. The fact that this has not occurred clearly indicates that a significant additional supply of sand has not occurred.

From the above analysis it is estimated that about 294 million tons (163.1 million m^3) of sand discharged is accounted for in the form of accreted beaches (in Mining Area 1, between the Orange River and Chameis Bay).

For the periods considered 361 million tons has been discharged: thus about 81% of all sediment discharged is accounted for. The remaining 19% amounts to 67 million tons of sand, with most of this originating from the south (within 45 km of the Orange River)

This sediment may be accounted for as follows:

- Some of the 67 million tons of sediment may originate from errors in estimates of sediment discharged. At least 20 million tons of seawall erosion was estimated, based on the known existence of seawalls and the rates of sand input associated with mining operations (CSIR, 1996a). Overestimation is a possibility;

- Some of the discharged sand may still be on the beach, in the form of remnants of seawalls (or may have been transported from the seawalls inland by wind). Considering a seawall cross-sectional area in the region of 100 m^2, this could amount to several million m^3 (roughly 10 million m^3 at most) over many kilometres of coastline;

- A small percentage (<5%) of fine sediment (<64 microns) in the discharged sediment would have been extremely mobile and would have been well distributed to great distances (as discussed in Section 6). This may amount to several million m^3 (e.g. 2% fines is equivalent to about 7 million tons);

- A small percentage of fine sand may have accumulated in the near-shore region. Survey data measured a few kilometres north-west of the Orange River indicate deposition of a veneer of sand 20-40 cm thick on the sea-bed extending well seaward of the near-shore profile, i.e. in depths of 13-17 m. (CSIR, 2002b). This may amount to several million m^3 (rough calculations suggest some five million m^3);

- Sand transported to the north, where it may result in subtle accretion in the beach and near-shore region. Much of this sand would accumulate in relatively wave-sheltered deposition zones, where it probably would feed into the dune system. It is conceivable that several million m^3 of sand supplied to the northern (Pocket Beaches) region over some 30 years would not cause easily observable accretion.

Impacts to date

Indications from mine plans are that almost the entire section of shoreline between the Orange River and Chameis Bay has been mined, employing the protection of sand seawalls. Total smothering of the localised area up to 100 m of the shoreline would have occurred at the time of construction of these seawalls. In places erosion of the shoreline has resulted in elimination of these seawalls and re-establishment of the beach profile similar to that before mining commenced.

The beach in the region of No. 3 Plant (about 23 km north-west of the Orange River mouth) was relatively unaffected by accretion due to mine sediment discharges in 1977. Surveys of this beach indicated beach slopes averaging about 1:13 (ranging from 1:10 to 1:18) (CSIR, 1979). Subsequent surveys indicate considerable increases in beach slope. Beaches have been steepened considerably in this region as a result of accretion due to sand seawall construction. Upper beach slopes of 1:8 were recorded near seawalls (e.g. CSIR, 1992).

Steepening of the beach is normally linked to an increase in sand grain size (resulting from increased swash wave action at the shore). Increases in beach slope which induce occurrence of a mean grain size coarser than 500 microns are a concern as this may impact on non-crustaceans dwelling on the beach face (Section 2.3). However, no clear increase in inter-tidal beach grain size can be discerned. Limited measurements conducted in 1979 indicated median grain sizes ranging from 400 to 650 microns in the region up to 10 km north-west of the Orange River mouth. Measurements of inter-tidal beach grain size between 1997 and 2002 in the region of dredging (which commenced in April 1997) just to the north-west indicate median grain sizes ranging from 353 to 626 microns (CSIR, 2002b), suggesting no significant change relative to the pre-mining period.

Smothering of near-shore reefs has occurred. About 25 km north-west of the Orange river a roughly 500 m long section of rocky shore existed and is evident on the 1976 orthophotograph. This rocky shore was totally inundated with sand discharged from tailings and seawall mining operations. While additional sub-tidal reef may have been smothered, no record of this reef is available (primarily due to the dearth of measurements in the treacherous surf in shallow water (6 m depth)).

7.3.2 Scenarios

Two scenarios of possible future mine sediment discharge are proposed. Both scenarios incorporate a major on-land dredging operation during which 12 million m^3/year of sand is to be disposed of first in the dredging area ("dredger discharge region" shown in Figure 7.7) and then further south towards the Orange River. Discharges from the mining plants (PTF, 3 Plant and 4 Plant) as discussed in Section 5 are also included. In addition to these sediment inputs:

(a) Scenario 1 includes a plant sediment discharge (resulting from possible treatment of dredged marine sediment) for one year. The rate of sediment discharge during this year is approximately 550 000 m^3/year. This is somewhat greater than presently planned discharge of coarse sediment (current estimates are in the region of 370 000 m^3/year);

(b) Scenario 2 includes a plant sediment discharge (resulting from treatment of dredged marine sediment) which continues for a period over 10 years. The rate of sediment discharge during this time is 1600 000 m^3/year. This scenario would assume that dredging technology is successful and that the volumes are therefore increased significantly.

7.3.3 Results

Figure 7.7 illustrates predicted shorelines for both Scenarios 1 and 2 at the end of 10 years. For both cases extreme accretion of over 500 m is predicted in the south as a result of land-based dredging. For the case of Scenario 1, at most about 80 m of accretion is predicted in the region of the anticipated tailings discharge (from plant processing of marine dredged material) after 10 years. For the case of Scenario 2, almost 300 m of accretion is anticipated in the same region after a 10-year period.

7.3.4 Impacts

It is estimated, based on the modelling results above, that impacts associated with beach steepening could occur over an area of roughly 4 km (at the very most 6 km), where accretion of the beach may be sufficiently severe to induce a beach slope change and corresponding change in beach material. This would depend largely on the grain size distribution of material discharged.

Rocky reef areas exist in the near-shore region more than 10 km north of the discharge site (which is situated near Uubvlei, at U90) – see Figure 6.1. As meaningful accretion (in the order of over 10 m) is only predicted within some 3-4 km of the discharge site, impact on these reefs is not considered likely.

Previous modelling indicates that on-land dredging involving massive tailings discharge as for the above scenarios a few kilometres north of the Orange River will cause accretion at the Orange River mouth and on the South African shore (extending about 5 km south) in the order of 100 m (CSIR, 2003a). Modelling indicates that this accretion could persist for decades. However, the CSIR (2003a) study indicated no major impacts on the estuary from this accretion.

7.4 POCKET BEACHES SITE 2

7.4.1 Background

Sediment input

Coarse sediment input to this region commenced in early 2004. The plant sand sediment input to Site 2 (location, Figure 4.17) was estimated (from plant discharge quantities in combination with sample grain size information – CSIR, 2005c) to be 1.3 million tons between March 2004 and September 2005. It was estimated that 2 million tons of material was effectively discharged into the region seaward of the high-water mark from seawall construction and maintenance between January 2004 and February 2005. This quantity is approximately half of the total quantity of overburden sediment excavated during mining activity.

Fate of sediment

The sediment input resulted in up to 110 m of accretion at the Site 2 beach, as was discussed in Section 4.6.3. An additional beach area of about 180 000 m^2 is the result. Assuming that sand build-out 10 m thick occurred, a volume of 1.8 million m^3 is estimated to have accumulated. This accounts for virtually all of sand input as estimated above

Impacts to date

Roughly 1.5 to 2 km of seawalls have been constructed at Site 2. The wide wall would have resulted in smothering of the inter-tidal zone. Where sand seawalls were “pushed” (bulldozed/dumped) into the sea, smothering would have extended tens of metres into the inner surf zone. Where such reclaiming was not employed, the beach extending up to about 100 m inland would have been smothered.

Significant natural beach morphology and sand grain size variations have been observed in a survey of both mining and control sites at the Pocket Beach Areas (Clark *et al.*, 2004; Clark *et al.*, 2005). However, in the areas of active mining, changes resulting specifically from mining are evident. For example, Anchor (2004) reports a 44% decrease in beach width at the south of Site 2. This beach change, which resulted from seawall construction, resulted in “the fewest species and the lowest biomass and number of individuals of all the beaches sampled” (i.e. at 12 sites). It was concluded that “while natural variability in beach macrofauna populations is clearly high on the Pocket Beaches, it was not so high as to mask even the initial effects of mining on these beaches.” Further changes in beach morphology and slope (including localised flattening as a result of deposition in the northern half of Site 2) were observed in 2005 (Clark *et al.*, 2005). It was inferred that changes in both beach width and slope between 2004 and 2005 were probably linked to the effects of mining on these beaches. Natural variation in macrofauna communities was evident both in space (i.e. between beaches) and time (i.e. in comparison with earlier surveys), but these were indicated to be “small in comparison with effects of mining which were noted at at least three of the 12 sites where sampling was conducted”.

Rocky reef habitat at either end of the beach has been smothered with sand accumulation, which is estimated to extend to a depth of about 13 m (CSIR, 2005c). At the southern end of the beach about 60 m of accretion has been recorded and at the northern end shoreline build-out of about 40 m has been recorded. As a result, an increase in sand level of well over a metre has been observed at both South Rock and on the rocky shoreline to the south of the Site 2 Beach (Clark *et al.*, 2005), causing smothering of rocky inter-tidal and shallow sub-tidal habitats. In this region a concomitant reduction in the extent of kelp beds, a decline in the biomass of reef-associated species and decline in rock lobster abundance due to habitat degradation and lack of food can also be expected.

7.4.2 Scenarios

Modelling was conducted to assess the future effects of tailings discharges planned until the end of 2006. The same annual climate of waves was employed in the model as that for the model validation (Section 4.6). The plant sand sediment input to Site 2 was estimated (from plant discharge quantities in combination with sample grain size information – CSIR, 2005c) to total 1.4 million tons between September 2005 and December 2006.

7.4.3 Results

Shoreline configuration

It is predicted that the shoreline configuration at the end of 2006 will be similar to the September 2005 configuration (Figure 7.8), but with some limited, additional accretion to the south. Thus, it is predicted that the plant discharge rate will be sufficiently high to maintain the shoreline, but not to cause substantial further accretion. Some retreat of seawalls may occur as a result of storm erosion.

Once the plant discharge ceases, erosion of the beach (and seawalls) is predicted to occur. Using the model to predict the shoreline evolution for this period, it is estimated that the shoreline will return to its pre-mining position after approximately twelve years, i.e. by 2018.

The sand accretion was estimated, based on measurements of similar profiles to the south and engineering calculations, to extend to a depth of 13 m (CSIR, 2005c).

Transport of sand to the north

During the post-mining erosion of the accreted beach, the eroding material will be transported northward to the adjacent beaches (i.e. to Site 3 & 4 and to the beaches to the north). This northward transport process started as soon as the mining operations began causing accretion, i.e. in early 2004.

Employing the shoreline model, it is estimated that during the seawall construction and plant operating period (2004 to end 2006) some 0.9 million cubic metres (1.6 million tons) of sandy material would be transported to the beaches to the north of Site 2, in addition to that being transported there naturally. This represents an average 75% increase in the net natural longshore transport rate for this 2-year period. By the time the Site 2 shoreline has returned to its pre-mining position, after about 15 years, all the discharged material (from slimes discharge and from seawalls located seawards of the pre-mining shoreline) would have been transported to the north. This equates to a volume of approximately 2.5 million cubic metres (4.5 million tons) of sandy material and represents an average 42% increase in the net natural longshore transport rate for the 15-year period (from start of seawall construction to end of the "recovery" period).

Variations in annual longshore transport do occur naturally due to seasonal and annual variation in wave conditions. Such natural longshore transport increases can be of a similar order of magnitude to that caused by the seawalls and discharge at Site 2. However, they would not persist for sustained periods of time. The amount of sand leaving Site 2 in the longshore transport system is therefore in excess of what the natural system would experience.

Using the increased transport rates as a boundary input in a previously established shoreline model of Pocket Beach Site 3 & 4 (CSIR, 2001), accretion in the order of 30 m is estimated to occur at the southern end of this site. Such accretion is predicted to persist for a period of years to decades. The magnitude of accretion is within the range of shoreline changes that occur due to seasonal variations and giant cusp formations that have been noted to occur at this beach (CSIR, 2001). However, this accretion would occur in addition to any sand input from seawall construction at this site. From survey data, it is evident that seawall mining operations at Sites 3 & 4 have caused about 75 m of accretion along a 1 km extent of shoreline in September 2005. The location of this accretion (opposite seawall mining) clearly indicates the seawalls (and not Site 2 input) to be the cause of accretion.

7.4.4 Impacts

As mentioned above (Section 7.4.1), beach changes and impacts on beach macrofauna have occurred. Return of the beach to its former approximate **shape** may occur before recovery of the beach to its former alignment. For example, measurements in the southern mining area indicated a period of 4.5 years for a profile to recover its approximate original shape, after being artificially accreted by 200 m from seawall construction (CSIR, 2002d).

As mentioned, limited smothering of the rocky shoreline has occurred at the southern and northern boundaries of the Site 2 beach, extending to an estimated depth of 13 m. In addition, the large volumes of sand being transported northward from Site 2 during and after the mining have resulted in deposition along the rocky coastline north of Site 2. This deposition is expected to extend to about 13 m depth. Based on model predictions, these deposition effects are expected to persist for several years.

Along the rocky shore north of Site 3 & 4, deposition would reduce with increasing distance from Sites 2, 3 & 4 (the sources of the additional sand). The magnitude of any accretion or deposition on this northern coastline is likely to be similar to the extent of typical seasonal variations, although the persistence of such deposition is likely to be longer (years instead of weeks to months).

When sediment from Site 3 & 4 beachwall operations is added to the supply from Site 2, a concern is the possible additional sediment supply to the wave-sheltered depositional area at Bakers Bay. The island in Bakers Bay is situated close to the shore. Reference to extensive literature on tombolo formation (CSIR, 1995) indicates that a ratio of island length (parallel to the shore) to offshore distance of 1 or more can result in tombolo formation. As the ratio is presently about 0.8, tombolo formation triggered by additional sand supply (which could increase the ratio) is a possibility.

7.5 POCKET BEACH SITES 11 & 12

7.5.1 Background

Pocket Beach Sites 11 & 12 (Figure 4.35 shows the planned mining sites) occur in an undisturbed area, where no mining of the beach area has occurred to date.

7.5.2 Scenario

Future discharge of 4 084 400 m^3 (7 351 900 tons) of sand from dredging activity at Mining Site 11 is proposed, with a further 2 027 000 m^3 (3 649 000 tons) of sand to be discharged opposite Site 11 from dredging of a pond linking to Site 12 (termed “Link Pond”) and from dredging of Site 12. In addition, an estimated volume of 410 000 m^3 is to be discharged in order to maintain the position of the shoreline opposite Site 11 (i.e. providing protection of the Site 11 excavation from wave action) for a period of about 60 days after the mining sites have been dredged.

The detailed volumes to be discharged are summarised in Table 7.1 below.

Table 7.1: Summary of dredging and discharge plan at Site 11&12

Dredging area	Time (days)		Volume discharged (m^3)
	From	To	
Link Pond	0	2.8	60 425
Site 11	2.8	154.9	3 228 081
Site 11 Accretion	154.9	192.0	795 875
Link Pond	192.0	211.2	368 377
Site 12	211.2	383.8	1 658 801
Additional Maintenance	383.8	443.8	410 000

A single discharge position was assumed throughout the dredging, located opposite the centre of Site 11.

The discharge rates will vary during the course of operations. The highest rates will occur when the dredger is operating close to the discharge position, with rates reducing as the pumping distance increases. These various rates were schematised for input to the model, as indicated in the following Table 7.2.

Table 7.2: Schematised discharge rates used in the shoreline model

Time (days)		Effective modelled rate (m^3/year)*
From	To	
0	89	7 827 749
89	109	7 495 804
109	192	7 761 608
192	201	8 111 111
201	207	6 083 333
207	211	6 239 401
211	318	4 135 955
318	384	2 468 412
384	444	~2 500 000

* These exclude allowance for loss of fine material in suspension and are calculated with the days rounded to integer values.

The shoreline modelling was conducted assuming that dredging commences on 1 April 2006 (recent information indicates a later date).

7.5.3 Results

Figure 7.9 shows the predicted shoreline position from sediment discharge, at the end of dredging at Site 11 (i.e. after 192 days). It is predicted that the beach opposite the discharge point will be approximately 210 m wide at this time. Also shown in the figure is the predicted shoreline configuration at the end of sediment discharge from Site 12 (after 384 days). It can be seen that, while sediment discharge from dredging of the Link Pond and Site 12 has maintained the beach width opposite the discharge point at an approximately constant position, the beach on either side has increased in width. This increase in beach width is due to the continual lateral distribution of material to the north-west and south-east from the discharge position.

Figure 7.10 provides a representation of predicted beach width over time at locations along the beach (opposite the discharge position, labelled "DP", and opposite positions A and B – see Figure 7.9). Considerable fluctuations in beach width are predicted to occur opposite the discharge point. This is due to erosive wave events transporting material away from the accreted and vulnerable area, and due to intermittent relatively calm wave conditions during which accretion occurs rapidly at the discharge point. The beach width changes at positions A and B are predicted to be less extreme and more stable.

Based on measurements in the region and engineering calculations, it is estimated that discharged sand will result in measurable deposition (i.e. more than a few centimetres) to a depth of about 16 m. Figure 7.11 provides an estimate (based on accretion observed in the region) of how the +2 m MSL, +6 m MLS and +9 m MSL contours will shift seaward as a result of sand input, after a discharge period of 2 years. Also shown is the 16 m contour which defines the maximum limit of significant accretion.

It is predicted that by the time all dredging ceases (apart from possible dredging operations to rehabilitate excavated areas) approximately 1 million m^3 of sand will have been transported to the beach north of Bogenfels Arch. This estimate is in addition to material that would have naturally have been transported to the north prior to mining. As a result of this sand input, it is likely that the small pocket beach to the north of the arch will accrete "by a few tens of metres" (CSIR, 2005e). If the supply of sand from the accreted beach at Site 11 & 12 is not interrupted as a result of rehabilitation dredging, a total estimated 2.5 million m^3 of sand would be transported to the above-mentioned pocket beach within 5 years after the end of mining.

7.5.4 Impacts

A seawall of up to about 600-700 m in length is to be constructed at Site 11 in order to protect mining operations from wave attack. Associated impacts on beach fauna are expected. The seawall represents about 20% of the total length of the Site 11 & 12 beach.

While shoreline accretion of up to 250 m may result in steepening of the beach, this is unlikely to be much steeper than the present inter-tidal beach, which has an average beach slope of 1:8. Grain size increases are not expected to be significantly more than the existing coarse average grain size of 968 microns.

Available bathymetric survey data indicate that reefs occur at depths of over 30 m (CSIR, 2002d). Therefore sand accretion extending to an expected depth of 16 m seaward of the beach at Site 11 & 12 would not impact on these sub-tidal reefs.

Smothering of rocky reef at the north-western and south-eastern ends of the Site 11 & 12 beach would affect an estimated 300 m to 400 m of shoreline. This smothering would extend offshore to an estimated maximum depth of 16 m.

Accretion of “a few tens of metres” of the shoreline at the pocket beach to the north of the Bogenfels Arch may result in minor inundation of reef on the north-west and south-eastern borders of this beach.

7.6 ELIZABETH BAY

7.6.1 Background

Sediment input

A total of 21.2 million m^3 (38.8 million tons) of sediment, more than 95% of it sand, has been deposited on the beach at a number of locations, generally situated near the centre of the sandy beach, at Elizabeth Bay between 1991 and April 2005.

Fate of sediment

Accretion to date (Figure 7.12) has resulted in shoreline accretion of up to 450 m in the centre of the bay. From surveys of the beach and near-shore region (CSIR, 2001) in January 1990 (prior to mining) and in June 2001, the accumulation of sand in the bay during this period is estimated to be 9.575 million m^3. This corresponds to a discharged volume of 8.933 million m^3.

Whereas most estimates of accretion (e.g. in the southern mining area) were less than the volume discharged, the above result suggests that more material has accumulated than was discharged. This discrepancy may be the result of uncertainty associated with conversion of mass to volume of sand. In addition the percentage of oversize material is not accurately determined. However, it is not impossible that some sediment has accumulated in the near-shore region. Previously, fine sediment transported northwards by means of littoral drift (and possible a fraction of discharged sand) would have deposited on the Elizabeth Bay beach to be mobilised and transported inland by wind. Now that the beach is steep, the same sediment cannot deposit on the beach because of the steepness of the beach and the associated increased turbulence from wave action. As a result this sediment is effectively trapped in the near-shore region. Thus, apart from directly causing accretion of the beach by discharging material, accumulation of additional material may be caused indirectly by means of this “trapping” mechanism.

Impacts to date

Input of large quantities of sand has resulted in steepening of the beach. The beach has been altered from a dissipative state to a more reflective state, accompanied by an increase in sand particle size. Pre-mining inter-tidal beach sediment sizes (5 samples along the beach) were between 150 and 180 microns (CSIR, 1988). However, recent sand sampling (8 samples along the beach on 3 separate occasions in 2004) indicates average grain sizes to range from 490 to 720 microns (CSIR, 2005d). This increase in sediment size and associated wave conditions has resulted in a loss of diversity of beach-dwelling species and has led to a shift in benthic community structure from a mussel-dominated community to a community dominated by crustaceans (Pisces, 2004b).

The gradual increase in cover of sand in sub-tidal and inter-tidal habitats in Elizabeth Bay over the past decade reflects the inundation of reef habitat as beach accretion continues.

Approximately 1 km of rocky shoreline has been smothered. This smothering extends to a depth of several metres. Survey data indicate this depth of accretion to be about 5 m in the west of the bay and about 8 m in the east of the bay.

7.6.2 Scenarios

A total discharge of about 1 691 000 million m^3/year (3.04 million tons/year) of undersize sediment is to be discharged. Two scenarios were tested: Scenario 1 was set to have a coarse sediment (sand) content of 60% of the total to be discharged, while the sand content was increased to 95% in Scenario 2. (This has recently been determined to be the most likely scenario.) Inferred discharge rates, between 1998 and 2004, were a compilation of past and current discharge rates, as provided by Namdeb. The proposed discharge rate, after July 2005, was obtained from available information (CSIR, 2004). Future discharge rates used in the simulation, and their position, are depicted in Table 7.3.

Table 7.3: Future discharge rates and positions used in the model.

Scenario	Percentage of coarse sediment	Discharge station number	Discharge rates ($m^3.yr^{-1}$)	
			Sept 2004 to June 2005	July 2005 to end of simulation
1	60%	11.4	289 916	326 155
		14	724 790	815 389
2	95%	11.4	459 034	516 413
		14	1 147 584	1 291 032

7.6.3 Results

Figure 7.13 illustrates the predicted shorelines at the end of mining (estimated to be in the year 2013) for Scenarios 1 and 2, as well as the measured shoreline of 27 January 2004. Accretion patterns for the scenarios are similar with more accretion predicted for Scenario 2 than for Scenario 1.

7.6.4 Impacts

Further accretion of the beach will probably result in increased steepening of the beach, with a possible increase in the associated impacts on beach fauna (CSIR, 2004b). Further smothering of rocky shores by sand is predicted. A predicted total of 1 300 m of rocky shoreline, either side of the bay, will be inundated for the case of 60% sand content scenario.

In the case of the 95% sand content scenario, it is predicted that 1 900 m of rocky shoreline will be inundated with sand (present indications are that the latter case will apply).

7.7 DISCUSSION

7.7.1 Fate of sand

Studies on the southern Namibian shoreline (from the Orange River to Chameis Bay) have indicated north-bound longshore sand transport to be in the order of 2 million tons/year (i.e. just over a million m^3/year) (e.g. CSIR, 2002b). An assessment of shoreline stability in response to decreased sand input from the Orange River and concomitant increase in mine sand input corroborated this longshore transport rate. The result of sand placed in the inter-tidal zone has been accretion of the near-shore zone. From several near-shore surveys (e.g. CSIR, 2002b) it is evident that accretion is primarily contained in the near-shore region, to a maximum depth of 15 to 16 m relative to MSL (i.e. within a few hundred metres of the shoreline). This near-shore survey data together with shoreline data have facilitated an assessment of the extent of accretion resulting from discharged sand (and sand from seawall construction) in the southern region. Of a total 361 million tons estimated to have been discharged, 294 million tons or 81% of the discharged sediment was accounted for in this manner.

The remaining 67 million tons sediment was accounted for by means of estimation errors, accumulation in remnant seawalls on the beach, fine sediment losses, a small amount of fine sand accumulation seaward of the near-shore profile (i.e. deeper than 15-16 m) and transport of sand to the north (where sand depositing in bays may be subject to aeolian transport). Considering the time period over which sediment was dispersed (about 35 years) and the area of the receiving environment primarily to the north of Chameis Bay, it is possible that much of this volume of sediment was “absorbed” by the system. The lack of obvious accretion of the shoreline north of Chameis Bay and the lack of permanent tombolo formation at Sinclair Island (where a relatively small additional supply causing a few tens of metres of accretion would result in this occurring) support the concept that sand has been “absorbed” in the near-shore system.

While sand discharged in the southern Namibia area has been significantly redistributed along the coast, roughly 38 million tons of sand discharged at Elizabeth Bay tends to accumulate within the bay. Data from bathymetry and beach surveys indicate all discharged sand to be accounted for in the form of near-shore and beach accretion.

7.7.2 Natural deposition on reefs

Onshore/offshore changes are typically ±17 m (with maxima of up to ±35 m) on the exposed beaches in Southern Namibia (CSIR, 2002b) and less in wave-sheltered areas (e.g. Elizabeth Bay). Corresponding vertical changes in the order of two to three metres have been recorded. These beach and near-shore changes occur in response to natural effects such as:

- seasonal storm erosion with interim calm periods;
- the formation of *beach cusps,* i.e. localised sedimentary headlands with embayments in between;
- variations in longshore transport.

When such changes occur in areas of a combination of sandy and rocky shores (the latter often underlying the sandy shore), this may result in intermittent smothering and exposure of rock habitat. This smothering and exposure would be expected to occur approximately on a seasonal time scale. Typically, the summer beach and near-shore profile has a large volume of sand occupying the upper beach (and smothering near-beach rocky reef), while in winter this sand is transported and deposited further offshore, sometimes exposing these near-shore inter-tidal reefs. This type of change in the Pocket Beach areas is corroborated by near-shore divers, who report vast changes in sand cover.

7.7.3 Mine discharge-induced deposition on reefs

As manifested by modelling and measurements of accretion of coarse sediment/sand on the shoreline (in this section), a total of about 3 km of rocky inter-tidal and near-shore sub-tidal smothering of reef (to a thickness of centimetres to metres, for a period of years to decades – i.e. therefore causing impact according to Table 2.2) in the demonstration areas will have occurred by 2013. This is based on measured accretion to date, future accretion based on planned mining rates, and on known coastal rocky shore areas (based on aerial photographs and on-site observations). Table 7.4 provides a breakdown of where this accretion has occurred and will occur. This smothered 3 km of rocky shore translates to only 1% to 2% the rocky shore in the Namibian part of the project area (Orange River to Spencer Bay), which is over 180 km in length. However, the possibility that this small area may be an important habitat, for example for breeding, must be considered.

Table 7.4: Locations and extent of rocky shore smothering

Site	Length of rocky shore smothered to date (m)	Length of additional rocky shore to be smothered by 2013 (m)	Total (m)
Mining Area 1 (Orange River to Chameis Bay)	**500 ***	**0 m**	**500**
Pocket Beaches Site 2	**100 ****	**0 m**	**100**
Pocket Beaches Site 11 & 12	**0 m**	**350 m**	**350**
Elizabeth Bay	**1000**	**900**	**1900**
		Total	**2850**

* This may be greater - due to smothering of sub-tidal reefs that are not seen in aerial photographs (and are not surveyed).

** Slight accretion of rocky shore in the region of Site 3 & 4 is possible, depending on quantities placed on seawalls.

7.7.4 Other impacts

On-land dredging in the near future is likely to cause considerable (order of 100 m) accretion at the Orange River Mouth. CSIR (2003a) concluded that this is unlikely to have a detrimental effect on the Orange River estuary (but that changes in river flow would have an impact). It is relevant to note that, according to available data, a vast decrease in sediment (and sand) discharge by the Orange River would otherwise probably have resulted in erosion.

The assessment of impacts in Section 2 indicated that seawall construction would constitute an almost instantaneous and comprehensive smothering of beach biota at the time of construction. From available information it is evident that in the order of 100 km of such seawalls have been constructed in total. Smothering of the localised area up to 100 m of the shoreline would have occurred at the time of construction of these seawalls. In places erosion of the shoreline has resulted in elimination of these seawalls and re-establishment of the beach profile similar to that before mining commenced.

Beach steepening and particularly the associated increase in grain size can impact on beach fauna. Steepening has been recorded in the southern Namibia area, but not sufficient to significantly change the sand grain size (according to limited measurements – e.g. CSIR, 1979, CSIR, 2002b). Steepening and narrowing of the beach has occurred at Pocket Beach Site 2, with associated impacts on beach fauna, and is predicted to occur at Pocket Beaches Sites 3 & 4 and 11 & 12.

Beach steepening at Elizabeth Bay has caused a significant increase in average grain size (to greater than the impact threshold indicated in Table 2.2), resulting in a loss of diversity of beach-dwelling species and a shift in benthic community structure (from a mussel-dominated community to a community dominated by crustaceans).

8. CUMULATIVE EFFECTS

8.1 INTRODUCTION

The definition of cumulative effects is reiterated: "*changes to the environment that are caused by an action in combination with other past, present and(or) future human actions".* It is perceived that the potential effects of discharges (and seawalls) from mining projects to date have been generally evaluated in isolation. For example, the effects of discharges at Elizabeth Bay were originally evaluated without considering potential vessel mining in the region. Another example is the evaluation of environmental impact as a result of on-land (coastal) dredging in southern Namibia, which does not consider previous, future and concomitant (neighbouring) mining operations. This approach can result in an effect occurring which is not anticipated.

In this study, cumulative effects have been addressed up to this point to some degree. For example, fine sediment discharges in southern Namibia (from the various plants associated with different operations) have been considered (Section 6.3) in a cumulative sense. Similarly, an assessment of accretion from coarse sediment discharges in the same area incorporated all known discharges (i.e. on-land dredging together with all plant discharges), as described in Section 7.3. The cumulative effects that result from these sediment inputs are clearly described in the relevant parts of Sections 6 and 7.

In this section, areas of potential cumulative effects are considered which have not been considered previously. Recognising the differing behaviour of fine and coarse sediments, these are dealt with separately.

8.2 FINE SEDIMENT

Potential cumulative effects of a tailings discharge from a land-based mining operation in combination with a tailings discharge from vessel-based mining have not been addressed to date. Therefore the effect of discharges from a dredging operation in combination with a tailings discharge from land-based mining in the Chameis Bay region was tested. This represents the situation which occurred in early 2005. In addition, the effect of a mining vessel discharge in combination with a mine discharge at Elizabeth Bay was tested. Although simultaneous mining did occur and the locations of mining are correct, the discharge rates which are employed in the model may not be appropriate and are fairly conservative (i.e. large) in order to rigorously test whether a cumulative effect could have occurred or may occur in future (if similar simultaneous mining occurs).

In terms of the above definition of cumulative effects, only changes to the environment from human actions are considered. However, it is of interest to investigate the effect of a combination of a natural event (specifically, a flood) in combination with mine sediment discharges. This situation is tested for the southern Namibia region.

To assess the cumulative effects of different fine sediment inputs, a series of simulations were conducted in which the separate inputs (e.g. vessel inputs and land-based inputs) were combined in each of the fine sediment models discussed thus far (i.e. Orange River/Southern Mining area, Chameis Bay, and Elizabeth Bay). The results are presented in Figures 8.1 to 8.6. These plots include the contours of the maximum concentrations and deposition thicknesses reached, and the percentage of simulation time that specific concentrations and thicknesses have been exceeded, for the simulation incorporating combined sediment discharges. Overlain on to these plots are black lines marking the footprints of concentrations and deposition resulting from the individual inputs. In the plots of results for Chameis Bay and the Orange River, the black lines delineate the area where 1 mg/l concentration is exceeded and where the 0.0005 mm deposition thickness is exceeded. For Elizabeth Bay, lines delineate the area where 1 mg/l concentration is exceeded and where the 0.01 mm deposition thickness is exceeded. In all plots showing percentage time of exceedance of various parameters, the black lines indicate areas where exceedance occurs for more that 1% of simulation time.

8.2.1 Chameis Bay

To assess the cumulative effects of dredge overspill and plant discharge, a simulation was conducted combining the two sediment inputs into the Chameis Bay model, i.e. the overspill discharge from dredging operations, simultaneous to plant tailings discharge from coastal mining of a diamondiferous deposit. These can be construed as two separate projects as they were originally planned as separate projects. The results of predicted suspended sediment and deposition are presented in Figures 8.1 and 8.2, respectively. An animation of this simulation is provided on the attached compact disk – the animation is in the directory "Chameis" and is named *Dredger_and_plant_combined_discharge.avi* (instructions for viewing are provided with the disk). For more information as to which area corresponds to a respective input (dredge overspill or plant discharge) Figures 6.12 to 6.15 display the results for the individual sediment input simulations (described in Section 6.4).

Concentrations

'Max turbidity reached' shown in Figure 8.1 indicates that in the area of the plant discharge, the maximum concentrations increase slightly when dredge input is incorporated, relative to the plant discharge only case (Figure 6.12). In other words, a cumulative effect is evident. The cumulative effect is also clearly evident in concentration maxima in the north: where before concentrations in the north of the region shown for the dredger or the plant discharge alone were less than 5 mg/l, the combined simulation shows concentrations between 5 and 10 mg/l exiting the area. On the other hand, in the area south of the plant discharge, concentrations reflect those of dredge overspill input only.

Only a very slight increase (almost not discernable in Figure 8.1) in maximum concentrations was evident for the combined scenario (relative to the individual discharge cases). Therefore, impact on the environment is not expected to increase significantly as the time and extent over which the threshold concentration is exceeded is not significantly greater.

Deposition

There appears to be an increase in the extent of maximum deposition (Figure 8.2) beyond the lines marking the individual input simulation footprints. The deposition within these areas is below 0.001 mm and is a direct result of increased suspended sediment due to the combined effect of the two individual inputs. Area of deposition exceeding 0.001 mm slightly exceeds areas of individual input footprints (Figures 6.13 and 6.15). In the dredge overspill simulation a deposition thickness of between 0.005 and 0.01 mm was observed west of Site 3 & 4. However, the thickness increases to between 0.01 mm and 0.02 mm when combined with plant discharge.

The assessment of impact thresholds (Table 2.2) indicates that sub-millimetre deposition which lasts for hours to days is considered to have a low, neutral impact. Based on this information, the deposition from either the individual tailings or the individual plant discharges was determined to have an insignificant impact. As the maximum deposition from the combined discharges is less than 0.01 and is certainly short-lived (definitely less than 1% of the time), the cumulative impact of deposition for the combined discharges is also considered to be insignificant.

8.2.2 Elizabeth Bay

To assess the cumulative effects of mining vessel and land-based discharges, a simulation was conducted combining these two sediment inputs into the Elizabeth Bay model. The results of predicted suspended sediment and deposition are presented in Figures 8.3 and 8.4, respectively. An animation of this simulation is provided on the attached compact disk – the animation is in the directory "Ebay" and is named *Vessel_and_plant_discharge_combined.avi* (instructions for viewing are provided with the disk). For information on the extent of suspended sediment concentrations and deposition as a result of individual vessel or land-based discharges, reference is made to Figures 6.22 to 6.25 (Section 6.5).

Concentrations

The 'Max turbidity reached' plot of Figure 8.3 shows the maximum turbidity of the combined simulation. The sediment plume reaches further than the areas marked for the individual simulations. This is the result of increased suspended sediment from both discharges settling to lower layers increasing the concentration. As would be expected not much difference is expected in the bay, where land-based discharge alone would have impact. Further offshore, predicted concentrations between 0 and 10 mg/l have increased in extent.

Exceedance of the 100 mg/l "impact-threshold" concentration occurs only within the bay, where the isolated land-based discharge exhibited impact (Section 6.5.4). As no unacceptable exceedance of concentrations is predicted elsewhere, no cumulative impact is expected in the Elizabeth Bay region.

Deposition

In the region offshore of Elizabeth Bay, a cumulative effect of the two discharges (land and vessel-based) is predicted. Predicted deposition thickness in some places has increased from values predicted to be between 0.02 and 0.05 mm (for "land-based discharge only" case) and between 0.05 and 0.1 mm (for the "vessel discharge only" case) to a cumulative thickness greater than 0.1mm. The area of maximum deposition (defined by deposition greater than 0.01 mm) has also increased relative to the combined areas of land-based and vessel discharge deposition.

In terms of the impact of deposition, predicted persistence of deposition greater than 0.05 mm thickness increases to a maximum of just less than 20% of total simulation time (approximately 25 days in total). Furthermore, the extent of this deposition increases. The combined simulation also resulted in an additional area of deposition greater than 0.05 mm, for the same percentage of exceedance, which extends beyond the area of interest. While the effect of the cumulative scenario is greater than that of the individual scenarios, the associated impact is still negligible according to the criteria set out in Table 2.2.

8.2.3 Southern mining area and Orange River

As it is informative to assess the cumulative effects of a natural and a mining discharge, a simulation was conducted combining the natural (1 in 20-year flood scenario) and anthropogenic sediment inputs into the Orange River model. An animation of this simulation is provided on the attached compact disk – the animation is in the directory "Orange" and is named *1in20yr_flood_and_mine_discharge_combined.avi* (instructions for viewing are provided with the disk). The results for suspended sediment and deposition are presented in Figures 8.5 and 8.6, respectively. For more information as to which area corresponds to a respective input (natural/flood or land-based discharge) Figures 6.6, 6.8, 6.9 and 6.11 display the results for the individual sediment input simulations (described in Sections 6.2 and 6.3).

Concentration

When comparing the cumulative (Figure 8.5) and the individual (Figures 6.6 and 6.9) simulations, it clear that the flood discharge totally dominates sediment plumes in the area. While lines delineate the area where mine discharges would coincide with flood discharge, the increased concentrations indicating a cumulative effect are not evident. Near the individual mine discharge sites concentrations are higher (relative to concentrations caused by the flood discharge only). The total percentage of time exceeding the threshold concentration of 100 mg/l increases by approximately 2% to 3% in the area of the mine discharges, over and above the impacts associated with a 1 in 20-year flood. 1:20-year flood predictions indicated that a considerable area of potential impact on biota is expected (Section 6.2.4). This area would be very slightly increased as a result of cumulative effects.

Deposition

With regard to deposition, it is evident that the effects of the 1 in 20-year flood dominate the effects due to mine discharge. In effect, the predicted cumulative potential impact to benthic fauna and flora is similar to that of the 1 in 20-year flood case. This deposition impact was assessed (Section 6.2.4) to be somewhere between *low/neutral* ("sub-millimetre for hours to days" – Table 2.2) or *high impact* ("cm to metres for years to decades").

8.2.4 Discussion and synthesis

In terms of the combined scenarios of fine sediment discharge at Elizabeth Bay (land-based and vessel discharge) and at Chameis Bay (plant tailings and dredger overspill discharge), a cumulative effect was predicted. However, considering the specified thresholds as described in Section 2, impacts due to the cumulative effects may be considered negligible.

While combined land and vessel fine sediment discharges have been investigated here, a series of several onshore (land) discharges have not been analysed. Findings (Section 6) suggest that exceedance of acceptable limits (according to Table 2.2) from fine sediment discharges occurs within a few hundred metres of the discharge point. For the case of small operations (e.g. relatively small contractor operations) this would reduce to the order of tens of metres. For larger operations, as long as adjacent operations are not too close (i.e. in the order of a few hundred metres apart), cumulative impacts from fine sediment discharges would not be expected.

From the investigation of cumulative effects of a flood in combination with mine sediment discharges, the natural source (i.e. river flood) appears to totally dominate man-induced sediment discharges (reinforcing the findings of Section 6). Comparatively, land-based discharges in an area of high, sediment-laden river flow seem insignificant.

Although not tested, based on the results of separate flood and vessel discharges in this study, it would logically be expected that for the case of a flood in combination with a vessel discharge, the flood-induced suspended and deposited sediment would totally dominate that from the vessel discharge. In addition, it would be expected that for the case of a flood in combination with both a vessel discharge and a land discharge, the flood-induced suspended and deposited sediment would totally dominate that from the other two sources.

8.3 COARSE SEDIMENT

As long as beaches are linked by means of the littoral transport of sand, there is potential for separate mining activities to cause cumulative effects on those beaches (i.e. effects such as accretion, smothering of reefs, beach steepening, etc.). All of the Southern Namibia operations are indeed connected by means of littoral sand transport and therefore have a potential for cumulative effects. Appropriately, the fate and impact of coarse sediment discharges in southern Namibia have been handled in a cumulative sense within this study (i.e. all of the sediment inputs from all plants for the entire period of mining and for future scenarios have been considered). The associated (cumulative) impacts of these inputs are discussed in Section 7.7

The Pocket Beach Area operations are also inter-connected (and connected to the southern mining operations) by means of littoral sand transport and therefore have a potential for cumulative effects. From survey, aerial laser (LIDAR) survey and orthophotograph data, the stability of shorelines (apart from that at mining sites 2, 3 & 4) suggests that no cumulative effects have occurred to date.

9. MODEL SENSITIVITY

9.1 INTRODUCTION

Through the application of models it is possible to assess the sensitivity of predictions of discharged sediment transport, concentrations and deposition to various physical and model parameters. The degree of sensitivity of predicted sediment behaviour to a particular parameter (e.g. to wave height) provides an assessment of how important the quality (and sometimes quantity) of that parameter is (e.g. for how long and to what accuracy wave measurements are needed). This information provides insight into what monitoring is required to better assess the behaviour of discharged sediments, particularly by means of modelling. This information is also intended to inform BCLME project BEHP/CEA/03/02 (on data gathering and gap analysis for assessment of cumulative diamond mining impacts), particularly in identifying the relevance of gaps in the data and in prioritising monitoring to fill these gaps.

Various tests on model input parameters follow. It should be noted that the scope of this project does not allow exhaustive testing of parameters. Therefore tests were carefully selected to achieve relevant insights.

9.2 WAVE HEIGHT

Sensitivity of the predicted sediment dynamics in Elizabeth Bay to wave height was tested for the simulation of the land-based discharge only (details of this scenario: Section 6.5) referred to as the *standard case*. Offshore wave heights of all conditions were increased by 10%, relative to the standard case. A 10% increase is estimated to be roughly the extent of a median wave-height increase which could occur in a season or possibly a year. Measurements have indicated a change of as much as 26% in median wave height between two seasons (CSIR, 2002b), indicating that this extent of change is possible.

9.2.1 Result

Figure 9.1 shows the maximum turbidity and maximum deposition for the standard and increased wave-height cases, on the left and right side of the plot respectively.

The plots of maximum turbidity do not show significant differences. The maximum deposition plots show only minor differences in the form of marginal changes in deposition thickness of 0.2 mm at most.

9.2.2 Implication

These results imply that predicted plume concentrations and deposition are relatively insensitive to small changes in wave height, particularly the case of a bay such as Elizabeth Bay.

9.3 WAVE PERIOD

Previous experience indicates the effect of changes in wave period on sediment dynamics to be less than the effects of wave height and wave direction. For example, the effect of a 5% change in wave period (as was found to be the case between waves measured in two successive seasons) caused a change of only 0.3% in the longshore transport rate (CSIR, 2002b).

9.4 WAVE DIRECTION

Sensitivity of predicted sediment behaviour near the Orange River mouth to wave direction was tested relative to the ‘cumulative’ simulation of the 1 in 20-year flood combined with Southern Mine Area discharges (as described in Section 8.2.3) – referred to here as the “standard case”. Median wave directions from hindcast data offshore of Oranjemund during the same time of year as the 1 in 20-year flood (February and March) were assessed for the years 1996 to 2000. The range of median directions was from 184.1° to 196.3° (i.e. varying by about 12°). Based on this result, and taking into account that the dataset used to obtain this value was relatively small (5 years), the total range of change of 12° was applied to all wave directions. The change was applied to attain a more westerly wave direction, in order to test the effect of an anomalously more shore-normal wave direction along the southern Namibian shoreline.

9.4.1 Results

Figure 9.2 shows the predicted maximum turbidity and maximum deposition for the standard case and the altered wave-direction case, left and right side of the plot respectively.

Maximum concentrations, inshore of the 40 m depth contour, are predicted to be higher for the sensitivity test (more westerly waves) than for the standard case. Predicted maximum concentrations are higher by almost four times in the near-shore area, with this discrepancy decreasing with distance offshore; beyond the 40 m depth contour, where concentrations fall below 100 mg/l, suspended sediment patterns and concentrations are similar to the standard case.

As for the concentrations, predicted offshore patterns and thicknesses of deposition are similar further offshore. Closer to land, but still beyond the 40 m depth contour, the area where deposition exceeds 5 mm is predicted to be larger. Predicted maximum thicknesses in this area increase by almost four times relative to the standard case, but towards the northern model boundary values are more similar.

9.4.2 Implications

Sensitivity to wave direction of the prediction of fine sediment behaviour in the Orange River region is evident. The more shore-normal wave directions clearly result in reduced dilution of concentrations through reduced northerly alongshore transport and increased on/offshore transport. (In other words, suspended sediment remains in the region close to the river source, rather than being rapidly transported northwards by waves.) The predicted increased sediment in the system is matched by increased deposition. This sensitivity to wave direction was also evident from tests on predictions of shoreline evolution (CSIR, 2002b). Thus it is vital that adequate measurements (or validated hindcast data) of waves be obtained for several years, if the fate of discharged sediments is to be accurately predicted. Schoonees (2000) determined that 5-8 years of directional wave data are needed to accurately define (within 10%) the average longshore transport climate on the east coast of South Africa. This provides a guideline for the minimum number of years of measurements to adequately define a directional wave climate for prediction of the fate of discharged sediments.

9.5 WIND SPEED

Sensitivity of predicted sediment behaviour in Elizabeth Bay to wind speed was tested on the simulation of the land-based discharge. Wind speed was increased by 15%. This was considered to be a reasonable estimate of possible annual variability in wind speed, based on available wind data (CSIR, 1998c).

9.5.1 Results

Figure 9.3 shows the maximum turbidity and maximum deposition for the simulation of the Elizabeth Bay land-based discharge (assigned as the *standard case*) and the sensitivity test on wind speed, left and right side of the plot respectively.

In terms of maximum turbidity, increase in wind speed resulted in no significant change in predicted maximum suspended sediment concentrations above 10 mg/l. Relatively minor changes to the extent and configuration of maximum concentrations between 1 and 10 mg/l could be discerned.

Some minor differences in maximum deposition were evident between the standard and “increased wind” cases. Deposition thickness beyond the 40 m depth contour reduced from less than 0.05 mm in the land-based discharge to less than 0.02 mm in the sensitivity test. Inshore of the 40 m depth contour the differences were not as prevalent. In Elizabeth Bay, the area of deposition south-east of Elizabeth Point reduced in extent but not in thickness. Similarly, the areas south of the bay and west of Possession Island reduced in size between the land-based discharge simulation and the sensitivity test.

9.5.2 Implications

The predicted sediment dynamics in Elizabeth Bay show only a slight sensitivity to a relatively severe change in wind speed. Relatively small changes in suspended sediment concentrations and in deposition were evident. None of the changes were deemed to be of the extent that they would significantly affect conclusions relating to the fate and impact of discharged sediments.

9.6 WIND DIRECTION

Sensitivity of predicted fine sediment behaviour at Chameis Bay to wind direction change was tested on the ‘cumulative’ simulation of the plant tailings combined with dredger discharges (Section 8.2.1), referred to here as the “standard case”. Median wind directions of the summer seasons (the time of year of the cumulative scenario) of data measured from 1989 to 2002 at Elizabeth Bay were obtained. The range of median directions was 146° to 194°. Taking into account that the dataset used spanned 13 years, and that the sensitivity test would span only some 6 weeks, half of the range (i.e. 25°) subtracted from the wind input directions should serve as a relatively stringent test of the effect of wind direction change. Thus, 25° more easterly winds were applied. The more easterly wind was tested as it was assumed that this would cause a more severe change in plume behaviour by driving plumes offshore. More westerly wind, on the other hand, may simply cause plumes to “hug” the coast as they are presently predicted to do in the standard case.

9.6.1 Results

Figure 9.4 shows the predicted maximum turbidity and maximum deposition for the standard case and the case of more easterly wind, left and right side of the plot respectively.

Predicted maximum suspended sediment concentrations for both scenarios do not show significant differences. Noticeable are the maximum concentrations in areas of the northern dredge panel and at the site of plant discharge. Compared to the standard case, the areas where concentrations greater than 50 mg/l (and less than 100 mg/l) are very slightly reduced.

The deposition plots show a similar situation in that patterns of deposition are similar for both cases. The deposition areas are slightly smaller. In addition, the thicknesses of deposition appear to be slightly less. For example, west of Panther Head, where deposition in the cumulative scenario exceeded 0.002 mm, deposition remained below 0.002 mm in the sensitivity test. Inshore of the 20 m depth contour, deposition adjacent to the plant discharge is also less in the sensitivity test, reducing from approximately 0.007 mm in the cumulative scenario to 0.005 mm in the sensitivity test. However, these sub-millimetre changes are considered to be negligible in effect.

9.6.2 Implications

Slight differences between the standard case and the “more easterly wind” case suggest that sensitivity of the Chameis Bay model to wind direction is minor. In general, the predicted suspended sediment plumes show little sensitivity to the direction change, with areas close to discharge showing slight differences indicating the increased dispersing effect of more offshore-directed wind. Reasons for this result may be a combination of the domination of wave-driven transport in the near-shore zone and orientation of the coastline guiding sediment movement towards the north. Deposition was slightly less for the changed wind-direction case, which may be a result of more frequent driving of suspended sediment offshore, thus dispersing suspended sediment more widely and reducing the amount of sediment depositing in any area.

It is somewhat surprising that a severe change in wind direction has limited predicted effect. It is concluded that this is primarily a result of the shoreline orientation and the significant role of wave-driven flow in defining fine sediment transport. While the accuracy of wind direction measurements (and thus model input) for this particular case is not apparently important, it is certain to be relevant for other coastline configurations. For example, the role of wind in the Orange River flood model was clearly observed to be important (Section 6.2)

9.7 INCREASED SEDIMENT DISCHARGE RATE

Sensitivity tests were conducted on effect of discharge rates on predicted sediment dynamics in Elizabeth Bay. For both the "standard" 1) land-based and 2) vessel discharge scenarios (described in Section 6.5) the discharge rate was doubled.

9.7.1 Results

Figures 9.5 and 9.6 show the maximum turbidity and maximum deposition for the simulation of land-based discharge and vessel discharge (left side of the plots), together with the associated sensitivity test (right side of the plots).

1) Doubling of the land-based discharge (Figure 9.5) results in a further spreading of the suspended sediment plume (concentrations greater than 1 mg/l) when compared to the land-based discharge scenario of Section 6.5.3. As would be expected, concentrations in the area immediate to the discharge site in Elizabeth Bay are higher than in the original land-based discharge scenario. However, in general, suspended sediment concentrations predicted are double those presented in Figure 6.20.

   Deposition results show that, in the sensitivity test, the thickness of deposition increases; however, the general pattern and overall size of areas of deposition do not change significantly. As with concentration, it is predicted that a doubling in discharge rate results in increased deposition by approximately double. This can be seen most clearly in the area south of Elizabeth Bay, where deposition is predicted to increase from less than 0.1 mm in the standard case to less than 0.2 mm in the sensitivity test.

2) Doubling the rate of discharge from the vessel (Figure 9.6) results in similar increases in the suspended sediment plume size and concentrations as the results for doubling land-based discharge. Where in the standard case only concentrations less than 2

mg/l reached the shoreline, concentrations between 2 and 5 mg/l reached the shoreline in the sensitivity test.

As with the deposition results of doubling the land-based discharge rate, the thickness of deposition increases in general, while the size and patterns of deposition do not change between the standard case of vessel discharge and the sensitivity test. Again, as an example, maximum deposition thickness almost doubles from 0.35 to 0.62 mm in the area approximately 7 to 8 km south-west of the bay.

9.7.2 Implications

It may be concluded that the predicted sediment behaviour in Elizabeth Bay is sensitive to an increase in land-based discharge as well as an increase in vessel discharge. The results show a virtually linear relationship between the rate of discharge and the concentrations and associated deposition. Therefore accurate measurement of discharge rates is important, since a 10% error implies a 10% error in predicted concentration or deposition.

9.8 CRITERIA FOR DEPOSITION AND RESUSPENSION

The critical shear stress values for resuspension and deposition employed in the Orange River model (as described in Section 6.2) are presented in Appendix D. In order to simulate the mass deposition that was observed in the area of the river mouth during the flood of 1988, the critical shear stresses were varied spatially. The critical values were higher in the immediate area of the river plume to promote sedimentation and inhibit resuspension, so causing deposition. For the rest of the model, the values presented in Appendix D were implemented. Therefore, a sensitivity test with the condition of constant critical shear stresses (with values presented in Appendix D) for sedimentation and resuspension **throughout the modelled area** was conducted. This was compared to the *standard case* of the Orange River flood as described in Section 4.2.

9.8.1 Results

Figure 9.7 shows the maximum turbidity and maximum deposition for the simulation of the flood of 1988 and the sensitivity test, left and right side of the plot respectively.

Plots of maximum turbidity show a significant difference between the predicted results for the standard case of the Orange River flood 1988 and the sensitivity test on critical shear stress. Predicted concentrations are generally higher in the offshore area (seaward of the 40 m depth contour) for the test condition. Where concentrations range between 2 and 5 mg/l approximately 15 km south-west of No. 3 Plant in the standard case, concentrations range between 10 and 50 mg/l in the sensitivity test. South of the Orange River mouth concentrations are also higher in the sensitivity test: 15 to 20 km southwards of the river mouth concentrations exceed 100 mg/l in the sensitivity test, while in the standard case concentrations remain below 10 mg/l. However, in the near-shore area, landward of the 20 m depth contour, the standard case predicted higher concentrations, in general, than the sensitivity test. The reason for greater concentrations in the offshore region is that less deposition is predicted to occur adjacent to the Orange River. Therefore, the sediment that would have deposited is suspended and transported offshore by the river flow.

Maximum deposition plots of the two simulations also showed significant differences. As expected, deposition in the immediate area of the river mouth is not evident in the sensitivity test. Just beyond the 40 m depth contour, adjacent to the river mouth, deposition varies between less than 20 and up to 80 mm in the standard case, while in the sensitivity test deposition is higher (between 40 and 100 mm). Further to the north (approximately 60 km from the area of the river mouth) deposition greater in the standard case than in the sensitivity test. For example, 25 km south-west of No. 2 Plant deposition in the 1988 flood simulation ranges between 10 and 20 mm, whereas in the sensitivity test deposition ranges between 2 and 5 mm. The reduced deposition to the north for the sensitivity test is because of the above-mentioned effect of more sediment being transported seaward by river flow. As a result, this sediment is not available on the pro-delta (as it was for the standard case) for subsequent transport northward by wave-driven longshore transport and wind-driven flow.

9.8.2 Implications

Such results suggest that predicted sediment behaviour near the Orange River is sensitive to inputs regarding criteria for resuspension and deposition. This highlights the need for measurements of the critical shear stresses for deposition and resuspension, particularly during flood conditions.

9.9 SEDIMENT COMPOSITION

The second sensitivity test was to reduce the fall velocity of each of 3 fractions of discharged sediment that are represented in the model. Appendix D presents the key inputs as specified for the Orange River 1988 flood model. A reduction in fall velocity effectively changes the nature of the sediment in the model. This test is pertinent since information on the exact *in situ* fall velocities during the flood was not available. By reducing the fall velocity, more sediment would be available for transport in suspension for longer periods of time. Therefore, a reduction by 50% in fall velocities of all fractions, considered to be a possible variation from that employed, was implemented

9.9.1 Results

Figure 9.8 shows the maximum turbidity and maximum deposition for the simulation of the flood of 1988 (standard case) and the sensitivity test (reduced fall velocity), left and right side of the plot respectively.

In terms of sediment concentrations, the results of this comparison are similar to those of the critical shear stress sensitivity test, with the exception of the area adjacent to the river mouth. As with the previous sensitivity test, concentrations offshore of the 40 m depth contour and south of the Orange River mouth are predicted to be higher in the sensitivity test. Differences in offshore concentration values exist north of and adjacent to the river mouth. South of the river mouth, the differences are less significant. Concentrations greater than 50 mg/l are predicted up to 35 km south of the river mouth, while in the flood of 1988 simulated concentrations were less than 5 mg/l. In the sensitivity test, predicted maximum concentrations landward of the 40 m depth contour are lower than the 1998 flood simulation from the river mouth area northwards.

Depositional patterns offshore of the 40 m depth contour are also similar to those of the sensitivity test discussed previously, except that in this sensitivity test a pro-delta exists adjacent to the river mouth (due to identical defined critical shear stresses to those of the 1988 flood simulation). Compared to the 1988 flood simulation, the predicted pro-delta evident in the sensitivity test is larger in area (i.e. approximately 230 km^2 compared to 110 km^2) and deposition thickness of this pro-delta is less (i.e. between 10 and 700 mm compared to between 10 and 1500 mm).

Lower predicted concentrations of near-shore suspended sediment in the bottom layer, in the sensitivity test, are the result of the transport of the slower descending particles over greater distances in the upper layers when compared to the flood of 1988 simulation. This transported material is then available for deposition in the deeper waters, offshore of the 40 m depth contour.

Deposition in the area of the mouth is still induced. However, the thickness of this deposition is reduced relative to the standard case, because of less material being available (in suspension near the bed) for deposition. With a 50% reduction in fall velocity, the amount of suspended sediment available for deposition is predicted to be reduced by roughly half.

9.9.2 Implications

The results of this sensitivity test indicate that predicted sediment behaviour near the Orange River is sensitive to sediment fall velocity (which in turn is affected by sediment composition). Thus a clearer definition of *in situ* fall velocity from measurements is required.

9.10 DISCUSSION

In the above, a number of sensitivity tests on parameters were tested. These selected parameters are deemed to be key to the assessment of the behaviour of sediment discharged from mining operations or from natural sources. The scope of this study does not allow for all parameters to be tested. For example, tests on variations in tides and bathymetry were excluded. However, from experience it is estimated that the accuracy of measurements of these parameters is sufficiently reliable for prediction of behaviour of sediments. Therefore, testing of significant variations in these parameters is not relevant.

The tests clearly indicated the need for accurate directional wave data, with wave direction being the most important parameter.

While sensitivity tests on wind speed and direction did not indicate major changes in predicted sediment behaviour, this was deemed to be a result of the coastline configuration in the region tested. It is known from experience (e.g. from the Orange River flood modelling) that accurate wind data are vital for accurate prediction of fine sediment behaviour.

A linear relationship was found between discharge rate and both predicted concentrations and deposition. For example, a 10% change in the discharge rate would result in a 10% change in predicted concentrations and deposition. This highlights the need for accurate sediment discharge information.

Tests on sediment characteristics such as resuspension and deposition critical shear stresses and fall velocities highlight the need for more accurate in situ measurements of these parameters. If such measurements cannot be achieved, then, at the very least, a clear definition of discharge grain size distribution is needed and, where possible, models should be validated against measured concentrations.

9.11 MONITORING

Based on the above assessment, the following guidelines to monitoring are proposed (Table 9.1 below provides suggested responsible parties and time frames):

- That a detailed log of the hourly/daily rates of sediment discharge are recorded, together with frequent (daily/weekly) measurements of the grain size distribution of the discharge (this includes assessment of floods);

- That accurate directional wave data are essential. Analysis of South African east coast sediment transport (Schoonees, 2000) indicates that 5 to 8 years of accurate directional wave measurements are needed to characterise average net longshore transport rates. A compromise would be to employ hindcast wave data (predicted from pressure and/or wind data). However, this hindcast data should be validated against at least one year of measurements;

- That accurate wind data be measured. Ideally, several years of wind data would be needed to accurately define the average conditions (a 15-20 year period was suggested to define average weather conditions – Ian Hunter, South African Weather Service, pers. comm., but it is estimated that five years would be adequate for assessment of sediment transport). A compromise may be to employ model data, but this should be validated against at least a year of measurements;

Where possible, marine fine sediment behaviour measurements are needed, particularly of *in situ* settlement, deposition shear stress and resuspension shear stress. Suspended sediment concentrations and sediment deposition are highly sensitive to these parameters.

Apart from the identified monitoring needs originating from modelling, other data gaps have come to the fore in the course of this project, which highlight further monitoring needs. These needs are as follows:

Wind-blown sediment grain sizes

It has been identified that wind-driven exchange of sediment between the near-shore/surf zone and the beach is highly dependent on the grain size distribution of material being blown into the sea and the grain size distribution of material on the beach (section 5.2.2 and Appendix J). A detailed coastal sand sampling programme is therefore recommended. This will aid in the clarification of the volume of sand depositing in the marine environment.

Wind-blown sand transport

Estimates of wind-blown sand transport vary considerably. Monitoring of aeolian sand transport rates is recommended in order to validate calculations of annual rates of transport. Transport rate can be estimated from measurement (surveying) of deposition in mine pits (e.g. sampling trenches) or by deployment of sand traps.

Fluvial sand input

Sand discharge from rivers is not accurately determined. For example, sampling of river-borne sediment concentrations in the Orange River (e.g. Bremner *et al.,* 1990) has been relatively crude and intermittent. A more detailed programme of sampling of suspended and bed-load sediment transport, particularly during floods, is recommended. As the primary contributor of fluvial sediment input into the marine environment, the Orange River should be the focus. As it is difficult to determine bed-load via measurements, it is proposed that accurate bathymetry surveys at the Orange River mouth be conducted (before and after flood events).

Airborne dust

A major potential source of sediment in the form of bergwind-transported airborne dust was identified. It is recommended that this be quantified by means of monitoring and/or satellite image interpretation. Computational dispersion modelling may be required.

Table 9.1: Details of monitoring items, suggested responsible party and time frame.

Monitoring item	Frequency of measurement	Suggested Responsible party	Time frame
Sediment discharge	Hourly/daily	Mining companies. (Namdeb already do this)	While discharges are operational
Grain size sampling of sediment discharges	Weekly (with occasional more frequent measurements)	Mining companies.	While discharges are operational
Directional wave data	Hourly	Mining companies (Namdeb have a wave buoy)	For at 5-8 years, to characterise the wave climate (longer for design data needs)
Wind measurements	Hourly	Mining companies. Measurements are in progress at Kleinzee, planned at Oranjemund, done at Elizabeth Bay	For at least 5 years. Up to 15 years to characterise average weather.
Fine sediment behaviour	Hourly (During intensive 1-2 weekly exercises)	Competent measurement expertise (e.g. CSIR).	Until parameters are well-quantified. (Estimate 4-5 measurement exercises)
Coastal sand sampling	Once-off	Mining companies, with assistance from e.g. CSIR	Once-off, to characterise sand sizes
Wind-blown sand transport rates	Once-off	Mining companies, with assistance from e.g. CSIR	Once-off, to relate transport to wind speed
Fluvial sand transport (suspended load)	Monthly/weekly during floods	Mining companies (Namdeb are collecting samples intermittently)	10-20 years in order to characterise sediment from various Orange River catchments.
Fluvial sand transport (bed-load)	After large floods	CSIR/Mining companies	Surveys after a series of 5 large floods will provide reasonable quantification.
Airborne dust	Once-off	Specialist measurements (e.g. by CSIR/Wits University)	Once-off, to quantify bergwind input.

10. TAILINGS SEDIMENT MANAGEMENT

10.1 INTRODUCTION

In this section the following question as posed in the project terms of reference is addressed:

How can the tailings discharges be managed in order to minimise any effect on the rock lobster resource?

In this section, management actions are not restricted to tailings but also to management/rehabilitation of beaches on which seawalls have been constructed. Thus, not only are effects on rock lobster habitat considered, but also effects on beach biota. As a result of their different behaviour, management of fine sediment discharges is considered separate to coarse sediment discharges.

10.2 FINE SEDIMENT MANAGEMENT

10.2.1 Effect of a more exposed discharge site

A simulation was conducted to investigate the effects of moving the position of the land-based discharge position from within Elizabeth Bay (as described in Section 6.5) to a position just west of the previous CDM discharge site, beyond the confines of the bay. This site is just north of Elizabeth Point (approximate location, see Figure 10.1). Historically, at this site a plant operated between 1911 and 1948, initially by a German company and later by Consolidated Diamond Mines of South West Africa Ltd. (Pallet, 1995). The discharge of sediment tailings at this site must have caused temporary accretion. However, recent observation of the shoreline at this site suggests that all of this material (coarse and fine) was removed by wave and wind action. This site is tested in a simulation as a discharge position for fine material. In the simulation all of the material which was discharged in the bay (at positions 11.4 and 14) is shifted to the single, more exposed previous discharge site. It was thought that more exposed wave conditions at such a site may serve to mobilise fine sediment more efficiently and reduce harmful concentrations. However, the fact that discharge onto a rocky shore (as is the case at the old CDM discharge site) may not be acceptable is recognised.

In the simulation, hydrodynamic conditions identical to the simulation of land-based discharge scenario of Elizabeth Bay were used. An animation of this simulation is provided on the attached compact disk – the animation is in the directory “Ebay” and is named *Plant_discharge_exposed_site.avi* (instructions for viewing are provided with the disk). Figures 10.1 and 10.2 depict the results of this simulation. For comparative purposes, Figures 6.22 and 6.23 are referred to.

Concentrations

Figure 10.1 shows the maximum concentrations predicted throughout the simulation and the percentage of simulation time that the 100, 50 and 10 mg/l concentrations were exceeded. Similar to the previous land-based discharge scenario (Figure 6.22), the plume footprint (as indicated by the maximum turbidity) is predicted to occur in Elizabeth Bay and in the south towards Possession Island. However, concentrations in the bay remain below 50 mg/l, while in the previous scenario the maxima of the simulation (>200 mg/l) were reached in the bay. Concentrations between 10 and 20 mg/l are confined to the area around the discharge site and approximately 2.5 km east, into Elizabeth Bay. To the west, these concentrations extend to about 3 km from the discharge site.

The areas over which the impact threshold concentrations (100 mg/l) have been exceeded are smaller compared to those depicted in Figure 6.22 (Section 6.5.4), and are located seaward of Elizabeth Bay. While exceedance of 100 mg/l occurs in an area approximately 500 m alongshore and 100 m offshore at the old CDM discharge site, discharge into Elizabeth Bay resulted in predicted exceedance of 100 mg/l in an area approximately 2 km alongshore and 500 m offshore. The greatest percentage of exceedance of 100 mg/l is 30% of simulation time (approximately 37 days), which is less than that for the case of discharge in Elizabeth Bay. The reason for the reduced concentrations is probably the more dynamic and turbulent wave action, which would tend to disperse fine sediment more efficiently.

Deposition

Figure 10.2 shows that a maximum deposition thickness of between 0.02 mm and 0.05 mm is reached east of Elizabeth Point, east of Possession Island, as well as over a large area beyond the 20 m depth contour. Compared to the scenario for which discharge occurs within Elizabeth Bay (Figure 6.23), deposition is less in areas far from and within Elizabeth Bay, but higher in areas close to the discharge site of this scenario. The results show that deposition above 0.05 mm thickness is less in terms of time and area, while other threshold thicknesses show very limited change.

10.2.2 Effect of changing the discharge location

Figure 10.3 illustrates the result of a hypothetical test of fine sediment discharge (of 3 million m^3/year). This was suggested as a possible "worst case" maximum future discharge resulting from the processing of marine dredged material. The test indicated episodic occurrences of concentrations over 100 mg/l (above background concentrations) in the Kerbe Huk lobster fishing region. Although not initially problematic in terms of impact, the probability for impact to occur could potentially be avoided by shifting the offending discharge further south or north. By a process of experimentation, it will be possible to find a site for which predicted concentrations of suspended sediment at Kerbe Huk will be negligible.

This process of locating a discharge by means of trial and error modelling has been followed previously, in order to estimate the required minimum distance of a mine tailings discharge from the site of a power station cooling water intake (CSIR. 2005f). It is vital that this process takes cognisance of all possible mine sediment inputs as well as all possible sensitive sites.

A second example of this approach employed a simplified model for prediction of concentrations in assessing whether the WOMS dredger discharge would be sufficiently far from the Orange river mouth to avoid elevated concentrations of fines (from WOMS) from entering the Orange River mouth on a flood tide. It was found that at a distance of 4 to 6 km from the mouth, concentrations at the mouth, during isolated worst-case wave conditions, were in the region of 10 to 25 mg/l, i.e. below the 100 mg/l impact threshold (CSIR, 2003a).

10.3 COARSE SEDIMENT MANAGEMENT

While the above modelling and findings relate directly to fine sediment, the following does not exclusively relate to coarse sediment. However, coarse sediment is the focus.

10.3.1 Slimes dams/tailings dumps

In South Africa legislation dictates that mine sediment tailings should not be disposed of in the sea. This has resulted in the creation of slimes dams, which have the following impacts:

- They have an aesthetic impact (i.e. they are visually unappealing);

- They eliminate patches of natural habitat (by smothering);
- Dust originating from slimes dams (or tailings dumps) can impact on the downwind environment. This has been found to be a major negative impact of mining operations south of the Orange River (CSIR, 1994)

It is considered that, in arid areas, recovery of desert vegetation and possibly fauna from impacts such as the above would be an extended process, compared to the rate of recovery of biota the marine environment. This observation suggests favouring marine discharge, as is practised in Namibia. However, in the event that the marine environment at the mining site is highly sensitive (e.g. critical to lobster breeding), perhaps on-land slimes dam discharge could be considered (with permission from the authorities).

10.3.2 Thickening and degritting

If technically and economically feasible, consideration should be given to engineering solutions to reduce the volumes of sediment discharged. For example, the installation of a “degrit” and/or “thickening” process in the Elizabeth Bay Mine could have reduced the overall volumes of sediments discharged from 2.9 to 2 million tons/year, and could have reduced the rate of coarse sediment discharge from 426 to 213 tons per hour. (Note these rates were valid at the time of consideration.) However, the volume of fine material discharged would not have been influenced. It is anticipated that an overall reduction in the coarse fraction of the discharged material may result in the particle-size distribution of the discharge more closely resembling that of the original beach sediments. This may help to reduce the magnitude of the impacts associated with increases in the mean grain size of the beach sediments. In addition, a reduction in the coarse sediment discharge would result in reduced smothering of rocky habitat.

10.3.3 Replacement of sediment into mined-out areas

Discharge of both oversize material and plant tailings back into mined-out (i.e. already disturbed) areas may be possible, but would require:

- Compliance with legislation;
- Consideration of the composition and compaction of material replaced (avoiding creation of quicksand/muddy areas or areas from which fine sediment can be easily mobilised by wind);

- Consideration of impacts of increased salinity in groundwater.

Benefits of discharge of tailings into mined-out areas would be:

- Recovery of water. Overflow water from dredged material discharged into mined-out areas at Pocket Beach Site 2 was shown to contain very low concentrations of sediment – demonstrating potential for clean-water recovery (CSIR, 2005c). This clean water could be used in plant processing;
- Rehabilitation of mined-out areas by refilling them. This could be enhanced by replacing topsoil at the top of refilled areas, to ensure vegetation regeneration;
- Less effects of discharged sediment on the marine environment (e.g. potential tombolo formation at near-shore islands, impacts on marine biota, and other impacts as described in Table 2.2).

10.3.4 Discharge location of coarse sediment discharge

Subtle shifts in the position of a coarse discharge may have a big effect in reducing smothering of a rocky shore. For example, at Elizabeth Bay model predictions indicate how shifting discharge further east (from position 11.4 to position 14 – positions shown in Figure 10.4) can result in a decrease in shoreline accretion in the year 2014 near the jetty on the rocky shore at Elizabeth Point. More accretion is predicted at the eastern end of the bay (which is also a rocky shore). However, this increase is relatively limited. Thus, a subtle shift in discharge position by 650 m can reduce accretion on a rocky shore by about 135 m. Unfortunately in this case, it is balanced by almost as much accretion (115 m) on the eastern rocky shore. (If this shore was also sandy, the benefit would be more significant.)

10.3.5 Strategic dredging

The discharge of dredger tailings (WOMS) is predicted to possibly result in accretion in the order of 500 m near the Orange River mouth in the southern Namibia area. The bedrock region of this accreted area can be mined while the shoreline is in an accreted state. In order to reduce the effect of sustained accretion, which is predicted to spread to the Orange mouth, it may be possible to accelerate the erosion of the shoreline back to its original condition. This could be achieved by means of strategic dredging (CSIR, 2003c). This simply involves dredging out the most of accreted area (which could then be subsequently mined) close to bedrock level, discharging the tailings inland, into mined-out areas. Only a very narrow strip of "barrier beach" should be left. If possible the top of this narrow barrier should be skimmed off by means of a bulldozer. This beach will erode as a result of longshore transport until a breach in the barrier occurs. Wave overtopping should also occur at times. If the region landward of the barrier beach was dredged to some 10-15 m depth, the narrow barrier beach will ultimately be "overwashed" and transported into this deep area. It is anticipated that considerable reworking of sediment would occur and the beach profile will ultimately be re-established to a condition similar to the pre-mining/pre-dredging condition.

10.3.6 Strategic bulldozing

The effect of the seawalls on the process of retreat of an accreted shoreline at Pocket Beaches Site 2 was investigated with a shoreline model (CSIR, 2005c). By reducing the height of the beach, it was found that the time for the accreted shoreline to retreat to its original condition could be shortened by approximately 30%. This would correspond to flattening the seawalls by, e.g., bulldozing the material that lies above the natural beach elevation landward into the mined-out areas

10.4 DISCUSSION AND SUMMARY

There is little doubt that there is considerable opportunity for practical management actions to be conducted in order to mitigate the effects of discharged fine and coarse sediment.

For the case of fine sediment discharges, the following guidelines are relevant:

- Discharge at a more wave-exposed site will result in more rapid dispersion of fine material than at a wave-sheltered site, with the result that lower concentrations will be experienced near the discharge point. This solution may not always be ideal since separation of fine from coarse material may be problematic (and expensive) and the more exposed site may be a sensitive rocky shore;
- Modelling can be employed in order to site fine sediment discharges optimally, relative to sensitive sites (e.g. power station water intake, estuary);
- The modelling of fine sediment discharges has indicated that elevated concentrations (i.e. in the region of 100 mg/l, which may cause impact) are generally limited to within a few 100 m of the discharge location (distance in the order of a kilometre for large discharges). This information provides a rough guideline for siting of fine sediment discharges relative to existing fine sediment discharges.

For the case of coarse sediment discharges, the following guidelines are relevant:

- Small changes in the siting of a coarse sediment discharge on the shoreline can affect the extent of smothering of rocky shores. The siting of discharge locations on the shoreline should take this into account;
- Consideration should be given to the potential discharge of mine tailings into mined-out areas. Numerous benefits can be achieved from this approach; however, consideration must be given to salinity effects on groundwater and to the possible creation of quicksand or muddy areas;
- Consideration should be given to mechanical means of managing tailings, e.g. by means of thickening/degrit processes (the product of this process would be coarse material which could be used to infill mined-out areas) which may result in a discharge composition/quantity of sediment having a reduced impact;
- Consideration should be given to the use of bulldozers and dredging to aid the process of retreat of accreted beaches.

11. CONCLUSIONS AND RECOMMENDATIONS

This study focuses on the cumulative effects of mine sediment discharges in the Benguela Current Large Marine Ecosystem. The project scope defined that only the region shallower than 40 m depth would be considered. In this study meaningful impacts of mine sediment discharges from large-scale mining are not found to extend more than a few kilometres from their source. Therefore, a project area which considered only regions where large-scale mining is actively practised or planned was defined: *from the high-water mark extending to 40 m depth, from the Olifants River in the south to Spencer Bay in the north*.

11.1 POTENTIAL IMPACTS

A review of available information indicated that elevated fine sediment concentrations (>100 mg/l for more than just "hours to days") would have an impact on biota, particularly on reefs. In addition, available information indicated that a relatively thick layer of sediment deposition for a sustained period (i.e. more than a millimetre, for longer than "hours to days") could have an impact on biota, particularly on reefs. Change in beach slope, particularly steepening of beaches in response to sand discharges, was also identified as an impact. A rule of thumb indicates that the increase in grain size, associated with beach steepening, to above a threshold of 500 μm would impact on non-crustaceans. Scouring of biota dwelling on reefs was identified as an impact, but no clear threshold of when this impact occurs was available. The impact of mine-induced oxygen depletion (particularly compared to the scale of natural oxygen depletion) was deemed to be insignificant in the defined project area (less than 40 m depth).

11.2 DEMONSTRATION AREAS

Based on several criteria, demonstration areas were selected. These were all situated in Namibia. An advantage of sites being in Namibia is that this is where most data and operational computational models are available. In addition, in Namibia the policy is to discharge tailings into the marine environment (unlike South Africa where tailings are discharged to slimes dams) and therefore this is where impacts are more likely.

The disadvantages of a focus on Namibia are a) lack of attention paid to the rock lobster in the Port Nolloth/Kleinzee area, and b) since mine tailings in South Africa are discharged to slimes dams (as opposed to in the sea in Namibia), the potential to provide a comparison between the two major classes of mine tailings treatments (on-land in South Africa versus into the sea in Namibia) has been lost. **It is therefore recommended that future studies focus on accessing available data, monitoring and analysis of the South African coastal mining impacts and of South African rock lobster in order to provide this comparison.**

11.3 MODEL VALIDATION

A suite of numerical models of wave transformation, flow, fine sediment transport and coarse (wave-driven) sediment transport were employed in the study. These models were validated against measured data. For the cases of modelling the behaviour of fine sediment discharged from floods, the model validation results suggested a relatively low level of accuracy. Thus, sediment concentrations and deposition are probably within order of magnitude accuracy and are probably not geographically precise.

For the cases of modelling fine sediment discharged from mining operations, comparisons with measurements suggest a reasonable level of accuracy, with concentrations probably within roughly ±10 to ±20 mg/l.

For all of the shoreline modelling cases, comparisons with surveyed data indicate that accuracy for medium-term predictions (up to 3-4 years into the future) would be generally within the range of natural variability of shorelines in the area of interest. Longer-term predictions would be slightly less accurate.

11.4 SEDIMENT INPUTS TO THE PROJECT AREA

In the last few decades the Orange River sediment input has ranged from an average of 34 million tons/year (1960 to 1969) to an average of less than 17 million tons (1980s). Based on these values, it is likely that 400 to 800 million tons were discharged from 1968 to April 2005. In comparison, 404 million tons were estimated from available mining data, indicating the volumes from the two sources to be of the same order of magnitude in that period.

A primary difference between natural and mine sediment sources is the rate of discharge: while mine sediment discharges tend to have a relatively constant rate, flood sediment discharge tends to be large and more intermittent. For example, during a major flood such as that of 1988, 64 million tons of sediment, discharged in a matter of a few months, is roughly equivalent to four times the annual average Orange River sediment discharge mass. This volume of discharge is also approximately equivalent to about four times the annual average mine sediment discharge to the project area in Namibia.

While million of tons of windblown fine sediment has been estimated for the total BCLME, only a fraction of this would be delivered to the <40 m depth region, from where it would be rapidly mobilised by wave action and transported into deeper water. Windblown sand input was estimated to be relatively minor.

Natural sediment input to the project area tends to be fine. For example, about 84% of sediment from the Orange River is indicated to be fine material. Most of the estimated windblown sediment input, primarily from bergwinds, is fine. On the other hand, most of the sediment discharged from mining is medium to coarse sand, with a small percentage of fine sediment – generally less than 5%.

11.5 FATE AND DEPOSITION OF FINE SEDIMENTS

It was evident from model predictions (supported by observations) that fine sediment is mobilised by wave action and is transported rapidly, generally by wind-driven currents. The result of this rapid transport is that fine sediment that is discharged moves beyond model domains extending tens of kilometres from discharge sites (generally moving northward) within periods of weeks to months.

For the cases of fine mine sediment discharge, concentrations which could cause impact on biota are generally limited to with a few hundred metres of the discharge position. For the case of fine sediment discharges from floods, sustained concentrations are one to two orders of magnitude higher than for the mine discharge cases.

For the case of the floods simulated, predicted deposition was considerable (order of millimetres to centimetres) and extended over several square kilometres. On the other hand, for all cases of mine sediment discharge, deposition is generally predicted to be an order of magnitude less than 1 mm.

For both floods and mine discharges, predicted fine sediment deposition tends to occur in water depths greater than 40 m, and does not tend to deposit (with meaningful thickness or for a meaningful duration) on the near-shore reefs.

11.6 FATE AND DEPOSITION OF COARSE SEDIMENTS

Studies have clearly demonstrated that sand is transported northward by littoral drift. Additional sand discharged from mining operations results in accretion. Of a total 361 million tons of sediment (fine and coarse) estimated to have been discharged from 1970 to recent years, 294 million tons or 81% of the discharged sediment is accounted for by measured accretion. The remaining sediment (particularly the fine sediment component) is deemed to have been transported offshore and to the north. The lack of observed obvious accretion offshore and in northern regions suggests that this volume of sediment was “absorbed” by the system.

Measurements of natural beach variations provide an indication that near-shore reefs can be seasonally covered and re-exposed. However, as demonstrated by both modelling and measurements, discharge of large volumes of sand can result in long-term (years to decades) deposition on reefs, which overshadows natural trends.

The total of about 3 km of rocky inter-tidal and near-shore sub-tidal smothering of reef in the demonstration areas will have occurred by 2013. This estimate is based on measured accretion to date, future accretion based on planned mining rates, and on known reef areas (based on aerial photographs and on-site observations). While care must be taken that this relatively small area of rocky shore is not a key habitat for the biota of the BCLME (e.g. a breeding area for lobster, or home to an endangered/endemic species), this smothered area comprises only 1%-2% of the rocky shore in the Namibian part of the project area.

From available information it is evident that as much as 100 km of seawalls have been constructed in total, which must have caused smothering of beach biota at the time of construction. In addition, beach steepening has occurred. While fauna on most of the exposed beaches appear not to have been severely affected by this steepening, indications are that the change in conditions and grain size associated with steepening has affected community structure at the Elizabeth Bay beach.

11.7 CUMULATIVE EFFECTS

Model simulations of fine sediment behaviour indicated that simultaneous vessel and land-based mining operations could result in a detectable cumulative effect. However, this effect was predicted to be minor, such that no meaningful cumulative impacts resulting from fine sediment would occur.

For the case of coarse sediment, all of the Southern Namibia operations are connected by means of littoral sand transport and therefore have a potential for cumulative effects. In this study the fate and impact of coarse sediment discharges in southern Namibia have been handled in a cumulative sense (i.e. all of the sediment inputs from all plants for the entire period of mining (and a future scenario) have been considered). The associated (cumulative) impacts of these inputs are as discussed above (Section 11.6).

The Pocket Beach Area operations are also inter-connected (and connected to the southern mining operations) by means of littoral sand transport, indicating a potential for cumulative effects. From survey, aerial laser survey and orthophotograph data, the stability of shorelines is indicated (apart from that at currently operational mining sites 2, 3 & 4). The lack of observed accretion in this region suggests that no significant cumulative effects of coarse sediment discharges have occurred to date.

11.8 MONITORING

Model sensitivity tests provided some insight into which parameters are important to measure in order to accurately predict the behaviour of discharged fine and coarse sediment. The following guidelines to monitoring are recommended to facilitate the accurate prediction of sediment transport, concentrations and deposition:

- A detailed log of the hourly/daily rates of sediment discharge should be recorded, together with frequent (daily/weekly) measurements of the grain size distribution of the discharge (this includes assessment of floods);
- Accurate directional wave measurements should be conducted: 5 to 8 years of accurate directional wave measurements are needed to characterise conditions. A compromise would be to employ hindcast wave data (predicted from pressure and/or wind data). However, this hindcast data should be validated against at least one year of measurements.
- Accurate wind data should be measured. Ideally, several years of wind data would be needed to accurately define the average conditions, but it is estimated that 5 years would be adequate for assessment of sediment transport. A compromise may be to

employ model data, but this should be validated against at least a year of measurements.

- Where possible, measurements of *in situ* settlement, and both deposition and resuspension shear stresses for sediment must be measured as concentrations and deposition are highly sensitive to these parameters.

Apart from the identified monitoring needs which originating from modelling, other data gaps have been identified in this project, which highlight further monitoring needs. These needs are as follows:

Wind-blown sediment grain sizes

It has been identified that wind-driven exchange of sediment between the near-shore/surf zone and the beach is highly dependent on the grain size distribution of material being blown into the sea and the grain size distribution of material on the beach. A detailed coastal sand sampling programme is therefore recommended. This will aid in the clarification of the volume of sand depositing in the marine environment.

Wind-blown sand transport

Estimates of wind-blown sand transport vary considerably. Monitoring of aeolian sand transport rates is recommended in order to validate calculations of annual rates of transport.

Fluvial sand input

Sand discharge from rivers is not accurately determined. For example, sampling of river-borne sediment concentrations in the Orange River (e.g. Bremner *et al.,* 1990) has been relatively crude and intermittent. A more detailed programme of sampling of suspended and bed-load sediment transport, particularly during floods, is recommended.

Airborne dust

A major potential source of sediment in the form of bergwind-transported airborne dust was identified. It is recommended that this be quantified by means of monitoring and/or satellite image interpretation.

11.9 TAILINGS AND ASSOCIATED BEACH ACCRETION MANAGEMENT

There is little doubt that there is considerable opportunity for management actions to be conducted in order to mitigate the effects of discharged sediment, as follows:

- Discharge at a more wave-exposed site will result in more rapid dispersion of fine material than at a wave-sheltered site, with the result that lower concentrations will be experienced near the discharge point (however, this must be evaluated against the sensitivity of the discharge site, economical issues relating to separating fine from coarse sediment, etc);
- Modelling should be employed to site both fine and coarse sediment discharges relative to sensitive sites (e.g. power station water intake, estuary);
- The modelling of fine sediment discharges indicated that elevated concentrations (which may cause impact) are generally limited to within a few 100 m of the discharge location (distance in the order of a kilometre for large discharges). This provides a rough guideline for siting of fine sediment discharges relative to existing fine sediment discharges;
- Consideration should be given to the potential discharge of mine tailings into mined-out areas. Numerous benefits can be achieved from this approach (one of which is avoiding discharge into the marine environment). However, consideration must be given to salinity and composition of sediment (the latter to avoid possible creation of a bog with excessive fine sediment);
- Consideration should be given to mechanical means of managing tailings, e.g. by means of thickening/degrit processes (the product of this process would be coarse material which could be used to infill mined-out areas);
- Consideration should be given to the use of bulldozers and dredging to aid the process of natural erosion and retreat of accreted beaches.

12. REFERENCES

ACES. 1992 – Automated Coastal Engineering System. User's Guide. Dept. of the LA Army. Corps of Engineers, Vicksburg, Mississippi.

AMERICAN PETROLEUM INSTITUTE. 1991 – Recommended practise for planning, designing and constructing fixed offshore platforms. API Recommended Practise. ZA (RPZA) 19th edition. Washington DC, 159 pp.

ANZECC and ARMCANZ. 1999 – National Water Quality Management Strategy. Australian and New Zealand *Guidelines for Fresh and Marine Water Quality (1999).* Volumes 1, 2 and 3. Draft. Australia and New Zealand Environment and Conservation Council, and Agriculture and Resource Management Council of Australia and New Zealand.

APPLEBY, J. R. and D. J. SCARRATT 1989 – Physical effects of suspended solids on Marine and estuarine fish and shellfish with special reference to ocean dumping: A literature review. *Can. Tech. Rept Fish aquat. Sci.*, 1681: 1-33.

AULD, A. H. and J. R. SCHUBEL 1978 – Effects of suspended sediment on fish eggs and larvae: A laboratory assessment. *Estuar. Coast. Mar. Sci*. 6: 153-164.

BAGNOLD, R. A. 1941 – The Physics of Blown Sand and Desert Dunes. Chapman and Hall Ltd., London.

Bailey, G. W. 1985 – Distribution and cycling of nutrients at four sites in the Benguela system. *Symp. Upw. W Afr. Inst. Inv. Pesq.,* Barcelona, 1, pp 305-317.

BAILEY, G. W. 1991 – Organic carbon flux and development of oxygen deficiency on the modern Benguela continental shelf south of 22°S: spatial and temporal variability. In Tyson, R.V., Pearson, T.H. (Eds.), Modern and Ancient Continental Shelf Anoxia, No58, pp171-183.

BARKAI, A. and M. O. BERGH 1992 – The effects of marine diamond pumping operations on the littoral and shallow sublittoral benthos along the South African west coast, Namaqualand region, with special attention to possible effects on the rock lobster resource: a pilot study. UCT Unpublished Report. 43 pp.

BAUR, B. 1991 – Aeolian decoupling of beach sediment. Annals of the Association of American Geographers 81(2).

BOOIJ, N., RIS, R. C. and L. H. HOLTHUIJSEN 1999 – A third generation wave model for coastal regions, Part I, Model description and validation, *J. Geoph. Research*, 104, C4, 7649-7666.

BRANCH, G. M., EEKHOUT, S. and A. L. BOSMAN 1990 – Short term effects of the 1988 Orange River floods on the intertidal rocky-shore communities of the open coast. *Trans. Roy. Soc. S. Afr*. 47 (3): 331-353.

BREMNER, J. M., ROGERS, J. and J. P. WILLIS 1990 – Sedimentological aspects of the 1988 Orange River floods. T*rans. Roy. Soc. S. Afr*. 47 (3): 247-294.

BROWN, J. R. and E. B. HARTWICK 1988 – A habitat suitability index model for suspended tray culture of the Pacific oyster, *Crassostrea gigas* Thunberg. *Aquaculture Fish. Man.* 19: 109-126.

BUSS, L. W., 1986 – Competition and community organization on hard surfaces in the sea. In: DIAMOND, J. & T.J. CASE (Eds). Community Ecology. Harper and Row, New York, pp 517-536.

CANADIAN COUNCIL OF MINISTERS OF THE ENVIRONMENT (CCME) 2002 – Summary of existing Canadian Environmental Quality Guidelines. www.ccme.ca/assets/pdf/e1_06.pdf

CHAO, S. 1998 – Hyperpycnal and buoyant plumes from a sediment-laden river. *J. Geophys. Res*. 103(C2): 3067-3081.

CLARK, B. M., MEYER, W. F., EWART-SMITH, C., PULFRICH, A. and J HUGHES 1999 – Synthesis and assessment of information on the BCLME. Thematic Report 3. Integrated overview of diamond mining in the Benguela Current Region. AEC Report # 1016/1 March 1999 http://www.bclme.org/factfig/diamond_mining.asp

CLARK, B. M., SMITH, C. E., and W. F. MEYER 1998 – Ecological Effects of Fine Tailings Disposal and Marine Diamond Pumping Operations on Surf Zone Fish Assemblages near Lüderitz.

CLARK, B. M., ATKINSON, L. J., STEFFANI, N. and A. PULFRICH 2004 – Sandy Beach and Rocky Intertidal Monitoring Studies in the Bogenfels Mining Licence Area, Namibia: Monitoring Report 2004. Prepared for Namdeb Diamond Corporation.

CLARK, B. M., ATKINSON, L. J. and A. PULFRICH 2005 – Sandy Beach and Rocky Intertidal Monitoring Studies in the Bogenfels Mining Licence Area, Namibia: Monitoring Report 2005. Prepared for Namdeb Diamond Corporation.

CLARKE, D. G. and D. H. WILBER 2000 – Assessment of potential impacts of dredging operations due to sediment resuspension. DOER Technical Notes Collection (ERDC TN-DOER_E9). U.S. Army Engineer Research and Development Centre, Vicksburg, MD.

CORBETT, I. B. 1989 – The Sedimentology of Diamondiferous Deflation Deposits within the Sperrgebiet, Namibia. *PhD Thesis,* University of Cape Town.

COUNCIL ON ENVIRONMENTAL QUALITY. 1997 – Considering Cumulative Effects under the National Environmental Policy Act, Executive office of the President of the United States, Washington DC.

CSIR 1979 – Oranjemund Beach Study. CSIR Report C/SEA 7935.

CSIR 1981a – Estuaries of the Cape, Part II. Synopses of available information on individual systems. Report no. 3. Groen (CW7). CSIR Research Report 402.

CSIR 1981b – Estuaries of the Cape. Part II. Synopses of Available Information on Individual Systems. Report No. 1 Spoeg (CW5). CSIR Research Report 400.

CSIR 1981c – Estuaries of the Cape, Part II. Synopses of available information on individual systems. Report no. 2. Buffels (CW3). CSIR Research Report 401.

CSIR 1981d – Estuaries of the Cape. Part II. Synopses of Available Information on Individual Systems. Report No. 4 Swartlintjies (CW4). CSIR Research Report 403.

CSIR 1981e – Estuaries of the Cape. Part II. Synopses of Available Information on Individual Systems. Report No. 5 Holgat (CW2). CSIR Research Report 404

CSIR 1981f – Estuaries of the Cape. Part II. Synopses of Available Information on Individual Systems. Report No. 6 Bitter (CW6). CSIR Research Report 405.

CSIR 1984 – Estuaries of the Cape, Part II. Synopses of available information on individual systems. Report no. 26. Olifants (CW10). CSIR Research Report 425.

CSIR 1988 – Elizabeth Bay Production Facility: Environmental Impact Study. Volume 2: Technical Report. CSIR Report EMA-C 8887/2.

CSIR 1990 – Potential harbour sites on the Namibian Coast between the Swakop and Ugab river mouths. EMA-C 90194.

CSIR 1992 – Oranjemund Inshore Mining Project. Data Report. September 1991 to May 1992. CSIR Report EMAS-C 92.

CSIR 1994 – Alexkor Environmental Management Programme Report. Volume 2. Specialist Study Report. CSIR Report EMAS-C 94037(2).

CSIR 1995 – Jumeirah Coastal Zone Project. Coastal Engineering Assessment. Prepared for Dubai Municipality. CSIR Report. EMAS-C 95031.

CSIR 1996a – Coastal Evolution due to the Disposal of Dredger Tailings in the G68-G90 Region. CSIR Report EMAS-C 96022.

CSIR 1996b – Coastline Predictions to Optimise Exploitation of Mining Terrain: G0 to G180 Region. CSIR Report ENV/S-C 96063.

CSIR 1996c – Strandmynbou tussen Alexanderbaaihawe en die Oranjeriviermond. CSIR Report ENV/S-C 96004.

CSIR 1997 – An analysis of seawall maintenance requirements: No. 2 Plant to Chameis Bay. CSIR Report ENV/S-C 97019

CSIR 1998a – Wave Analysis offshore of Oranjemund. CSIR Report ENV/S-C98052.

CSIR 1998b – Coastal evolution as a result of the disposal of dredger tailings in the G68 to G90 region: Volume II: Main Report. CSIR Report ENV/S-C 98034.

CSIR 1998c – The Composition and Dynamics of Turbid Plumes at Elizabeth Bay. CSIR Report ENV/S-C 98093. 2 Volumes.

CSIR 1998d – Saldanha Bay General Cargo Quay Construction: Monitoring of Suspended Sediment Distributions Generated by Dredging in Small Bay. CSIR Report ENV-S-C 98100.

CSIR 1999 – Coastal evolution as a result of the disposal of dredger tailings in the G68 to G90 region: 1998 Study. CSIR Report ENV-S-C 99058.

CSIR 2000 – Update on metocean data summary: West Coast of South Africa and Namibia. CSIR Report ENV-S-C 99128.

CSIR 2000a – Coastal evolution as a result of the disposal of dredger tailings in the G68 to G90 region: 1999 Study. CSIR Report ENV-S-C 2000-020.

CSIR 2001 – Chameis Pocket Beaches: Coastal Evolution Predictions to Address Critical Issues. CSIR Report ENV-S-C 2001-054.

CSIR 2001a – Elizabeth Bay monitoring project: 2000 review. CSIR Report ENV/S-C 2001-037

CSIR 2002 – The effects of marine sediment discharge from extended mining operations at Elizabeth Bay. CSIR Report ENV-S-C 2002-056.

CSIR 2002a – Metocean Data Summary: Offshore of Oranjemund. CSIR Report ENV-S-C 2002-028.

CSIR 2002b – Coastal Modelling study for Southern Mining Area 1: Accretion, Safety, Environment. CSIR Report ENV-S-C 2002-113, Stellenbosch.

CSIR 2002c – A Decision Support Tool: Operational time for the Namdeb Inshore Mining Project. CSIR Report ENV-S-C 2002-120.

CSIR 2002d – Coastal Modelling Study at the Pocket Beach Areas: Accretion, Safety, Environment. CSIR Report ENV-S-C 2002-107, Stellenbosch.

CSIR 2002e – Dredging of Berth 306 for the South Dunes Coal Terminal in the Port of Richards Bay: Numerical modeling of the physical impacts of dredging. CSIR Report ENV-S-C 200-023, Stellenbosch.

CSIR 2002f – Elizabeth Bay monitoring project: 2001 review. CSIR Report ENV/S-C 2002-044

CSIR 2003a – Shoreline Accretion Effects at and South of the Orange River Mouth Resulting from Future Dredge Mining Operations. CSIR Report ENV-S-C 2003-084.

CSIR 2003b – Elizabeth Bay monitoring project: 2002 review. CSIR Report ENV/S-C 2003-066

CSIR 2003c – Post-mining assessment and mitigation of accretion for the WOMS project. CSIR Report ENV-S-C 2003-119.

CSIR 2004 – Elizabeth Bay mine upgrade environmental studies: Shoreline modelling. CSIR Report ENV-S-C 2004-090, Stellenbosch.

CSIR 2004a – Elizabeth Bay monitoring project: 2003 review. CSIR Report ENV/S-C 2004-032.

CSIR 2004b – Preliminary modelling of suspended sediment and shoreline effects from Marine Dredging at Chameis Bay. CSIR Report ENV-S-C 2004-110, Stellenbosch.

CSIR 2005a – Shoreline Predictions for Optimisation of Mining at Pocket Beaches Sites 11and12. CSIR Report ENV-S-C 2005-034.

CSIR 2005c – Physical Effects of Sediment Discharged from Marine Dredging, Plant Operations and Seawall Mining in the Chameis Bay Region. CSIR Report CSIR/NRE/ECO/ER/2005/0011/C.

CSIR 2005d – Elizabeth Bay physical environmental monitoring: 2004 review. CSIR Report ENV/S-C 2005-071

CSIR 2005e – Assessment of Potential Sedimentation at a Water Intake: Pocket Beaches Sites 11&12. CSIR Report ENV-S-C 2005-101.

CSIR 2005f – Assessment of Fine and Coarse Sediment at the Cooling Water Intake for the Proposed CCGT Power Plant at Uubvlei, Oranjemund. CSIR Report no. ENV-S-C 2005-081.

CSIR2005b – Shoreline Evolution as a Result of Dredger Tailings Discharge in Southern Mining Area 1: July 2005 Study. Addendum included. CSIR Report ENV-S-C 2005-086.

DAVIS, H. C. 1960 – Effects of turbidity-producing material in seawater on eggs and larvae of the clam (*Mercenaria mercenaria*). *Biol. Bull.* 118: 48-54.

DAVIS, H. C. and H. Hidu 1969 – Effects of turbidity-producing substances in sea water on eggs and larvae of three genera of bivalve mollusks. *Veliger* 11: 316-323.

EGGLESTON, D. 1972 – Factors influencing the distribution of sub-littoral ectoprocts of the south of the Isle of Man (Irish Sea). *J. Nat. Hist.*, 6: 247-260.

EMBECON 2004 – Dredging-related re-suspension of sediments: Impacts and guidelines for the Marine Dredging Project. EMBECON Marine Biological Consultants, 11 Clifton Rd, Mowbray, South Africa.

ENGLEDOW, H. R. and J. J. BOLTON 1994 – Seaweed alpha-diversity within the lower eulittoral zone in Namibia: The effects of wave action, sand inundation, mussels and limpets. *Botanica Mar*., 37:267-276.

FREDSØE, J. 1984 – Turbulent boundary layer in wave-current interaction. *Journal of Hydraulic Engineering,* ASCE, Vol1000, pp1103-1120.

GRANT, J. and B. THORPE 1991 – Effects of suspended-sediment on growth, respiration, and excretion of the soft-shelled clam (*Mya arenaria*). *Can. J. Fish. Aquatic. Sci*. 48: 1285-1292.

GREEN, L. 1950 – At Daybreak for the Isles. Howard. B. Timmins. Cape Town, South Africa.

GREENWOOD, B. 1996 – The Cunene/Kunene River Delta complex: Evaluation of the physical environment and assessment of the impact of the Epupu Falls Hydro Power Project. Scarborough College Coastal Research Group.

HEGMANN, G., COCKLIN, C., CREASEY, R., DUPUIS, S., KENNEDY, A., KINGSLEY, L., ROSS, W., SPALING, H. and D. STALKER 1999 – Cumulative Effects Assessment Practitioners Guide, Prepared by AXYS Environmental Consulting Ltd. and the CEA Working Group for the Canadian Environmental Assessment Agency, Hull, Quebec.

HERRMANN, C., KRAUSE, J. TSOUPIKOVVA, CHR, HANSEN, N. and K. 1999 – Marine Sediment extraction in the Baltic Sea. *Status Report. BalticSea Environment Proceedings,* No. **76**.

HISCOCK, K., 1983 – Water movement. In: Earll, R. & D.G. Erwin (eds). *Sublittoral Ecology: the Ecology of the Shallow Sublittoral Benthos.* Clarendon Press, Oxford, pp. 58-96.

HUNT, H.L., and R. E. SHEBLING 1997 – Role of post-settlement mortality in recruitment of benthic marine invertebrates. *Mar Ecol. Prog. Ser.,* 155: 269-301.

HUNTLEY, B. J. (ed) 1985 – The Kuiseb environment: the development of a monitoring baseline. *S. Afr. Nat. Sci. Prog*. Report 106.

JACOBSON, P. J, JACOBSON, K. M, ANGERMEIER, P. L. and D. S. CHERRY 2000 – Variation in material transport and water chemistry along a large ephemeral river in the Namib Desert. *Freshwater Biology* 44: 481-491.

KIØRBOE, T. F., MOHLENBERG and O. NOHR 1981 – Effects of suspended bottom material on growth and energetics in *Mytilus edulis*. *Mar. Biol.* 61: 283-28.

KRAPF, C. B. E, STOLLHOFEN, H. and I. G. STANISTREET 2003 – Contrasting styles of ephemeral river systems and their interaction with dunes of the Skeleton Coast erg (Namibia). *Quarternary International* 104: 41-52.

LANCASTER, N. 1989 – The Namib Sand Sea: Dune forms, processes and sediments. A.A. Balkema, Rotterdam.

LANE, S. B. and R. A. CARTER 1999 – Generic Environmental Management Programme for Marine Diamond Mining off the West Coast of South Africa. Marine Diamond Mines Association, Cape Town, South Africa. 6 Volumes.

LENHOFF 1982 – Incipient Motion of Particles under Oscillatory Flow. Proc. of the 18th Coastal Engineering Conference, Vol 2, pp 1555-1568

LOOSANOFF, V. L. 1961 – Effects of turbidity on some larval and adult bivalves. Proc. Carib. Fish. Inst. 14: 80-95.

LOUTIT, R. 1991 – Western ephemeral rivers and their importance to wetlands in Namibia. *Madoqua* 17(2): 135-140.

MCLACHLAN and DE RUYCK 1993 – Survey of Sandy Beaches in Diamond Area 1: A report to CDM, Oranjemund, Namibia.

MCLACHLAN, A., NEL, R., BENTLEY, A., SIMS, R. and D. SCHOEMAN 1994 – Effects of Diamond Mine Fine Tailings on Sandy Beaches in the Elizabeth Bay Area, Namibia. Report for CDM.

MENDELSOHN, J., JARVIS, A., ROB, R.M. (eds.) 1989 – Oceans of life off South Africa. Vlaeberg Publishers CC, South Africa.

MOORE, P. G. 1978 – Inorganic particulate suspensions in the sea and their effects on marine animals. *Oceanogr. Mar. Biol. Ann. Rev*. 1: 225-364.

NELSON, G. and HUTCHINGS, L. 1983 – The Benguela upwelling area. *Progress in Oceanography*, 12, 333-356.

NEWCOMBE, C. P. and D. D. MACDONALD 1991 – Effects of suspended sediments on aquatic ecosystems. *North American J. Fish. Man.* 11: 72-82.

NEWCOMBE, C. P. and J. O. T. JENSEN 1996 – Channel suspended sediment and fisheries: A synthesis for quantitative assessment of risk and impact. *North American J. Fish. Man*. 16: 693-727.

NEWELL, R. C., SEIDERER, L. J. and HITCHCOCK, F. D. R. 1998 – The impact of dredging works in coastal waters: Review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea-bed. *Oceanogr. Mar. Biol. Ann. Rev.,* **36**, pp 127-178.

NICKLING W. G. and M. ECCLESTONE 1981 – The effects of soluble salts on the threshold shear velocity of fine sand. *Sedimentology*, 1981, Vol 28, 505 – 510.

O'CONNOR, J. M., D. A. NEUMANN and J. A. SHERK 1976 – Lethal effects of suspended sediment on estuarine fish. Technical Paper No. 76-20. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

PALLET, J. (ed.) 1995 – The Sperrgebiet: Namibia's least known wilderness. DRFN & NAMDEB, Windhoek, Namibia.

PAYNE, A. I. L. and CRAWFORD, R. J. M. (eds.) 1989 – Oceans of life off South Africa. Vlaeberg Publishers CC, South Africa.

PEDDICORD, R. K., V. A. MCFARLAND, D. P. BELFIORS and T. E. BYRD 1975 – Dredge disposal study, San Francisco Bay Estuary. Appendix G. Physical impact, effects of suspended solids San Francisco Bay organisms. U.S. Army Engineer District, San Francisco, California.

PENNEY, A. J. and G. G. SMITH 2004 – Inception Workshop Report for projects BCLME/CEA/03/02 and BCLME/CEA/03/03. Prepared for the Benguela Current Large Marine Ecosystem Program . 20 August 2004.

PERRY, J. 1988 – Basic Physical Geography/Hydro Data for "Estuaries" of the Western Cape (CW1-32). NRIO Data Report D8802.

PILLAY, T. V. R. 1992 – *Aquaculture and the Environment.* Fishing News Books, Oxford, England. 189 pp.

PISCES 2004 – The Potential Impacts of Marine Dredging Operations on Nearshore Reef Communities and the Rock Lobster Fishery. Specialist Study 1. Pisces Environmental Services (Pty) Ltd. Tokai, Cape Town, South Africa.

PISCES 2004a – Baseline survey of intertidal and subtidal rocky shore communities at Elizabeth Bay: Intertidal and subtidal monitoring report 2004. Prepared for Namdeb Diamond Corporation.

PISCES 2004b – Baseline survey of sandy beach macrofaunal communities at Elizabeth Bay: Beach Monitoring Report 2004. Prepared for Namdeb Diamond Corporation.

PISCES 2005 – An assessment of the effects of dredging-related suspended sediments on intertidal and subtidal communities in the Chameis Bay area. Prepared for De Beers Marine Namibia.

PULFRICH, A. 2002 – The Potential Effects of Increased Sediment Disposal from the Elizabeth Bay Mine on Intertidal and Subtidal Communities. Specialist Study prepared for CSIR Environmentek, Stellenbosch, South Africa.

READERS DIGEST 1984 – Atlas of Southern Africa.

REPUBLIC OF SOUTH AFRICA DEPARTMENT OF WATER AFFAIRS AND FORESTRY (RSA DWAF) 1995 – South African water quality guidelines for coastal marine waters. Voume 1. Natural Environment. Volume 2. Recreation. Volume 3. Industrial Use. Volume 4. Mariculture. Pretoria

ROBINSON, W. E., W. E. WEHLING and M. P. MORSE 1984 – The effects of suspended clay on feeding and digestive efficiency of the surf clam *Spisula Solidissima* (Dillwyn). *J. Exp. Mar. Biol. Ecol.* 74:1-12.

RODRÝGUEZ, S. R., OJEDA, F. P. and N. C. INESTROSA 1993 – Settlement of benthic marine invertebrates. *Mar Ecol. Prog. Ser.,* 97: 193-207.

ROGERS, J. 1977 – Sedimentation on the continental margin off the Orange River and the Namib Desert. *PhD Thesis*, University of Cape Town.

ROOSEBOOM, A. 1975 – Sedimentproduksiekaart vir Suid-Afrika, Technical Report No.61, Dept. of Water Affairs.

ROOSEBOOM, A. 1978 – Sediment-afvoer in Suider-Afrikaanse Riviere. *Water SA* 4 (1): 14-17

ROOSEBOOM, A. and N. F. MAAS 1974 – Sedimentafvoergegewens vir die Oranje-, Tugela- and Pongola-riviere. *Tech. Report. Dept Water Affairs. South Africa.* Vol. 59.

ROOSEBOOM, A. and H. J. VAN HARMSE 1979 – Changes in the sediment load of the Orange River during the period 1929-1969. *Sci. Publ. Int. Assoc. Hydrol.* Vol. 128, pp 459-470.

ROSENTHAL, G. and S. GRANT 1989 – Simplified tidal prediction for the South African coastline. *S A Journal of Science,* Vol. 85, pp 104-107.

SAREC 2000 – Coral Reef Degradation in the Indian Ocean. Status Report 2000. CORDIO, SAREC Marine Science Program, Dept of Zoology, Stockholm University, Sweden.

SCHOONEES, J. S. 2000 – Annual variation in the net longshore sediment transport rate. *Coastal Engineering* 40. pp 141-160.

SHANNON, L. V. and F. P. ANDERSON 1982 – Applications of satellite ocean colour imagery in the study of the Benguela Current System. S*. Afr. J. of Photogrammetry, Remote Sensing and Cartography.* 13 (3): 153-169.

SHERMAN, D. J., JACKSON, D. W. T., NAMIKAS, S. L. and J. WANG 1998 – Wind-blown sand on beaches: an evaluation of models. Geomorphology 22 (1998) 113-133. Elsevier.

SHILLINGTON, F. A., BRUNDRIT, G. B. and J. R. E. LUTJEHARMS 1990 – The coastal current circulation during the Orange River flood 1988. *Trans. Roy. Soc. S. Afr.* 47 (3): 307-330.

SMITH, G. G. and C. SOLTAU 2003 – Shoreline modelling insights from projects in Southern Africa. *Proceedings of Coastal Sediments* '03.

SOUTH AFRICAN WEATHER BUREAU 1988 – Monthly Weather Reports January to June. Dept. of Environment Affairs, South Africa.

STEFFANI, C. N. and A. PULFRICH 2004 – Potential Impacts of Marine Dredging Operations on Benthic Communities in Unconsolidated Sediments. Specialist Study 2. For the EIA for the pre-feasibility phase of the Marine Dredging Project in Namdeb's Atlantic 1 Mining Licence area and in the nearshore areas off Chameis.

STENGEL, H. W. 1964 – Die Riviere der Namib und ihr zulauf zum Atlantik. Teil I: Kuiseb und Swakop. Desert Research Station 22: 4-32.

SWART, D.H. 1986 – Prediction of wind-driven transport rates. Proc. Of the 20th International Conference in Coastal Engineering (ICCE), Taipei, Taiwan, Vol. 2, pp 1595-1611.

SWART, D. H., CROWLEY, J. B., MÖLLER, J. P. and A. DE WET 1990 – Nature and behavior of the flood at the river mouth. *Trans. Roy. Soc. S. Afr*. 47 (3): 217-245.

TALJAARD 2006 – The Development of a Common Set of Water and Sediment Quality Guidelines for the Coastal Zone of the BCLME. Project BEHP/LBMP/03/04. Prepared for the Benguela Current Large Marine Ecosystem Programme.

TALJAARD, S, VAN NIEKERK, L HUIZINGA, P, BASSON, G and J. BECK 2005 – Olifants/Doring Ecological Water Requirements Study. RDM Report on Estuarine Component. Appendix C: Abiotic components. *In press.*

TINLEY, K.L. 1985 – Coastal Dunes of South Africa. South African National Scientific Programmes. Report No. 109.

URBAN, E. R. and D. L. KIRCHMAN 1992 – Effect of kaolinite clay on the feeding activity of the eastern oyster *Crassostrea virginica* (Gmelin). *J. Exp. Mar. Biol. Ecol.* 160: 47-60.

VAN BALLEGOOYEN, R. C. 1995 – Forced synoptic coastal-trapped waves along the southern African coastline. *M.Sc. thesis*, Department of Oceanography, University of Cape Town.

VAN HEERDEN I. L. 1986 – Fluvial sedimentation in the ebb-dominated Orange Estuary. *S.A. Journal of Science,* Vol. 83 pp141-147.

VAN RIJN, L. C. 1993 – Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. Aqua Publications., Amsterdam, The Netherlands.

VAN TAMELEN, 1996 – Algal zonation in tidepools: experimental evaluation of the roles of physical disturbance, herbivory and competition. J*ournal. Exp. Mar. Biol* and *Ecol*, Vol. 201, pp 197-231.

WHITAKER, A. 1984 – *Dust Transport by Berg Winds off the Coast of South West Africa: Directions, Sources and Flux to Marine Sediments.* Unpublished Honours Project, Department of Geological Sciences, University of Cape Town, 42 pp.

WHITE, J. R. and M. J. DAGG 1989 – Effects of suspended sediments on egg production of the calanoid copepod *Acartia tonsa. Mar. Biol.* 192: 315-319.

WILDISH, D. J., A. J. WILSON and H. AKAGI 1977 – Avoidance of herring of suspended sediments from dredge spoil dumping. Int. Council Explor. Sea C.M. 1977/E: 11. pp 6.

WL|DELFT 1999c – Unibest V5 for Windows. User Manual. WL|Delft Hydraulics, The Netherlands.

WL|DELFT HYDRAULICS 1999a – DELFT3D-FLOW User Manual Version 3.05. WL|Delft Hydraulics, Delft, The Netherlands.

WL|DELFT HYDRAULICS 1999b – DELFT3D-WAQ User Manual Version 3.01. WL|Delft Hydraulics, Delft, The Netherlands

WL|DELFT HYDRAULICS 2000 – DELFT3D-WAVE User Manual Version 1.02. WL|Delft Hydraulics, Delft, The Netherlands.

WONG, W. H. and S. G. CHEUNG 1999 – Feeding behaviour of the green mussel, *perna viridis* (L.): Responses to variation in seston quantity and quality. *J. Exp. Mar. Biol. Ecol.,* 236: 191-207.

ZOUTENDYK 1994 – Alexkor Environmental Management Programme Report. Specialist study to address the issues and impacts relating to mining operations affecting intertidal rock and sand shores and the neritic environments. *Volume 2. Specialist Study Report*. CSIR Report EMAS-C 94037(2).

Appendix A:
Delft-3D Hydrodynamic model equations.

The equations and their numerical implementation are described in detail in the DELFT3D-FLOW user manual (WL|Delft Hydraulics, 1999a); simplified versions are as follows:

Conservation of momentum in x-direction:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \eta}{\partial x} - f.v + \frac{g.u\,|U|}{C^2(d+\eta)} - \frac{F_x}{\rho(d+\eta)} - \upsilon\left(\frac{\partial^2 u}{\partial^2 x} + \frac{\partial^2 u}{\partial^2 y}\right) = 0$$

Conservation of momentum in y-direction:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \eta}{\partial y} + f.u + \frac{g.v\,|U|}{C^2(d+\eta)} - \frac{F_y}{\rho(d+\eta)} - \upsilon\left(\frac{\partial^2 v}{\partial^2 x} + \frac{\partial^2 v}{\partial^2 y}\right) = 0$$

Conservation of mass, continuity equation:

$$\frac{\partial \eta}{\partial t} + \frac{\partial[(d+\eta)u]}{\partial x} + \frac{\partial[(d+\eta)v]}{\partial y} = 0$$

Advection-diffusion equation:

$$\frac{\partial C}{\partial t} - \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x} - u.C\right) - \frac{\partial}{\partial x}\left(D_y\frac{\partial C}{\partial y} - v.C\right) - \frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z} - w.C\right) = 0$$

where

η	=	water-level elevation
d	=	water depth
u,v,w	=	velocity in the x-, y-, and z-directions, respectively
U	=	magnitude of total current velocity
Fx,y	=	x- and y- components of external forces

f = Coriolis parameter 2Ω sin θ, where Ω is the earths angular velocity and θ is the geographic latitude

g = acceleration due to gravity

ρ = water density

υ = eddy viscosity

c = Chézy coefficient

C = concentration

Dx,y,z = dispersion coefficients in x-, y-, and z- directions

In this study the Chézy coefficient is obtained from the White Colebrook formulation:

$$C = 18 \log_{10}\left(\frac{12d}{k_s}\right)$$

where k_s is the Nikuradse roughness length (m).

The magnitude of the wind shear stress is determined by the following widely used quadratic expression:

$$\tau = \rho_a . C_d (U_{10}) . U_{10}^2$$

where:

ρ_a = air density (kg/m^3)

U_{10} = wind speed (m/s)

C_d = wind drag coefficient, which is a linear function of wind speed (-)

Appendix B: Equations of the DELFT-3D WAQ model for predicting fine sediment behaviour.

The model solves the advection-diffusion equation, and includes source and sink terms representing deposition and resuspension. The model equations are as follows:

$$\frac{\partial c}{\partial t} - \frac{\partial}{\partial x}\left(D_x \frac{\partial c}{\partial x} - u\,.c \right) - \frac{\partial}{\partial y}\left(D_y \frac{\partial c}{\partial y} - v\,.c \right) - \frac{\partial}{\partial z}\left(D_z \frac{\partial c}{\partial z} - w.c - V_{sed}\,.c \right) = \text{Res} - \text{Depo}$$

where:

c	=	concentration of the suspended sediment (kg/m^3)
u,v,w	=	current velocity in the x-, y- and z-directions, respectively (m/s)
$D_{x,y,z}$	=	dispersion coefficients in the x-, y- and z-directions, respectively (m^2/s)
Res	=	resuspension flux of sediment particles (kg/m^3.s)
Depo	=	deposition flux of sediment particles (kg/m^3.s)
V_{sed}	=	settling velocity of sediment particles (m/s)

When the particles approach the sea-bed, the probability of deposition is determined by the prevailing sea-bed shear stress (τ_{seabed}) relative to the defined critical shear stress for deposition of the particles (τ_{depo}). Deposition will occur only if $\tau_{seabed} < \tau_{depo}$. The prevailing bottom shear stress conditions are obtained from the DELFT3D-FLOW hydrodynamic model and depend on the time- and space-varying current velocity, wave conditions and water depth. The deposition flux is given by the following equation:

$$\text{Depo} = \frac{(V_{sed} \cdot c)}{d} \cdot \left(1 - \frac{\tau_{seabed}}{\tau_{depo}} \right) \quad \textit{for} \quad \tau_{seabed} < \tau_{depo}$$

where d is the water depth and c is the concentration of suspended particles. The suspended material is modelled as three discrete fractions by mass, each fraction having a discrete settling velocity and critical shear stress for deposition.

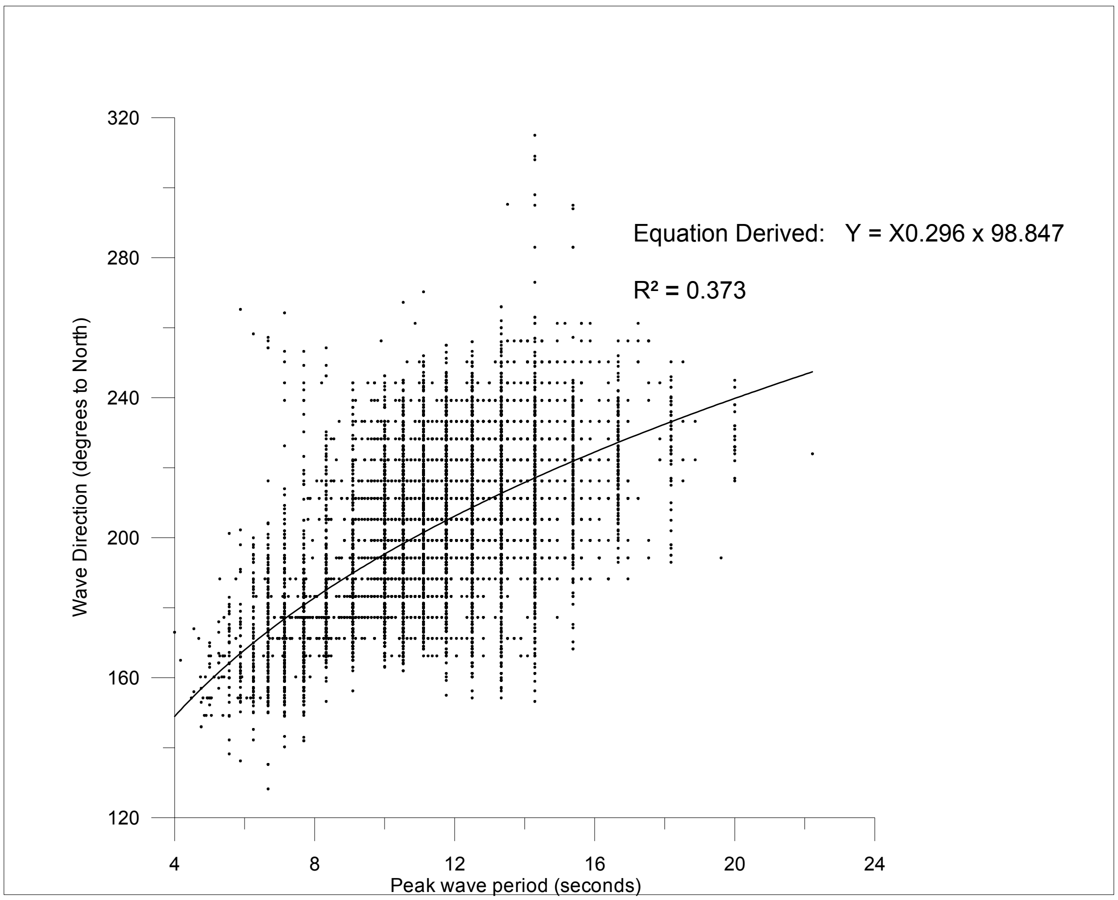
Resuspension is modelled in a similar manner. The resuspension flux is specified by the critical shear stress for resuspension (τ_{res}) and a zero order resuspension flux (Z_{res}), applicable to all three mass fractions. Resuspension will occur only if $\tau_{seabed} > \tau_{res}$. The resuspension flux is given by the following equation:

$$\text{Res} = Z_{res} \cdot \left(\frac{\tau_{seabed}}{\tau_{res}} - 1 \right) \quad for \quad \tau_{seabed} > \tau_{res}$$

The DELFT3D-WAQ model obtains the hydrodynamic database (currents, vertical diffusivity and combined wave-current seabed shear stress) through an offline coupling to DELFT3D-FLOW and employs the same curvilinear grid. An implicit upwind scheme with an iterative solver was selected to solve the advection-diffusion equation (WAQ Scheme 15).

Appendix C: Wave conditions for Orange River flood simulation

Employing Kudu wave data measured offshore of Oranjemund, a relationship between measured peak wave period and wave direction was derived. Figure A.1 depicts this relationship.



Based on this relationship, direction was derived for the omnidirectional time-series. Minor modifications were made to ensure that the distribution of directions is the same as for the Kudu data.

The resulting data consist of 3 to 6 hourly measurements, totalling almost 6000 measurements. Even after extracting, the period required (01/01/1988 to 30/06/1988) to include all conditions as measured would require a number of days to computationally simulate. Therefore, the data were decimated. This process involved the reduction of the number of wave conditions to be simulated without excluding relevant information of the offshore directional wave time series.

Using Fast Fourier Transform (FFT) filtering techniques in MATLAB, the significant points of inflection were identified in the graphical representation of each time series of wave height, wave period and wave direction. The aim was to retain sufficient information of each parameter so that the time series could be reproduced using the decimated data set. The order of priority was first significant wave height, then peak wave period and finally wave direction. The decimated conditions of the individual parameters were combined to form a continuous time series. Each time identified was retained as period of time during which the condition would be specified. The decimated set, relevant to the simulation period (27/02/1988 to 30/04/1988), consisted of 71 wave conditions (Table C.1), including significant wave height, peak wave period and wave direction.

Table C.1: The 71 wave conditions simulated in the refraction analysis of the Orange River mouth model.

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [from N]
1	1.29	10.67	199.1
2	1.57	5.51	163.8
3	1.31	6.17	169.3
4	1.36	5.82	166.4
5	1.32	10.67	199.1
6	1.96	10.67	199.1
7	2.66	10.67	199.1
8	3.52	9.66	188.3
9	2.43	9.66	188.3
10	1.53	10.67	199.1
11	1.60	10.67	199.1
12	0.91	10.67	199.1
13	1.69	7.53	179.6
14	2.36	10.67	199.1
15	1.89	10.67	199.1

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [from N]
37	1.49	11.91	205.7
38	1.51	11.91	205.7
39	1.21	10.67	199.1
40	1.41	8.83	188.3
41	1.38	9.66	188.3
42	1.73	10.67	199.1
43	2.91	13.47	221.3
44	2.59	10.67	199.1
45	2.67	11.91	214.2
46	2.09	10.67	199.1
47	2.19	13.47	221.3
48	2.42	8.13	183.7
49	2.57	9.66	188.3
50	1.20	15.52	237.4
51	1.04	13.47	221.3

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [from N]
16	1.40	9.66	188.3
17	1.18	9.66	188.3
18	1.44	9.66	188.3
19	1.83	13.47	221.3
20	0.81	11.91	205.7
21	0.79	13.47	221.3
22	0.91	11.91	205.7
23	0.95	10.67	199.1
24	1.07	10.67	199.1
25	1.54	10.67	199.1
26	1.51	10.67	199.1
27	1.21	10.67	199.1
28	2.34	13.47	221.3
29	3.03	13.47	221.3
30	1.67	11.91	205.7
31	3.13	11.91	214.2
32	3.44	13.47	221.3
33	2.93	13.47	221.3
34	2.26	13.47	221.3
35	1.86	11.91	214.2
36	1.61	11.91	205.7

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [from N]
52	1.19	10.67	199.1
53	2.38	11.91	214.2
54	1.42	11.91	205.7
55	1.27	13.47	221.3
56	1.84	11.91	214.2
57	2.06	10.67	199.1
58	3.81	10.67	199.1
59	1.78	10.67	199.1
60	1.56	10.67	199.1
61	1.40	9.66	188.3
62	1.24	8.83	188.3
63	3.35	13.47	221.3
64	3.51	11.91	214.2
65	2.98	11.91	214.2
66	2.59	10.67	199.1
67	2.11	6.56	172.4
68	2.46	11.91	214.2
69	1.56	13.47	221.3
70	1.55	13.47	221.3
71	1.29	13.47	221.3

Appendix D: River discharge and model set up details: Orange River region

River Discharge data employed in the Orange River Model

Table D.1: The Orange River discharge and corresponding suspended sediment concentration.

Date	Time	Discharge rate [m^3/s]	Suspended sediment concentration [kg/m^3]	Date	Time	Discharge rate [m^3/s]	Suspended sediment concentration [kg/m^3]
29021988	103000	1457	0.99	20031988	073500	6166	3.43
29021988	162000	1644	0.89	20031988	182500	6234	2.91
29021988	170500	2378	1.29	20031988	183000	6248	2.94
29021988	190000	4821	2.27	21031988	074500	6326	3.19
01031988	083500	6720	3.50	21031988	153000	6395	3.27
01031988	142500	6878	3.80	22031988	074500	6424	3.85
01031988	201800	7354	3.76	22031988	152500	6414	2.83
02031988	090000	7811	5.49	23031988	074500	6375	3.44
02031988	141500	8062	5.69	23031988	153000	6375	3.77
02031988	194500	8072	6.20	24031988	074500	6444	2.68
03031988	083000	7882	6.14	24031988	151500	6513	2.96
03031988	230000	7651	5.27	25031988	074500	6542	3.55
04031988	073500	7452	4.82	25031988	151000	6405	3.19
04031988	141500	7631	4.61	26031988	072000	6179	3.41
04031988	160500	7671	5.35	26031988	165000	5895	2.77
04031988	174000	7671	7.36	27031988	082500	5650	2.63
04031988	201400	7413	6.97	27031988	173000	5446	2.80
05031988	082000	7036	5.33	28031988	074500	5233	1.89
05031988	181000	6838	3.74	28031988	151500	5041	2.10
06031988	081000	6700	3.03	29031988	074800	4813	2.48
06031988	181500	6602	2.81	29031988	153000	4476	1.47
07031988	080000	6582	3.03	30031988	072500	4179	0.84
07031988	160000	6562	2.36	30031988	152500	3946	1.26
08031988	080000	6149	2.98	31031988	040000	3698	2.10
08031988	154500	6002	3.16	31031988	151000	3509	1.42
09031988	082000	5816	2.89	01041988	081500	3241	1.07
09031988	155000	5674	2.61	02041988	074500	3046	1.55
09031988	155500	5335	2.86	03041988	081500	2920	1.97
10031988	085500	5052	2.89	04041988	080000	2826	1.38
10031988	085900	5015	3.51	05041988	084500	2722	1.16

Date	Time	Discharge rate [m³/s]	Suspended sediment concentration [kg/m³]
10031988	153000	4967	3.28
10031988	153500	4853	3.25
11031988	074000	4713	2.59
11031988	074500	4656	1.86
11031988	152500	4626	2.96
11031988	153000	4505	1.96
12031988	090000	4354	1.69
13031988	083000	4447	1.57
14031988	074500	4671	1.49
14031988	153000	4756	1.47
15031988	074500	4775	2.07
15031988	152500	4793	1.67
16031988	074500	4812	2.02
16031988	153000	4831	1.96
17031988	074500	4994	1.85
17031988	153000	5291	2.20
18031988	075000	5543	3.30
18031988	153000	5777	2.47
19031988	073500	5927	3.79
19031988	074000	5986	3.02
19031988	153500	6019	3.70
19031988	154000	6048	3.69
20031988	073000	6088	3.36

Date	Time	Discharge rate [m³/s]	Suspended sediment concentration [kg/m³]
06041988	075000	2663	1.40
07041988	075500	2554	1.18
12041988	161000	2210	0.67
13041988	151500	1812	0.80
15041988	151500	1837	0.54
18041988	150000	1467	0.53
20041988	151000	1705	1.50
22041988	144500	1973	1.87
25041988	152000	1812	2.09
27041988	153000	2765	1.99
29041988	142000	2194	2.74
04051988	151500	1693	1.80
05051988	151000	1812	2.00
09051988	150000	1467	1.52
11051988	154500	1255	2.40
13051988	145800	1255	1.31
16051988	151200	1109	1.25
18051988	152500	697	0.94
20051988	151500	963	1.49
23051988	151500	853	1.35
26051988	160000	835	1.76
27051988	141500	809	1.39
30051988	144000	950	0.91

Delft 3D WAVE

Within WAVE module, the refraction model SWAN (Simulating Waves Near-shore) was used to simulate the transformation of offshore, deepwater waves travelling towards the coast. The processes simulated were: wave refraction, shoaling, reflection and breaking. Local wind-wave generation was not modelled as it had been previously found (CSIR, 2002b) to have only a minor influence on near-shore conditions.

The SWAN model *can* account for refractive propagation due to current and depth and represents the processes of wave generation by wind, dissipation by whitecapping, bottom friction and depth-limited wave breaking and non-linear wave-wave interactions (quadruplets and triads) explicitly with state-of-the-art formulations. Wave blocking by currents is also explicitly represented in the model. Diffraction (i.e. the lateral transfer of energy along the wave crest) is not explicitly modelled in SWAN, but diffraction effects can be simulated by applying directional spreading of the waves. Specular wave reflection can also be modelled.

Coefficients applied in the model have been used in a number of studies on the Southern African west coast and due to this previous experience, were deemed to be applicable.

Grid setup

A curvilinear grid was used to create the computational and bathymetric grids. These grids were designed to follow the shoreline wherever possible and provide refinement in the surf zone and in the areas of interest and detail (e.g. the area adjacent to the river mouth). The cell sizes increased from the immediate surf zone (190 m in the longshore direction and 30 m in the cross-shore direction) to the offshore area (1370 m in the longshore direction and 6360 m in the cross-shore direction). The reason for the increase is due to the response of waves to bathymetry. In the offshore area, at water depths of greater than 100 m, waves are unaffected by the sea-bed and low computational detail is required. Closer near-shore, in water depths shallower than 75 m, the seabed shows slight irregularities and depth begins to affect the progression and dimensions of waves. Because of this, computational detail had to be increased resulting in finer detail of the grid in the near-shore region. This created large aspect ratios (ratios between cell sizes in respective directions) which should be minimised but, due to the size of the model and the associated computational time, were acceptable. The grid used in the SWAN model is shown in Figure D.1.

The same grid was used for the wave, hydrodynamic and suspended sediment transport modelling, although the northern and southern boundaries were extended further along the coast in the wave model in order to prevent boundary effects being transferred into the hydrodynamic model.

The output files, a time series of wave conditions traversing the grid, were an essential component of the hydrodynamic simulation setup in the Delft 3D FLOW module.

Delft 3D FLOW

The hydrodynamic simulation, in the Delft 3D FLOW module, simulates currents and turbulence. A three-dimensional model was used that accounted for the following processes:

- wind forcing;
- wave forcing;
- barotropic currents;

- baroclinic currents and vertical mixing induced by differences in salinity (density) resulting from advection of fresh water/saline water;
- the effect of the earth's rotation (Coriolis force).

The system of equations in Delft3D-FLOW are comprised of the horizontal momentum equations, the continuity equation, the equation of state, and the advection-diffusion equations for heat, salt and other conservative tracers that are solved using the Alternating Direct Implicit scheme. Vertical turbulence is modelled using the k-ε turbulence closure model. The relevant equations and their numerical implementation are described in WL|Delft Hydraulics (1999a).

Grid setup

As mentioned above in the WAVE setup, the same grids as those used in the wave analysis were used in the hydrodynamic simulation. Only the hydrodynamic grid was shorter in the alongshore direction, and a sigma coordinate was included in the vertical (see Figure D.2).

The result of the hydrodynamic simulation provided the hydrodynamic basis for the simulation of the transport of suspended sediment.

Suspended sediment transport model

The dredging process is likely to create a plume of fine sediment particles both at the dredge location and at the discharge site. These particles will subsequently be transported and dispersed by the currents. The particles will tend to settle towards the seabed and will be deposited onto the seabed in those areas where the combined wave and current-induced bed shear stresses are sufficiently low. Should the bed shear stresses subsequently increase, for example due to high waves or strong currents, the particles may be re-suspended into the water column.

The Delft3D-WAQ water quality model (WL|Delft Hydraulics, 1999b) was used to simulate the advection-dispersion-settling-sedimentation-resuspension behaviour of the dredging-induced sediment plumes. The model solves the advection-dispersion equation with source and sink terms representing sedimentation and resuspension:

$$\frac{\partial c}{\partial t} - \frac{\partial}{\partial x}\left(D_x \frac{\partial c}{\partial x} - u\,.\,c\right) - \frac{\partial}{\partial y}\left(D_y \frac{\partial c}{\partial y} - v\,.\,c\right) - \frac{\partial}{\partial z}\left(D_z \frac{\partial c}{\partial z} - w.c - V_{sed}\,.c\right) = f_{res} - f_{sed}$$

where:

c	=	concentration
u,v,w	=	current velocity in the x-, y- and z-directions, respectively
$D_{x,y,z}$	=	dispersion coefficients in the x-, y- and z-directions, respectively
f_{res}	=	resuspension flux of particles
f_{sed}	=	sedimentation flux of particles
V_{sed}	=	settling velocity of particles

The Delft3D-WAQ model obtains the hydrodynamic database through an offline coupling to Delft3D-FLOW and employs the same curvilinear grid. The equation was solved using WAQ Scheme 14 (Flux Corrected Transport in the horizontal direction and in the vertical an implicit scheme in time and upwind in space). A timestep of 1 minute and a horizontal dispersion $D_{x,y}$ of 1 m^2/s was used. The vertical dispersion D_z was obtained from the hydrodynamic model, with minimum values set to 1E-3 at depths less than 5 m and 1E-4 for greater depths in order to approximate the wave-induced mixing processes.

As the sediment particles approach the seabed, the probability of sedimentation (or deposition) is determined by the prevailing seabed shear stress (τ_{seabed}) relative to the defined critical shear stress for sedimentation of the particles (τ_{sed}). Sedimentation will occur only if $\tau_{seabed} < \tau_{sed}$. The prevailing bottom shear stress condition is the sum of the wave and the current-induced components and varies in both space and time. The current-induced stress is based on the White-Colebrook parameterisation with a Nikuradse roughness length of 0.001 m. For the wave-induced stresses the Soulsby approach is followed (WL|Delft Hydraulics, 1999b). The sedimentation flux is given by the following equation:

$$f_{sed} = \frac{(V_{sed} \cdot c)}{d} \cdot \left(1 - \frac{\tau_{seabed}}{\tau_{sed}}\right) \quad for \;\; \tau_{seabed} < \tau_{sed}$$

where d is the water depth and c is the concentration of suspended particles. Resuspension is modelled in a similar manner. The resuspension flux is specified by the critical shear stress for resuspension (τ_{res}) and a zero order resuspension flux (Z_{res}). Resuspension will occur only if $\tau_{seabed} > \tau_{res}$. The resuspension flux is given by the following equation:

$$f_{res} = Z_{res} \cdot \left(\frac{\tau_{seabed}}{\tau_{res}} - 1\right) \quad for \;\; \tau_{seabed} > \tau_{res}$$

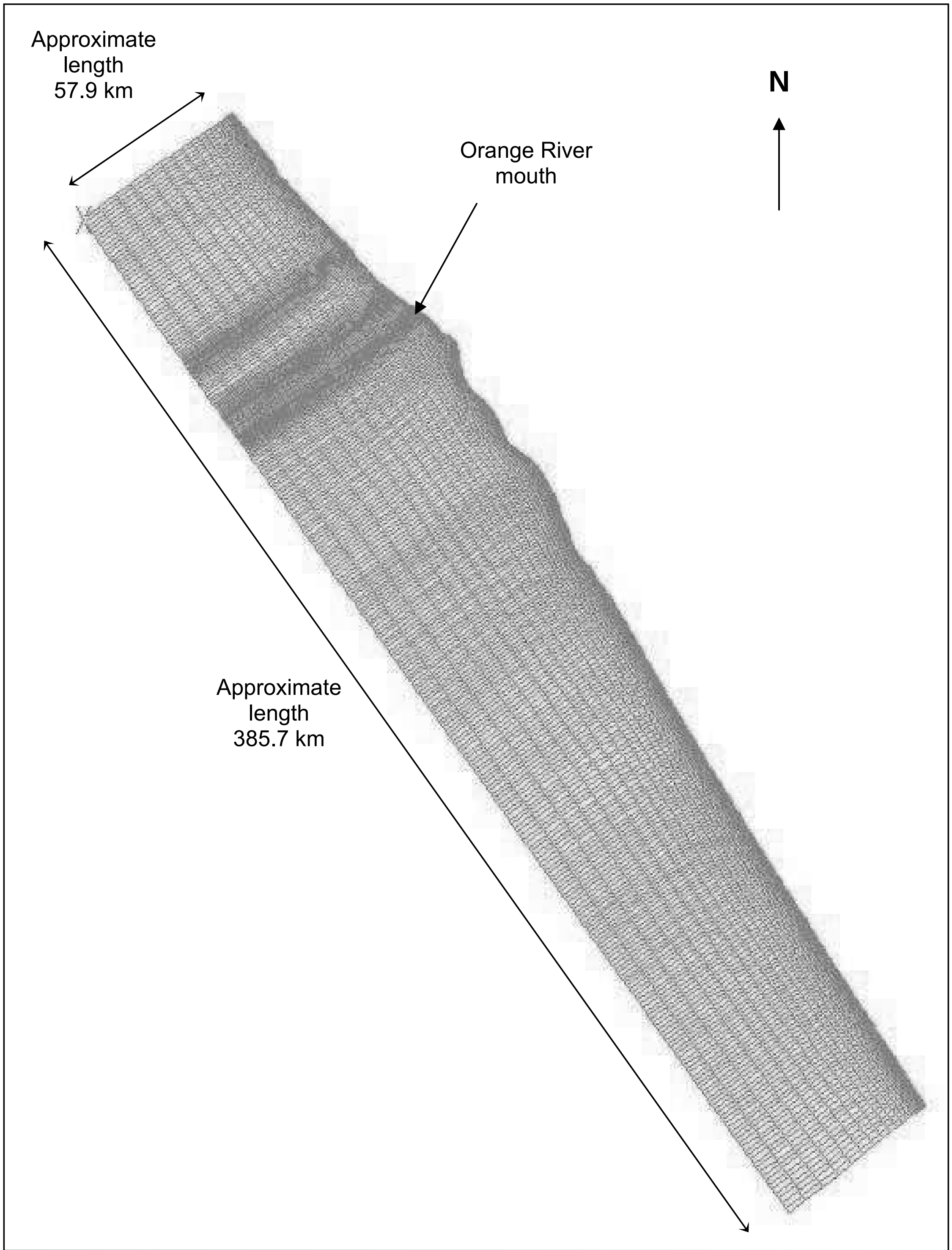
The suspended sediment particles are modelled as three size fractions, each having characteristic sediment properties. In the absence of site-specific measurements of the sedimentation properties of the fine sediment at the dredge site, the following parameters based on literature values (van Rijn, 1993) and other South African dredging projects (CSIR, 2000; CSIR, 2002a) have been applied.

Table D-1: Sediment parameters

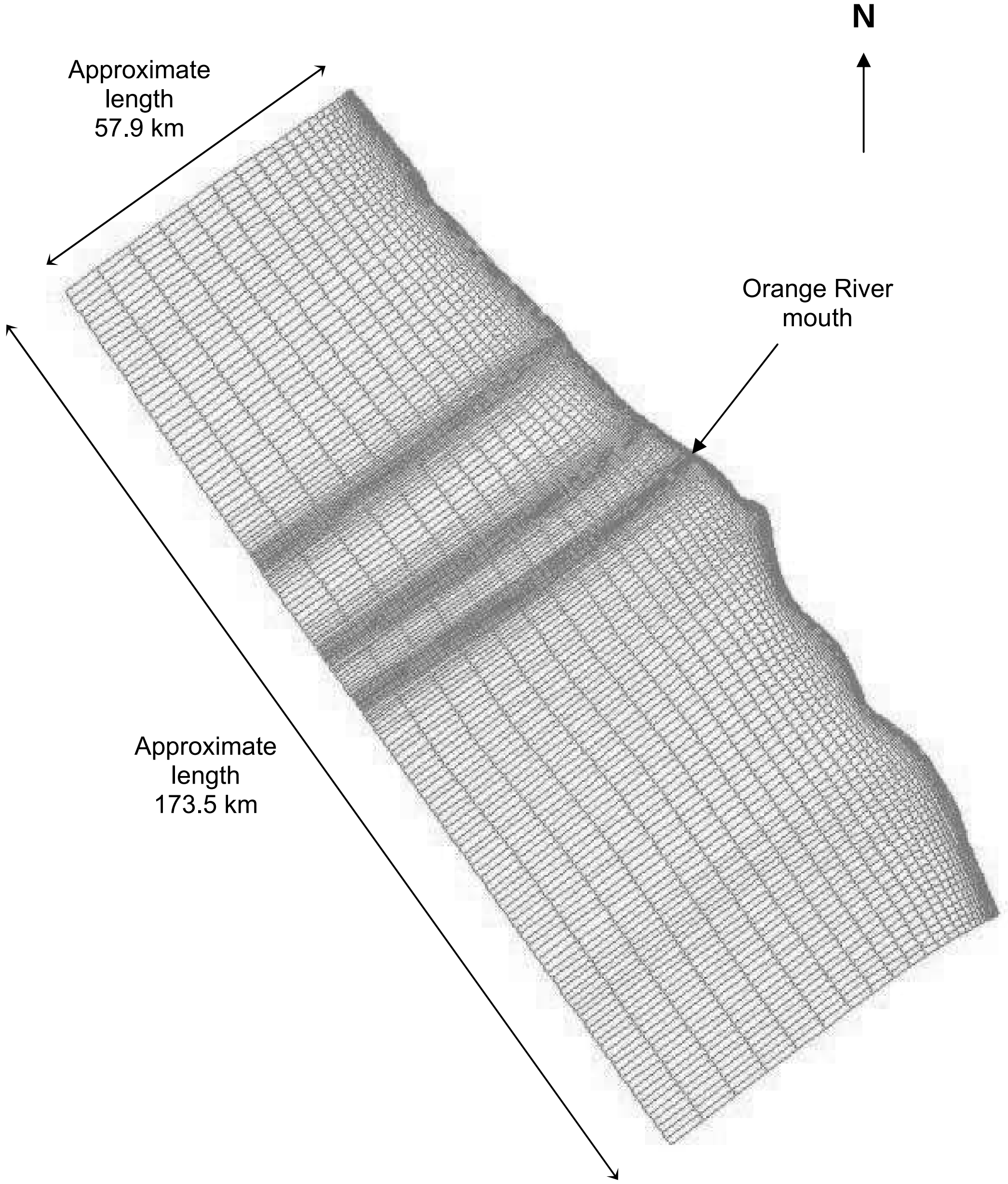
Parameter	10% Fines scenario
Settling velocity of 1st fraction	0.1 mm/s
Settling velocity of 2nd fraction	0.5 mm/s
Settling velocity of 3rd fraction	1.0 mm/s
Critical shear stress for deposition of 1st fraction	0.075 Pa
Critical shear stress for deposition of 2nd fraction	0.15 Pa
Critical shear stress for deposition of 3rd fraction	0.3 Pa
Critical shear stress for resuspension of all fractions	0.6 Pa
Zero order resuspension rate of all fractions	0.3 $g/m^2.s$

Note that the shear stresses in Table D.1 have been corrected by a factor 2 to take into account the fact that the bed roughness in DELFT3D-FLOW is based on form roughness (k_s = 0.001 m) and not skin roughness. In the model, the fine material was divided into three fractions, each with its own settling criteria. This allows partial settling and deposition to occur. The shear stresses provide an indication of the energy levels at which the material will either be deposited or re-suspended into the water column.

The sediment that is deposited on the bottom will begin to consolidate, which is the process whereby the deposited grains are compacted under the influence of gravity, leading to the expulsion of the pore water and the increase in density of the material and a reduction in the deposition thickness. In order to compute the deposition thickness in the model, a typical consolidation condition after one month has been assumed. This condition is characterised by a porosity of 90%, a wet density of 1 188 kg/m^3 and a dry density of 2 650 kg/m^3 (Van Rijn, 1993).



CSIR our future through science	**Grid structure of the grid used in the SWAN model.**	**Figure D.1**



CSIR our future through science	**Grid structure of the grid used in the FLOW and WAQ model.**	**Figure D.2**

Appendix E: Wave conditions employed in the shoreline study – Mining Area 1

The number of conditions in the offshore wave data time-series is too large for practical application in refraction and shoreline models, because of long computational times. Therefore, the data set must be rationalised to a relatively manageable set of wave conditions representative of conditions causing longshore sediment transport (and consequent medium to long-term evolution of the shoreline). In order to achieve this, the hindcast wave data were distributed into bins with increments of 1 m wave height, 1 or 2-second period and 22.5 degrees direction. The average wave height, period and direction were calculated for each data bin. The duration of occurrence of conditions in each bin was also calculated. This binning process resulted in a set of 178 discrete wave conditions (wave conditions travelling offshore were excluded from the analysis).

For each of these conditions, the longshore sediment transport was calculated, assuming linear refraction of wave conditions from offshore to near-shore. Selecting conditions causing a high percentage of transport per direction sector, and ensuring adequate representation of typical wave period and heights, a *morphological* wave climate of 31 conditions was resolved: see Table E.1 below. This number of conditions could be practically applied in the SWAN wave refraction model.

The morphological wave climate has a total duration of 320.08 days. This is because the morphological climate method generally results in selection of wave conditions with above-average height but shorter than average duration, as these conditions cause most of the longshore sediment transport.

Table E.1 Morphological wave conditions employed in this study

Condition number	Significant Wave height (m)	Peak Wave period (s)	Wave direction (degrees)	Duration (days)
1	3.27	7.31	160.09	1.99
2	2.53	7.01	160.6	10.56
3	3.24	12.97	164.07	1.07
4	3.42	8.62	165.69	0.66
5	2.47	9.14	165.87	1.12
6	2.46	7.29	177.98	18.15
7	3.33	9.12	178.9	12.28
8	2.45	9.22	179.67	27.28
9	2.48	10.56	183.21	9.53
10	2.45	11.44	184.84	14.33
11	4.4	12.95	202.59	6.96
12	2.48	11.47	203.21	39.89
13	3.39	11.55	203.86	12.92
14	3.39	12.88	204.25	20.08
15	3.47	14.61	204.51	9.85
16	2.52	12.78	204.59	28.97
17	4.34	16.62	218.55	0.58
18	5.38	14.8	219.16	0.87
19	3.35	12.95	221.19	12.09
20	2.4	11.47	221.5	18.09
21	2.48	12.9	222.39	26.5
22	3.41	14.78	223.87	6.36
23	1.61	12.86	224.22	16.81
24	2.44	14.72	225.27	12.97
25	3.44	15.04	239.89	0.52
26	2.29	14.7	242.63	2.13
27	2.36	11.57	243.81	1.1
28	2.34	13.01	244.41	3.42
29	1.57	14.75	245.34	2.61
30	1.11	15.25	261.25	0.15
31	2.32	13.33	262.8	0.12
32	2.11	7.14	264.25	0.02
33	2.39	14.29	266.33	0.08
				320.08

Appendix F:
Southern Mining Area I: Mine Discharges

Table F.1: Discharge Volumes 1997 – 2002 (as provided by Namdeb)

1997	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dredge	-	-	0	136 201	230 585	413 477	194 737	569 420	545 056	567 670	597 525	527 369	3 782 040
PTF	-	-	142 273	147 280	108 097	101 615	132 274	129 797	137 241	118 326	140 389	147 231	1 304 523
3 Plant	-	-	247 971	220 180	230 642	225 389	301 346	230 114	0	119 900	270 900	250 200	2 096 642
4 Plant	-	-	88 119	116 578	117 761	109 807	96 076	66 158	92 503	44 391	24 807	59 358	815 558
Total			478 363	620 239	687 085	850 288	724 433	995 489	774 800	850 287	1 033 621	984 158	7 998 763

1998	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dredge	407 831	289 036	464 080	352 999	333 448	469 411	579 595	639 329	614 884	446 260	683 401	461 309	5 741 583
PTF	99 821	119 428	140 526	131 785	137 038	135 577	144 558	144 720	177 037	134 448	146 522	75 773	1 587 233
3 Plant	210 000	253 016	263 563	225 482	206 686	179 200	174 328	137 032	195 111	164 095	154 378	134 572	2 297 463
4 Plant	70 039	139 678	109 936	73 735	96 954	111 115	81 509	73 857	73 597	78 920	84 321	25 695	1 019 356
Total	787 691	801 158	978 105	784 001	774 126	895 303	979 990	994 938	1 060 629	823 723	1 068 622	697 349	10 645 635

1999	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dredge	562 132	712 605	766 644	452 183	204 957	190 119	228 729	515 783	650 172	294 530	476 282	668 910	5 723 046
PTF	118 394	145 956	146 105	152 345	146 152	154 481	131 837	159 214	109 654	168 210	149 083	123 123	1 704 554
3 Plant	121 246	153 649	166 040	153 187	120 473	156 521	118 325	186 529	180 180	194 002	185 232	141 272	1 876 656
4 Plant	20 242	66 727	90 250	78 099	83 856	95 973	73 868	108 615	71 824	74 192	20 310	47 043	830 999
Total	822 014	1 078 937	1 169 039	835 814	555 438	597 094	552 759	970 141	1 011 830	730 934	830 907	980 348	10 135 255

2000	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dredge	555 541	533 025	455 637	465 200	272 195	498 475	654 399	808 014	184 696	476 093	695 530	640 536	6 239 341
PTF	100 113	153 889	163 747	132 004	140 074	139 906	108 894	155 826	146 026	167 368	138 752	113 654	1 660 253
3 Plant	104 726	107 135	156 409	114 091	144 541	134 063	156 687	161 604	183 727	224 889	208 796	124 885	1 821 553
4 Plant	45 660	74 462	76 159	55 313	71 375	108 482	94 466	132 876	16 366	37 494	37 232	16 640	766 525
Total	806 040	868 511	851 952	766 608	628 185	880 926	1 014 446	1 258 320	530 815	905 844	1 080 310	895 715	10 487 672

2001	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dredge	656 635	651 312	530 099	492 218	325 080	490 647	490 554	727 922	628 689	500 739	454 301	353 342	6 301 538
PTF	157 368	133 235	153 106	100 615	15 159	16 864	20 786	8 025	135 520	122 978	115 680	31 619	1 010 955
3 Plant	108 446	132 929	143 417	111 246	92 892	146 513	173 335	182 624	167 994	195 598	194 441	108 878	1 758 313
4 Plant	16 609	44 391	39 706	58 708	56 353	67 810	56 732	54 878	41 267	52 899	47 667	21 622	558 642
Total	939 058	961 867	866 328	762 787	489 484	721 834	741 407	973 449	973 470	872 214	812 089	515 461	9 629 448

2002	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dredge	596 170	597 670	448 655	466 627	419 180	499 559	508 257						3 536 118
PTF	126 119	84 787	122 823	103 984	80 619	120 702	128 602						767 636
3 Plant	241 124	239 093	242 022	222 092	208 416	234 779	262 529						1 650 055
4 Plant	68 800	53 619	54 502	49 242	71 212	63 388	76 083						436 846
Total	1 032 213	975 169	868 002	841 945	779 427	918 428	975 471						6 390 655

Table F.2: Dredge and Plant Discharge Positions Applied in the Model Calibration

(coordinates in Modified Clarke 1880 Spheroid, Gauss Conform, Lo 17)

Discharge line	Coordinates	
4-Plant	65759	3158991
3-Plant	70703	3153907
PTF	59400	3164100
Dredge-A	64123	3160528
Dredge-B	64665	3160126
Dredge-C	64885	3159988
Dredge-D	65109	3159809
Dredge-New A	64401	3160360
Dredge-Z	64040	3160709
Dredge-Z1	64734	3160171
Dredge-Z2	65145	3159801
Dredge-Z3	65215	3159735
Dredge-Z4	65519	3159583
Dredge-Z5	65421	3159714
Dredge-Z6	64401	3160360
Dredge-Z7	65589	3159505

Table F.3: Dates of Dredge Discharge Position Changes (as provided by Namdeb)

Date	Position Moved To
04-Apr-97	A
29-Nov-97	B
14-Jan-98	C
31-Jan-98	A
13-Feb-98	B
29-Apr-98	C
06-Oct-98	D
14-Jun-99	C
17-Aug-99	B
21-Sep-99	New A
14-Dec-99	Z
11-Jul-00	Z1
09-Oct-00	Z2
20-Feb-01	Z3
19-Jun-01	Z4
12-Nov-01	Z5
03-May-02	Z6
02-Aug-02	Z7

Appendix G: The 63 wave conditions simulated in the refraction analysis of the Elizabeth Bay model.

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [° from N]
1	2.25	5.7	159.7
2	3.27	7.3	160.1
3	2.53	7.0	160.6
4	3.24	13.0	164.1
5	3.42	8.6	165.7
6	2.47	9.1	165.9
7	6.03	10.5	166.3
8	4.39	14.8	167.3
9	3.25	7.6	175.3
10	6.54	11.6	176.9
11	2.46	7.3	178.0
12	3.33	9.1	178.9
13	2.45	9.2	179.7
14	1.63	9.2	181.2
15	2.47	12.7	183.0
16	2.48	10.6	183.2
17	3.44	12.8	183.3
18	3.38	10.5	183.6
19	3.37	11.4	183.9
20	6.72	12.9	184.0
21	4.37	14.3	184.2
22	2.45	11.4	184.8
23	4.37	13.0	185.9
24	2.42	9.5	200.4
25	2.44	10.6	202.2
26	4.40	12.9	202.6
27	2.48	11.5	203.2
28	3.39	11.6	203.9
29	3.39	12.9	204.3
30	3.47	14.6	204.5
31	2.52	12.8	204.6
32	4.39	14.8	205.4

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [° from N]
33	3.40	9.4	215.1
34	6.40	15.4	217.3
35	4.34	16.6	218.5
36	5.38	14.8	219.2
37	3.35	12.9	221.2
38	2.40	11.5	221.5
39	4.28	12.9	221.7
40	2.48	12.9	222.4
41	1.66	11.5	222.4
42	3.41	14.8	223.9
43	1.61	12.9	224.2
44	2.44	14.7	225.3
45	2.54	17.7	225.7
46	1.65	14.7	225.7
47	3.44	15.0	239.9
48	3.49	13.3	240.5
49	2.51	17.4	241.3
50	1.52	11.4	242.5
51	2.29	14.7	242.6
52	1.50	13.1	242.6
53	2.36	11.6	243.8
54	1.53	17.3	244.4
55	2.34	13.0	244.4
56	1.57	14.8	245.3
57	1.11	15.2	261.3
58	1.47	17.2	261.3
59	2.32	13.3	262.8
60	2.11	7.1	264.3
61	1.66	5.9	265.3
62	2.39	14.3	266.3
63	1.62	14.7	296.3

Appendix H:
Monthly sediment discharge onto the inter-tidal beach at Elizabeth Bay

MONTHLY DISCHARGES FOR 1998 (m^3)

	DP11.4	DP12.6	DP14	DP14.8	TOTAL
January	67811				67811
February	70261				70261
March	71019		5896		76915
April	58921				58921
May	63131				63131
June	59843				59843
July	73832				73832
August	66779				66779
September	59318				59318
October	38409				38409
November	53987				53987
December	82523				82523
TOTAL	**765833**		**5896**		**771729**

MONTHLY DISCHARGES FOR 1999 (m^3)

	DP11.4	DP12.6	DP14	DP14.8	TOTAL
January	43849				43849
February	61497				61497
March	64691				64691
April	52579				52579
May	60118				60118
June	80692				80692
July	53982				53982
August	81291				81291
September	64770				64770
October	73578				73578
November	70544				70544
December	40282				40282
TOTAL	**747873**				**747873**

MONTHLY DISCHARGES FOR 2000 (m^3)

	DP11.4	DP14	TOTAL
January	55188		55188
February	54523		54523
March	56643		56643
April	42382		42382
May	55592		55592
June	54358		54358
July	46543		46543
August	36984		36984
September	55921		55921
October	70924		70924
November	67939		67939
December	53630		53630
TOTAL	**650627**		**650627**

MONTHLY DISCHARGES FOR 2001 (m^3)

	DP11.4	DP14	TOTAL
January	59957		59957
February	59644		59644
March	67367		67367
April	57054		57054
May	60858		60858
June	63532		63532
July	71161		71161
August	65407		65407
September	57583		57583
October	45486		45486
November	45621		45621
December	46325		46325
TOTAL	**699995**		**699995**

MONTHLY DISCHARGES FOR 2002 (m^3)

	DP11.4	DP14	TOTAL
January	61658		61658
February	65849		65849
March	52123		52123
April	75057		75057
May	56334		56334
June	52406		52406
July	69409		69409
August	50622		50622
September	51051		51051
October	61503		61503
November	63135		63135
December	41744		41744
TOTAL	**700891**		**700891**

MONTHLY DISCHARGES FOR 2003 (m^3)

	DP11.4	DP14	TOTAL
January	55249		55249
February	55320		55320
March	56601		56601
April	46424		46424
May	48234		48234
June	62802		62802
July	61678		61678
August	54099		54099
September	50524		50524
October	49018		49018
November	46125		46125
December	37005		37005
TOTAL	**623079**		**623079**

MONTHLY DISCHARGES FOR 2004 (m^3)

	DP11.4	**DP14**	**TOTAL**
January	61926		61926
February	69964		69964
March	69909		69909
April	104435		104435
May	53210		53210
June	94378		94378
July	89540		89540
August	92104		92104
September	78132		78132
October	12598	71390	83988
November	9039	51222	60261
December	7806	44233	52039
TOTAL	**743041**	**166845**	**909886**

Appendix I:
Description of rivers north of the project area

The 4 largest of the ephemeral rivers in Namibia are the Kuiseb, Swakop/Khan, Omaruru and Ugab. Of these, the Kuiseb and Swakop/Khan rivers are best documented (Stengel, 1964 and Huntley, 1985).

The *Kuiseb River* is approximately 560 km long and terminates approximately 15 to 20 km south-east of Walvis Bay. Mean annual run-off and peak flow at Rooibank (10 to 12 km upstream) is 0.64 million m^3 and 7.4 m^3/s respectively. Generally, flow decays to no flow within 100 km from the mouth (Jacobson *et al*., 2000), and duration and frequency of flow decreases downstream (Lancaster, 1989). On average, the river experienced flow 22.6 days per year between 1962 and 1983 (range between 0 and 102 days) with no flow for 4 consecutive years (Loutit, 1991). Between 1837 and 1963 15 flood events reached the ocean (Stengel, 1964). During this period the flood of 1962/63 was most noteworthy. Not much data exist for the flood, but notes and accounts made by local inhabitants provide an idea of the magnitudes of the flood. During this flood, the maximum discharge was estimated at 122 million m^3 past Rooibank, and that a sediment load of 16 million m^3 was transported by the waters. This flood, however, did not reach the ocean. Between 1963 and 1978, flow approximately 70 km upstream was annual but only once did the river each the ocean (Lancaster, 1989). Between 1979 and 1993 12 floods occurred of which none reached the Atlantic Ocean (Jacobson *et al*., 2000). Therefore, the frequency of flow reaching the ocean is minimal and associated with this episodic flow is a lack of sediment discharge data.

The *Swakop River,* situated further north at Swakopmund, also lacks data for the same reasons. However, Loutit (1991) states that flow frequency and magnitude of both the Swakop and the Kuiseb Rivers has been decreasing since the 1960's for reasons unknown, but one of which may be reduced rainfall in the respective catchments. Since the turn of the century, flow at Swakopmund occurred twice in every 3 years. The 1960s saw a reduction in flow, and since 1972/73 only 3 flow events have occurred (Loutit, 1991). Notes by locals give accounts of flows in the Swakop River, and flow to the sea between 1893 and 1963 have been numerous (approximately 15 to 20 events). Anecdotal information indicates that of the 2 major floods in 1933/34 and 1962/63, the flood of 1933/34 resulted in a discharge of 500 million m^3 of water and 35 million m^3 of sediment into the ocean, enough sediment to produce shoreline progradation (building out) of approximately 1 km (Greenwood, 1996). The flood of 1962/63 produced a discharge of 200 million m^3 and 5 to 7 million m^3 of water and sediment, respectively, into the sea. The last comparable flood occurred in 1973/1974 with 190 million m^3 of water discharge (CSIR, 1990).

Appendix J: Aeolian sediment transport calculations and discussion

Considering the sand (>80 μm) fraction of coastal sediment input, the magnitude of both onshore and offshore wind-driven sand this input can be estimated by calculation. Employing a compilation of several aeolian transport formula (Swart, 1986) annual potential transports into the sea (offshore) and away from the beach (onshore) for three sites in the project area were calculated (Table J.1). These calculations assume dry, cohesionless sand of unlimited quantity, blowing along a flat, unvegetated surface, and therefore represent maximum potential transports. It is clear from the calculations that the potential for onshore transport is higher than the potential for offshore transport. This is particularly the case for the sheltered (pre-mining) beach at Elizabeth Bay. However, the availability of sand and the effects of the sea and associated wave action affect the offshore transport of sand by wind. Offshore sand transport from the hinterland will occur by means of saltation, resulting in deposition in the swash zone (zone of wave breaking onto the inter-tidal beach face). If part of the windblown sand is finer than that occurring naturally on the beach face (i.e. indicating it to be more mobile than the sand which deposits there), then this finer sand will tend to be winnowed out by wave action and transported further offshore. This finer sand will consequently not be available to be transported back onshore by wind and will be lost from the upper beach, thus constituting a sand source to the near-shore zone (and the project area).

Table J.1: Estimated potential onshore/offshore transport rates.

Location	Transport rate onshore direction (m^3/m/yr)	Transport rate offshore direction (m^3/m/yr)	Comments
Kleinzee	26.2	8.9	Based on >10 years of measured wind data. But grain size data were roughly estimated.
Oranjemund	13.5	9.0	Based on 1 year of measured wind data. Sand size input from back-beach sampling
Elizabeth Bay	79.3	6.5	Based on >10 years of measured wind data. Sand size input from sampling of the beach sand source

Some idea of sand input to the project area by this mechanism, for the case of an exposed beach, can be obtained from a comparison of natural beach-face sand at Oranjemund with sand from the back-beach sand source which would blow into the swash zone during offshore winds. Reference is made to an empirical "overfill" relationship which provides an estimate of the amount of sand which will be lost from the intertidal beach (ACES, 1992) when sand is placed on this beach. The average size distributions of the natural sand and of the back-beach sand at Oranjemund (as obtained from sampling) are shown in Table J.2

Table J.2: Comparison of back-beach and beach face sediment at Oranjemund

Sediment	D5	D16	D50	D84	D95	Reference
15 km NW of Orange Mouth – Back-beach sampling	130	214	451	947	1267	CSIR (1998b)
15 km NW of the Orange Mouth – beach face sampling prior to major mining	120	350	510	950	1350	Estimated from graphs in CSIR (1979)

Employing the overfill relationship with the above two grain size distributions, it is calculated that for every 1.02 m^3 of back-beach sand supplied to the beach by aeolian transport, only 1 m^3 will remain – i.e. a "one-way" input to the marine environment of about 2% of all the aeolian transported sand is anticipated. Thus for every 9 m^3 onshore wind transport per metre of beach per year (Table 5.6), only 0.18 m^3/m/year will end up in the sea after being winnowed from the inter-tidal beach (swash zone). Thus the remaining 8.82 m^3 (per metre per year) will deposit back on the beach and will be available for onshore transport. Assuming that these sand sizes and conditions apply to the first 100 km of sandy shoreline as occurs north of the Orange River, 0.18 m^3/m/year this translates to only 18 000 m^3/year of input to the near-shore environment.

This offshore transport of 9 m^3/m/yr (minus the permanently lost 0.02 m^3/m/yr) to the sea will be countered by onshore transport. While a potential of 13.5m^3/m/yr is indicated in Table J.2, this potential transport is likely to be significantly reduced due to the water and high salt content of the beach. Sherman *et al.* (1998) found that a moisture content of over 7% caused transport to be orders of magnitude lower than the transport of dry material for similar wind speeds. Nickling and Ecclestone (1981) conducted wind-tunnel experiments and found that the presence of salt forms bonds between particles and holds them together, thus increasing the threshold velocity for initiation of motion, and reducing transport.

The above example calculation and considerations of influences on aeolian sand transport suggest that:

- The magnitude of sediment transport onshore or offshore at the exposed beaches in the project area is relatively small;
- The magnitude and direction of net transport is affected by both the relative grain sizes of the inter-tidal beach and of the back-beach (sediment source);
- The magnitude and direction of net transport is affected by the effects of moisture and salt on aeolian transport.

However, these findings should be validated by means of (a) more extensive measurements of grain sizes at shore sand sources as well as on the inter-tidal beach face and (b) associated measurements of wind-blown sand transport.

Appendix K: Model inputs of the 1:20 year flood scenario

Table K.1: The 36 wave conditions simulated in the refraction analysis of the Orange River mouth model – 1:20 year Flood.

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [from N]
1	2.59	11.02	209
2	2.74	10.59	209
3	2.44	11.46	198
4	3.93	15.31	209
5	3.08	13.67	215
6	7.55	15.13	204
7	4.24	13.07	175
8	3.14	11.65	171
9	1.92	9.24	180
10	1.47	14.02	227
11	1.53	14.38	240
12	1.65	12.62	224
13	2.62	6.10	161
14	2.54	7.25	178
15	1.99	12.12	204
16	1.62	18.04	237
17	1.96	16.14	237
18	2.09	14.08	247

Condition	Significant wave height [m]	Peak wave period [s]	Wave direction [from N]
19	2.47	11.98	222
20	2.65	11.30	214
21	2.78	12.33	201
22	2.38	11.19	205
23	3.64	9.42	180
24	2.97	11.95	190
25	2.36	11.36	190
26	1.40	10.24	187
27	0.98	10.15	203
28	1.16	14.26	251
29	2.15	13.56	226
30	2.42	12.97	218
31	2.66	11.94	205
32	1.61	11.34	215
33	1.49	8.00	177
34	1.26	6.56	181
35	1.23	9.92	210
36	1.14	10.24	198

Appendix L: Orange River discharge and corresponding suspended sediment concentration for the 1 in 20 year flood scenario.

Date	Time	Discharge rate [m^3/s]	Suspended sediment concentration [kg/m^3]
06021996	194800	143.519	2.0302
07021996	041200	139.441	2.0287
07021996	053600	199.492	2.0505
07021996	091800	846.475	2.3157
07021996	111800	1013.719	2.3945
07021996	130600	1096.478	2.4353
07021996	161200	1184.933	2.4802
07021996	211200	1239.616	2.5086
08021996	070000	1266.794	2.5229
09021996	032400	1233.327	2.5053
09021996	143000	1172.264	2.4737
10021996	024200	1088.373	2.4313
10021996	081200	1052.378	2.4134
11021996	181200	851.877	2.3182
12021996	085400	806.438	2.2975
13021996	010600	774.047	2.2830
13021996	174800	756.338	2.2751
21021996	084200	459.758	2.1500
21021996	085400	493.978	2.1638
21021996	132400	511.283	2.1708
21021996	163000	564.844	2.1929
21021996	193000	684.686	2.2437
21021996	234200	871.572	2.3272
22021996	022400	953.326	2.3655
22021996	061200	1026.531	2.4008
22021996	162400	1119.858	2.4470
22021996	223600	1193.296	2.4845
23021996	173000	1392.228	2.5909
24021996	014200	1499.243	2.6513
24021996	064800	1590.443	2.7045
24021996	141200	1645.443	2.7374
24021996	191200	1705.819	2.7743
25021996	122400	1834.612	2.8557
26021996	000600	1887.704	2.8903
26021996	151800	1919.872	2.9115
27021996	195400	2002.342	2.9672
28021996	062400	2009.768	2.9723
28021996	103000	2019.070	2.9787
29021996	075400	2030.314	2.9864
01031996	050600	2098.828	3.0344
01031996	113000	2164.966	3.0817

Date	Time	Discharge rate [m^3/s]	Suspended sediment concentration [kg/m^3]
01031996	183000	2166.753	3.0830
01031996	224200	2126.474	3.0540
02031996	053600	2096.907	3.0330
02031996	143000	2091.373	3.0291
02031996	213000	2135.572	3.0606
03031996	050600	2237.886	3.1352
03031996	092400	2261.478	3.1528
03031996	143600	2257.831	3.1501
03031996	224200	2203.338	3.1097
04031996	064200	2188.758	3.0991
05031996	090600	2212.453	3.1164
06031996	213600	2175.918	3.0897
07031996	131200	2128.270	3.0553
07031996	200000	2131.976	3.0580
08031996	071800	2183.172	3.0950
08031996	111800	2210.563	3.1150
08031996	230600	2210.563	3.1150
09031996	064200	2197.786	3.1057
10031996	103000	2085.845	3.0252
11031996	040600	2047.005	2.9980
12031996	093000	1953.727	2.9342
13031996	010000	1899.130	2.8978
13031996	143000	1823.076	2.8482
14031996	125400	1719.426	2.7828
16031996	090000	1647.362	2.7386
16031996	171800	1643.526	2.7363
17031996	043000	1602.340	2.7116
17031996	194800	1501.197	2.6524
18031996	154200	1297.922	2.5395
21031996	021800	772.050	2.2821
21031996	115400	720.176	2.2591
22031996	053000	686.484	2.2445
22031996	122400	657.777	2.2321
22031996	131200	637.778	2.2235
22031996	151800	555.324	2.1889
22031996	184800	502.574	2.1673
23031996	091200	440.277	2.1423
23031996	105400	437.733	2.1413
23031996	173000	385.202	2.1206
24031996	123000	371.924	2.1154
24031996	210000	345.620	2.1053

Appendix M: Plant Discharges at Chameis Pocket Beaches Site 2 (as applied in modelling) for 22 January to 28 February 2005 (Discharged material originates from Site 2.

Date	Daily time of operation (hours)	Daily tons treated	Mass of sediment discharged onto the beach (tons)	Mass of fine sediment discharged onto the beach (tons)
22 January 2005	15	3965	3569	511
23 January 2005	17	4548	4093	586
24 January 2005	10	2762	2486	356
25 January 2005	15	4201	3781	541
26 January 2005	15	3909	3518	503
27 January 2005	16	4048	3643	521
28 January 2005	17	4775	4298	615
29 January 2005	15	4306	3875	555
30 January 2005	13	3325	2993	428
31 January 2005	20	5360	4824	690
01 February 2005	17	4510	4059	581
02 February 2005	16	4266	3839	549
03 February 2005	14	3554	3199	458
04 February 2005	21	5300	4770	683
05 February 2005	14	3887	3498	501
06 February 2005	17	5118	4606	659
07 February 2005	17	4016	3614	517
08 February 2005	14	3168	2851	408
09 February 2005	16	3893	3504	501
10 February 2005	21	5659	5093	729
11 February 2005	18	4407	3966	568
12 February 2005	18	4402	3962	567
13 February 2005	18	4994	4495	643
14 February 2005	22	6302	5672	812
15 February 2005	14	3768	3391	485
16 February 2005	0	0	0	0
17 February 2005	21	5844	5260	753
18 February 2005	20	5275	4748	679
19 February 2005	16	3879	3491	500
20 February 2005	13	3461	3115	446
21 February 2005	8	1941	1747	250
22 February 2005	11	2897	2607	373
23 February 2005	18	4710	4239	607
24 February 2005	20	5437	4893	700
25 February 2005	24	6718	6046	865
26 February 2005	15	3961	3565	510
27 February 2005	17	4552	4097	586
28 February 2005	16	4239	3815	546

Appendix N: Dredging details and estimated overspill mass per dredging trip (as applied in modelling)

Date in 2005	From time	To time	Dredging Panel	Dredging Trip no.	Concentration of sample (mg/l)	Volume in hopper (m^3)	Volume overspilt (water and fines) (m^3)	Mass of sediment in overspill (tons)	Percentage fines
22-Jan	14:20	16:15	1	1	9210	6771	32951	303	49
22-Jan	23:30	01:15	1	2	7206	7657	30843	222	92
23-Jan	06:55	08:40	1	3	6398	7681	30819	197	91
23-Jan	14:40	16:45	1	4	2398	7705	38128	91	87
23-Jan	22:05	00:05	1	5	4138	8449	35551	147	90
24-Jan	04:50	06:45	1	6	7004	8366	33801	237	96
24-Jan	12:45	14:50	1	7	2322	8142	37691	88	100
24-Jan	19:30	21:45	1	8	3716	8307	41193	153	29
25-Jan	03:05	05:50	1	9	4264	8449	52051	222	98
25-Jan	12:00	14:30	1	10	5892	7929	47071	277	86
25-Jan	19:20	22:15	1	11	4852	7977	56190	273	91
26-Jan	05:00	08:40	1	12	4416	8378	72289	319	90
26-Jan	17:50	00:50	1	13	2347	8142	145858	342	94
27-Jan	06:35	10:35	1	14	1799	8177	79823	144	99
28-Jan	01:35	03:35	1	15	4793	7977	36023	173	85
28-Jan	18:35	20:45	1	16	1094	4311	43356	47	99
29-Jan	15:10	17:25	3	17	4793	7870	41630	200	85
29-Jan	21:30	23:30	3	18	4793	7551	36449	175	85
30-Jan	04:10	06:50	3	19	4793	8201	50466	242	85
30-Jan	12:05	14:25	3	20	4793	8082	43251	207	85
30-Jan	18:45	20:50	3	21	4793	8003	37830	181	85
31-Jan	01:15	03:30	3	22	4793	8236	41264	198	85
31-Jan	08:35	10:40	3	23	4793	8106	37727	181	85
31-Jan	18:20	20:55	3	24	4793	8295	48538	233	85
01-Feb	00:50	03:50	3	25	4793	8307	57693	277	85
01-Feb	10:35	13:35	3	26	4793	8472	57528	276	85
01-Feb	19:10	22:15	3	27	4793	8507	59326	284	85
02-Feb	03:20	06:00	3	28	4793	7965	50702	243	85
02-Feb	14:25	17:30	3	29	4793	8036	59797	287	85
02-Feb	22:10	02:10	3	30	4793	8177	79823	383	85
03-Feb	07:35	10:40	3	31	4793	8083	59750	286	85
03-Feb	19:05	23:10	3	32	4793	8000	81833	392	85
04-Feb	13:50	15:00	3	33	4793	3472	22195	106	85

The table provides details from the 33 dredger trips from Panel 1 and Panel 3. The 6th column indicates the concentration of samples of the overspill. It is assumed that these concentrations are representative of the overspill composition (as observed by the on-board geologist - C. August, De Beers Marine Namibia Geologist, pers. comm.).

The 7th column indicates the volumes of material in the hopper, as provided by the dredging company. The 8th column provides an estimate of the total volume of water (and fines) that was released in the overspill. This is based on an assumed dredging rate of 22 000 m^3/hour, as provided by the dredging company. The mass of sediment released in the overspill is indicated in the 9th column. From the table it is estimated that 3 236 tons of fine sediment was released into the sea during dredging of Panel 1, and 4 150 tons of fine sediment released in the overspill during dredging of Panel 3. The total mass released into the sea is thus estimated to be 7 386 tons.

Appendix O: Capacity-Building Workshop Details

REPORT:

STUDENT CAPACITY-BUILDING WORKSHOP

Introduction to Contemporary Concepts and Methods in Environmental Monitoring, Assessment and Management using the following BCLME projects as examples and demonstration:

Held at the Polytechnic of Namibia, Hotel and Tourism School, Windhoek on 5 October 2005

Workshop Objectives

Capacity building and training is a high priority in the BCLME Programme.
The objective of the workshop was to introduce and create basic understanding of contemporary concepts and methods in environmental monitoring, assessment and management among participants. The workshop drew on the activities and interim findings of the BCLME project BEHP/CEA/03/03[1] for examples and demonstration to facilitate easy understanding.

The workshop covered the following (Annex 1 provides the programme that was followed during the one-day session):

- Introduction to environmental monitoring, assessment and management;

[1] Assessment of the Cumulative Effects of Sediment Discharges from On-shore and Near-shore Diamond Mining Activities on the BCLME

  - Introduction to Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA) and Integrated Environmental Assessment (IEA)

- Students exercises on SEA and EIA.
- Definition of concepts: gap analysis, cumulative effects, impacts, baseline, indicators, threshold and, modelling.
- Demonstration of the use of monitoring and modelling techniques in environmental assessment and management.

Resource People and Participants

Mr. Nico E. Willemse (Namibia) presented the morning session on EIA, SEA and IEA.
Mr. Geoff Smith and Miss Nadia Weitz (CSIR, South Africa) presented the session on the BCLME Project and demonstrated the use of monitoring and modelling techniques in cumulative impact assessment.

Twenty-seven 2nd, 3rd and 4th year students from the University of Namibia and Polytechnic of Namibia participated in the workshop. Students comprised a mixture of undergraduate pursuits inclusive of environmental management, land use/town planning, environmental biology, fishery science, nature conservation, geology, geography and GIS, zoology, botany and information technology (the latter preferably dovetailed with environmental science/ related course).

Annex 2 is an attendance and participation list.

Remarks

Gauging from the overall participation and responses from students, the majority of the group was extremely pleased with the one-day workshop. For many it was a first introduction to EIA, SEA, IEA and, monitoring and modelling. Apart from being introduced to different approaches to environmental assessment they learned about the role such techniques can play in sustainable development. For the participatory exercise the students were divided into smaller groups and given a task that entailed completing an SEA for an area and based on that advise on a location for the development of a lodge. The recommended site must be based on avoiding potential negative impacts the lodge development can have on the environment. The students found the exercise very engaging and participated commendably well.

The session on monitoring and modelling introduced the students to the BCLME project as well as environmental modelling. They learned about the magnitude of diamond mining operations along the Benguela, accompanying impacts on the environment, and the potential use and advantages of modelling in the presence of no or little data.

Annex 1:

Programme for Student Capacity-Building Workshop

1. Welcome and introduction
2. Introduction to the BCLME Project
3. Introduction to
    (a) Environmental Impact Assessment (EIA),
    (b) Integrated Environmental Assessment (IEA) and
    (c) Strategic Environmental Assessment (SEA)
    (d) Monitoring
4. Group Exercise
5. Lunch
6. Introduction to modelling, cumulative impact assessment
7. Evaluation
8. Closure

Annex 2: Workshop participants:

	Name and Surname	Field of Study (year)	Institution
1	Amon, Andreas	Nature Conservation	Polytechnic
2	Amutenya, Nangula	B.Sc. Natural Resources	UNAM
3	Congo, José Pilartes	Trainee at Geophysics	VAN – ANGOLA
4	De Miunda, Hugo	Urban Land use planning	P.O.N.
5	Edward, Alberthina	B.Sc. Natural Resources	UNAM
6	Eelu, Kaarina	Nature Conservation	Polytechnic
7	Fania, Kakya Gabriela R.	Geophysics	VAN – ANGOLA
8	Hofrie, Reginadia	B.Sc. Natural Resources	UNAM
9	Horaeb, Richard R.	B.Sc. Natural Resources	UNAM
10	Iiyambo, Inekela	B.Sc. Natural Resources	UNAM
11	Iiyambo, Vera	B.Sc. Natural Resources	UNAM
12	Indombo, Gabriel	Urban land use planning	PON
13	Kanime, Abraham I.	B.Sc. Natural Resources	UNAM
14	Kohima, Dino	B-Tech Land Management	P.O.N.
15	Matali, Simasiku F.	B.Sc. Natural Resources	UNAM
16	Naruses, Lourencia	B.Sc. Geology & Geography	UNAM
17	Ndinelago, Uushona	B.Sc. Fisheries and Marine Science	UNAM
18	Neshuku, Martha N.	B.Sc. Natural Resources	UNAM
19	Ngahahe-Hangero, Neville	Urban land use planning	P.O.N
20	Paulus, Sarah C.	B.Sc. Natural Resources	UNAM
21	Sakaria, Vistorina	B.Sc. Natural Resources	UNAM
22	Shikongo, Monika	Nature Conservation	Polytechnic
23	Shipunda, Pentapala	Nature Conservation	Polytechnic
24	Simon Simon N.	B.A. Geology & Enviro. Studies	UNAM
25	Somaës, Marchella	B.Sc. Natural Resources	UNAM
26	Tlipetekera, Cyrlius	Urban land use planning	PON
27	Vantinda, Tune	B.Sc. Natural Resources	UNAM