Marine diamond mining and the environment

by Håkan Tarras-Wahlberg

The Namaqualand coast is situated in the north-western part of South Africa. It sustains a fishery as well as a diamond mining industry, both of great importance for the South African economy. On the Namaqualand coast, diamonds have been mined from raised marine gravel-deposits since early this century. But coastal areas as this sustain some of the most productive and biologically diverse ecosystems in the world, and due to their riches, these areas are often threatened by human activities. The need for wise management is now urgent.

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Coastal areas world wide sustain some of the most productive and biologically diverse ecosystems in the world, and due to their riches, these areas are often threatened by human activities, which in turn often lead to environmental degradation and loss of biodiversity. As throughout the world pressures on the coastal zone are increasing, the need for wise management is now urgent.[1]

The Namaqualand coast is situated in the north-western part of South Africa, and although sparsely populated, the area sustains a fishery as well as a diamond mining industry, both of great importance for the South African economy. Diamond mining has long been an important industry in South Africa, and the first finds in Kimberley in 1868 and 1869 started what became a rapid development of the country's economy. In 1993, South African produced approximately 10.3 million carats of diamonds, to a value of more than 1 000 MUSD, representing 14 per cent by value of the world's total diamond production.[2]

On the Namaqualand coast, diamonds have been mined from raised marine gravel-deposits since early this century. The two largest ore deposits are situated at the mouth of the Orange River in the north, and at the Buffels River mouth 140 km further south. Until recently, offshore mining in South Africa was limited to shallow waters and the annual production was then approximately only 100 000 carats. Lately, with the availability of new technology, the scale and depths at which offshore operations can operate economically have increased, and at present, marine diamond exploration and mining is experiencing something of a bonanza.[3] The total off shore diamond resource has been estimated at more than 1.5 billion carats, and the yearly production is predicted to possibly reach 2 million carats, representing 10 per cent of the global production of gem diamonds, as early as by the year 2000.

According to Agenda 21, the most elaborate and far-reaching document produced at the UN Conference on Environment and Development in Rio (1992), coastal states should commit themselves to the wise use and the sustainable development of coastal areas and resources.[4] Along the Namaqualand coast, onshore diamond mining has often been done with scant regard for the environment as mined out areas have generally not been rehabilitated, leaving the coastal landscape riddled with scars which may remain for generations. Furthermore, in the last few decades fisheries off the South African west coast have experienced a dramatic decline due to severe over-fishing. The pilchard catch dwindled from a peak of 400 000 t in 1962 to 16 000 t in 1974, and off Namaqualand, the crayfish industry experienced reduction in the catch, from 2 000 t in the mid 1960s to an all-time low of 40 t in 1984.[5] Clearly, the need for careful management of future developments along the Namaqualand coast is pressing. Environmental Impact Assessments (EIAs) are not mandatory under South African law and consequently the environmental impact of large scale diamond mining on South African waters still remains to be scientifically assessed. Marine diamond mining is an industry with a life-span in the order of a few decades. The mining itself may, however, have significant impacts on sustainable marine resources, which may, if managed wisely, yield substantial benefits for many generations. As the Namaqualand coast is in serious need of economic development brought by the diamond mining industry, it is important that the environmental impact of marine mining is thoroughly investigated in order to assess the potential conflict of interest between mining and fisheries. Furthermore, as mining may impact on the ecological balance of the coastal zone it is important to optimise the environmental management of the offshore diamond mining industry, as wise management may lessen the extent of habitat destruction that is an inevitable consequence of any mining operations.

This paper attempts to identify and assess impacts on the physical environment of marine diamond mining. To achieve this aim, a case study approach is adopted, focusing on a mining operation conducted by the Cape Town based company Benguela Concessions Ltd at depths of 30 to 65 m. Data on salinity, temperature, dissolved oxygen, and nutrient status of an area covering the Benguela mining concessions and their surroundings were obtained from the South African Data Centre for Oceanography (SADCO). Having information on the oceanographic conditions, sea-floor geology as well as a detailed mining plan, the likely impact of the disposal of mining tailings is then simulated by use of a computer-based numerical model. Additionally, potential impacts of the mining operation were also identified when the author worked on a Benguela Concessions' sampling and exploration vessel during 1994 and 1995, and during a fact-finding visit to Cape Town in June 1996. The findings of this study are used to recommend management procedures to minimise and or mitigate the most significant of the identified impacts.

The Namaqualand coastal environment geomorphology

The Namaqualand coast is straight and has only very few sheltered bays or islands, and the coastline consists of wave-cut platforms, rocky headlands and sandy beaches.[6] The coast itself is backed by a coastal plain and a high escarpment that runs 35 to 100 km inland, and rises to a height of about 700 m. The coast is a tectonically stable, passive margin with a wide continental shelf which extends up to 230 km offshore (see map). The inner part of the shelf consists of a narrow, rugged, steep and largely sediment-free rocky platform with a steep shoreface, extending 2–10 km offshore.[7] A thick Orange River-derived, terrigenous mud layer on-laps the shelf at 50 to 70 m depth, outward of which the shelf is characterized by a low relief and a gentle seaward gradient.[8]

Geology of the Namaqualand diamond deposits

It has long been known that the primary source of diamonds are kimberlite pipes intruded into older parts of the continental interior.[9] In southern Africa, most the diamondiferous kimberlites are Late Cretaceous in age, and during the Tertiary and Quartenary, up to three billion carats of diamonds are believed to have been eroded out of these kimberlites. These diamonds were subsequently transported towards the sea, via the Orange River as well as a number of palaeo-rivers. In the sea, these diamonds have been further redistributed by currents and wave action. A major shift in the courses of the Orange River during 40 to 15 million year ago, when the Orange is believed to have entered the sea through what today is the Olifants River mouth, coupled with great fluctuations in sea-level during geological time, have produced diamond deposits along 700 km of the southern African west coast, from the Olifants River in the south to beyond Luderitz in Namibia in the north.[10] Experience has shown that diamonds are preferentially concentrated in very particular sedimentary environments. Diamonds, having a higher specific density than most other sedimentary constituents, are generally found at the base of sedimentary units, close to bedrock, and often deposited in high-energy environment sediments containing pebbles, cobbles and boulders. Gullies, potholes and old beach levels may often function as trap sites for diamonds.[11]

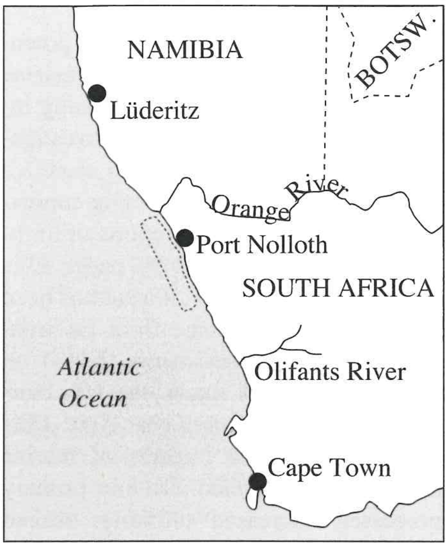
Oceanography

The marine environment off Namaqualand falls within the southern part of what is commonly referred to as the Benguela system. In the Benguela system the most important physical process occurring is wind-induced upwelling, bringing cold nutrient-rich water up to the surface, creating ideal conditions for the growth of phytoplanktons, and making the Benguela system one of the richest and most important fishing areas of the world.[12] As winds along the coast are not uniform, certain areas experience particularly strong upwelling, and the Namaqualand coast in one of six such areas of enhanced upwelling that exist in the Benguela system.[13] A consequence of the high productivity in the surface waters of the Benguela is that, following an upwelling event, considerable quantities of dead biogenic material fall down through the water column and decompose at sub-surface depths. As oxygen is consumed in this process, large areas in the Benguela system are characterised by bottom waters with a very low dissolved oxygen content.[14] Shannon (1985) and Boyd et al., (1992) indicate that a typical speed for the predominantly northward directed surface-currents in the area is about 15–20 cm/s. Other authors have also reported on a slow southward moving bottom current, having a current-velocity of 3–5 cm/s.[15] The Namaqualand west coast is classified as micro tidal (< 2 m) and wave-dominated, and the wave spectrum is dominated by south-easterly and southerly swells with periods of 10–15 s.[16] Wave heights are generally 1–3 m, but may sometimes exceed 5 m. The effect of tidal currents is considered to be insignificant.[17]

The environmental impact of marine mining

In the last couple of decades, the potential environmental impacts of marine mining have generated an increasing interest.[18] However many other investigations have, due to the inherently secretive approach taken by many mining companies, been in the form of reports of limited distribution.[19] In his 1987 paper, Ellis gave a thorough review of what had been learned up to that stage from Environmental Impact Assessments (EIAs) on marine mines in Canada, the US, Norway, the UK and south-east Asia. Ellis concluded that the impacts of marine mining can be divided into four primary processes: increased turbidity, seabed smothering, contamination of the water column, and toxicity effects due to suspension of harmful elements in the tailings plume. These impacts can in turn generate secondary impacts such as reduced productivity of coastal waters, contaminant magnification, pathologies and mortalities of biota.[20] Charlier and Charlier (1992) added lowered oxygen content and nutrient pollution of the affected waters to this list of potential impacts. Persson (1983) pointed out the importance of the sediment dynamics of the sea-floor, and, following Håkanson (1977), divided these into sea-floor conditions being dominated by sediment deposition, sediment transport or sediment erosion. Persson (1983) concluded that the impact of mining is unlikely to be severe in areas where the sea floor is in a natural state of change, i.e. in erosion and transport-dominated environments.

However, in depositional environments the impact of mining will not be masked by natural variability to the same extent, and here the excavated hollow may persist, changing bottom circulation patterns, possibly causing bottom water stagnation, and associated oxygen depletion. None of the above-mentioned research considered the South African marine diamond mines. The reason for this is that large-scale marine diamond mining is a relatively new industry, and furthermore, because Environmental Impact Assessments (EIAs) were (and are) not mandatory under South African law. To date, the only scientific assessment of marine diamond mining in South Africa is a report by Barkai and Bergh (1992), who investigated the environmental impact of small scale and shallow water, diver-manipulated diamond mining and found that the impact essentially is swamped by the great natural variation associated with the high energy environment of the shallow waters. However, the recent upsurge in interest of marine diamonds is associated with much larger scale operation than previously investigated, and the impact of this type of mining, thus, still remains to be scientifically assessed. In Namibia, however, the EIA procedure is state policy and therefore a number of assessments have been done in the last few years.[21] In 1994, a desk top study conducted by the Marine Centre at University of Cape Town, alerted to the possibility of oxygen depletion and nutrient fertilisation effects due to offshore mining, though the details of this investigation are confidential. An EIA study on a proposed Benguela Concessions operation off Luderitz, similar to the one investigated in this paper, concluded that mining would have only a small and short-term impact on the local ecology and marine resources. In modelling the behaviour of the extended tailings-plume, it was predicted that the concentration of suspended solids would not exceed 2.7 mg/l and therefore be fairly insignificant compared to natural background values. Savage (1996) reports on the effect of mining on benthic macrofauna in an area directly west of the Orange River mouth, in depths of 110–135 m, that the particle-size distribution of an area changes as sand and silt fractions are selectively removed during mining, and consequently that there was a relative enrichment in the gravel and clay fractions in mined areas. The relative enrichment in clay in the mined areas is, though not considered in detail by Savage, an interesting phenomenon as one would expect the clay-fraction to also be carried away by currents as the settling velocity of clay is less than that of sand and silt. However, if one envisages the clay behaving cohesively, and thus settling as clumps rather than as dispersed particles, these results make more sense. Savage concluded that the change in particle-size distribution of the affected sediments might cause irreversible changes in the structure of the benthic community structure. Such a significant shift in the community structure was observed though a progressive pattern of recovery in a time frame of a few years was also evident.



The west coast of southern Africa. The Namaqualand mining area is situated in the shaded area just south of the Orange River.

Table 1. Annual Mining Blocks.

Year	Area (m^2)	Volume (m^3)	Tonnes mined
1	151 912	180 231	306 393
2	248 488	258 348	439 192

Theoretical Mining Capacity: Volume of slurry: 7 000m^3/hr.
Head feed – solids à 3 per cent by volume: 210m^3/hr.
Source: BHP-Benguela, 1996.

Benguela Concessions' mining plan

Benguela Concessions are mining in two adjacent mining concessions, situated 30 to 95 km south of the Orange River mouth. On land, the nearest bigger settlements are Kleinzee, Port Nolloth, Alexander Bay and Oranjemund. The total area of the combined concessions is

267 243 670 m^2.[22] Six ore-deposits, at water depths varying from 25 to 65 m, have been identified for mining. The areas of the ore-bodies range from 33 608 m^2 to 122 380 m^2, totalling 400 400 m^2, which represents 0.15 per cent of the overall concession areas. The mining plan is a two-year operation involving only one ship, though it is hoped and believed that the operation will expand.[23] The schedule of mine block exploitation is shown in Table 1.

Mining method

The mining and processing of gravel is done by a ship which is approximately 79 m long and 16 m wide (at its widest), and which has a gross tonnage of approximately 3 500 t.[24]

During mining the vessel is positioned by a four-point mooring system. Two large diameter (500 mm) mining heads, connected to the ship's processing plant via rubber hoses, are deployed off the sides of the ship as shown in Fig. 2. The two mining heads are positioned on the sea floor and suction is created by the introduction of compressed air from the surface into the mining heads. The lower density of the gravel water air mixture inside the mining head then creates a strong enough suction to move the sediment-slurry, with a water solid ratio of approximately 3 per cent by volume, up to the surface for processing on board the vessel. This type of mining is known as the airlift technique. As the majority of diamonds are usually situated on or close to bedrock, it is important to clean up the mining area thoroughly. Experience from similar operations has shown that a total of three passes over each mining area is the economically optimal way of mining diamonds by use of the air-lift technique.

Once on-board the ship, the sediments are screened and split into fractions with oversized and undersized being immediately returned to the sea as tailings. The plant-feed fraction then goes through a Dense Media Separator, where gravel and water are mixed with Ferrous Silicone. This mixture is then passed through a cyclone, and a heavy mineral concentrate is produced. The heavy mineral concentrate is then further concentrated in a x-ray plant, producing a final concentrate from which diamonds are recovered by hand. The material retained as a final concentrate of the whole process constitutes less than 0.01 per cent of the sediment originally pumped to the surface. All tailings are discharged a few metres above the sea surface, via a chute, at the vessels stern.[25]

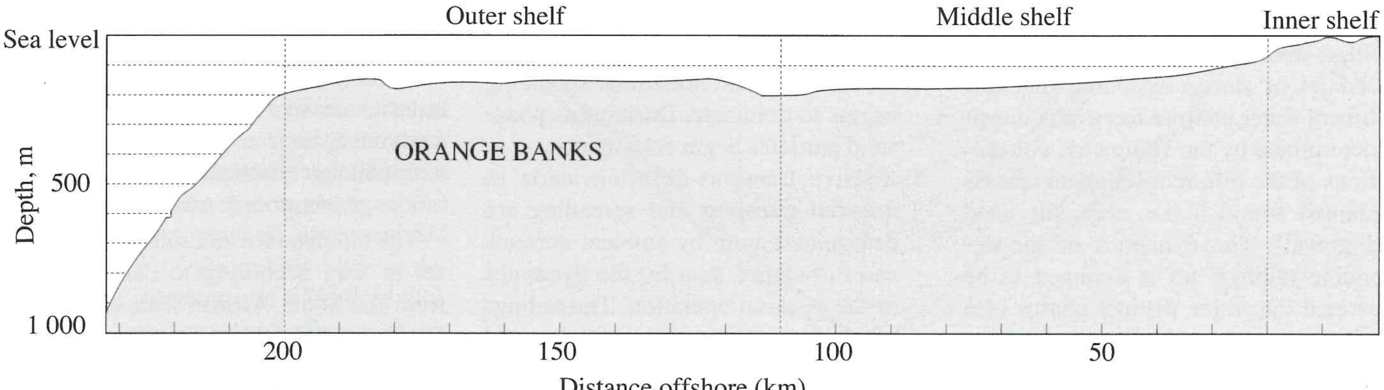
The mining site

The mining concessions are underlain by metamorphic rocks, lithologies varying between gneisses, schists, phyllites and quartzites, and structural features in these rocks have governed the development of sand and gravel filled gullies, basins and palaeo-river courses.[26] The sea-floor slopes very gradually to a depth of about 40 m, beyond which the profile steepens markedly to a depth of about 60 m where an on-lapping, offshore wedge of Holocene, Orange River-derived mud is reached.[27] Shallower than about 40 m, the bulk of the sediment in the area are terrigenous quartz and clay-minerals with minor components of shells, microfossils and glauconite.[28] The coarser sediments in the shallow areas contain very little organic matter, generally less than 0.5 per cent whereas the deeper laying mud drape may contain up to 4 per cent organic matter.[29]

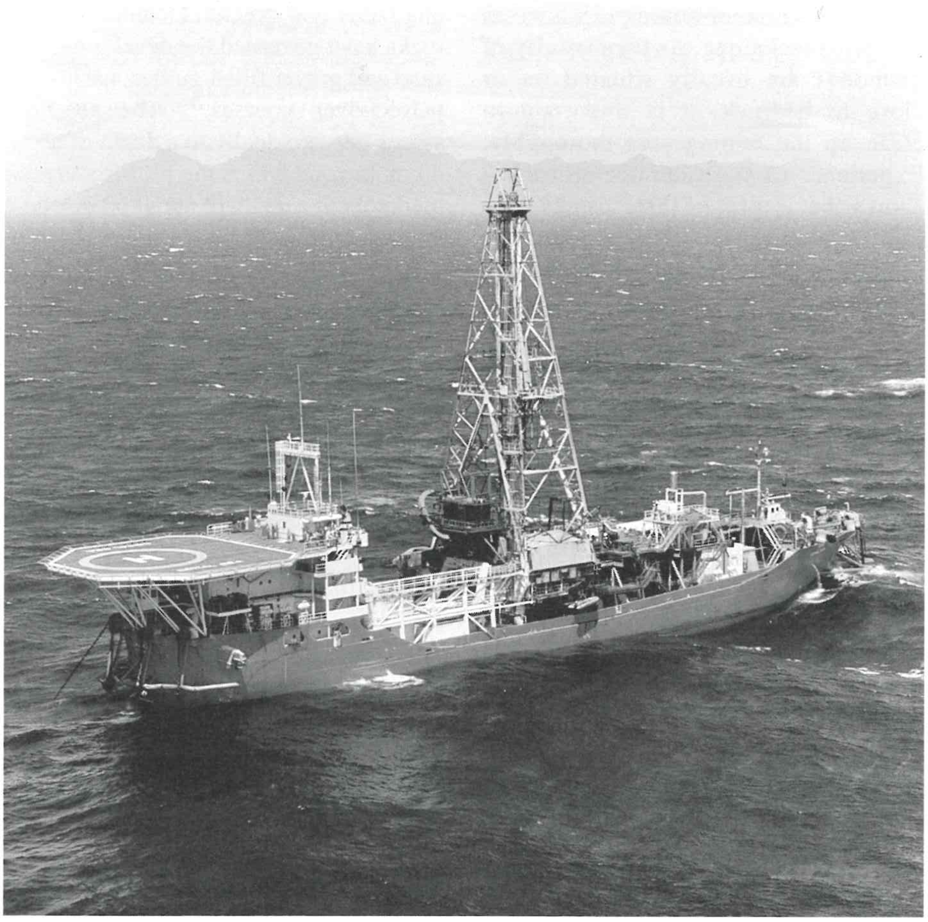
Modelling the tailings plume

The character of the tailings plume is modelled by use of the Stfate-module in the PC-based, Automated Dredging and Disposal Alternatives Management System (ADDAMS). The ADDAMS-system has been developed by the US Army Corps of Engineers, and Stfate simulates the short term fate of dredged material dumped into the ocean. Stfate has previously been used in at least two other similar studies to obtain first order insights into the nature of mining tailings disposal, and the subsequent dynamic evolution of the tailings plume.[30] Stfate Model

Figure 1. Profile across the continental shelf, directly off the Orange River, 28°50' S



Source: Rogers, 1977.



DeBeers' diamond mining vessel.

Stfate models dumping of dredged material from a hopper dredge. As the material is dumped, these hoppers open consecutively, creating a semi-continuous slurry jet which descends to the sea floor. In order to obtain a descending jet, the sediment slurry must be introduced to the water under pressure. This pressure is calculated from the change in draft of the vessel, before and after disposal.[31]

Stfate treat the tailings as an introduced jet of slurry, assuming that this sediment water mixture has a bulk density determined by the volumetric concentrations of the different sediment classes contained within it (i.e. clay, silt, sand and gravel). The dynamics of the descending tailings' jet is assumed to be separated into three distinct phases (see Fig. 3).

1. During convective descent the disposed tailings slurry descends under the influence of its initial buoyancy deficiency, momentum and gravity. As the slurry descends, it entrains ambient seawater, causing the jet to increase in dimension while its velocity, and the concentration of sediments contained within the jet, decreases.
2. Dynamic collapse occurs either as the jet impacts the bottom, or as a level of neutral buoyancy is reached. The descent velocity then becomes close to zero and instead, horizontal spreading begins to dominate. During this phase solid particles begin settling out.
3. Passive transport-diffusion starts as material transport and spreading are determined more by ambient currents and turbulence than by the dynamics of the disposal operation. The tailings plume then grows horizontally and vertically as a result of turbulent diffusion.

Limitations of model

Stfate only models continuous discharge over periods of a few minutes. If the jet encounters a level of neutral buoyancy, the collapse and passive diffusion phases cannot be simulated and the program terminates.

- The time step chosen must be greater than the time to the end of collapse phase. Thus, it is impossible to simulate an active discharge, as the first calculations must, by necessity, be at a time when discharge has already ended.
- The sea floor can only slope in one direction, and thus the potential effect of an uneven bottom-topography cannot be modelled.
- Once particles are deposited on the sea floor, they are assumed to remain there. The model should thus only be applied over periods in which erosion of newly deposited material is insignificant.

Application to this study

Two approaches are used in modelling the behaviour of the sediment plumes. First, an attempt is made to obtain a snapshot of a plume soon after sediment discharge has ended, after the end of the dynamic collapse phase. Second, a long-term simulation is performed in order to investigate the pattern of sedimentation on the sea floor. The input data necessary for a Stfate simulation are grouped into a description of the ambient environment, characterisation of the disposed sediments, data on the disposal operation and model coefficients. The model is run on three ore bodies that are chosen as being representative of all the ore bodies in the study area, both in terms of water depth and sediment characteristics. In all simulations, the bottom is assumed to be flat.

The temperature and salinity profile is set to vary according to data obtained from the South African Data Centre for Oceanography (SADCO). The sediment plumes are all simulated at two different ambient currents: normal (20 cm/s) and

The mining vessel is positioned by a four point mooring system, and the two mining heads produce two parallel mining ditches.

fast (50 cm/s). Default characteristics, contained in the Stfate software, is used to define the sediments in terms of specific gravity, settling velocity, deposit void ratio (volume-fraction of settled material occupied of solids), cohesiveness, and critical shear stress (which determines whether a fraction will stay in suspension or deposit on the sea floor). The silt and clay fractions are treated as behaving cohesively as this was widely observed to be the case during the exploration programme. The particle size distribution of the sediment is taken from data obtained from Benguela Concessions operations information. The continuous discharge of the mining operation is approximated by the discharge from one single hopper with a discharge diameter of 1 m. A discharge rate of 7 000m/hr of slurry, at a 3 per cent solids water ratio is used in all simulations. In all simulation a change in draft of at least 2 m was necessary in order not to reach a level of neutral buoyancy in which case the simulation will terminate. Model Coefficients Default values for a number of coefficients, such as vertical and horizontal diffusivity, are used. To change any of these default values, a calibration field study would be necessary.[32] Furthermore, experiments have shown that simulation results are fairly insensitive to many of these coefficients.[33]

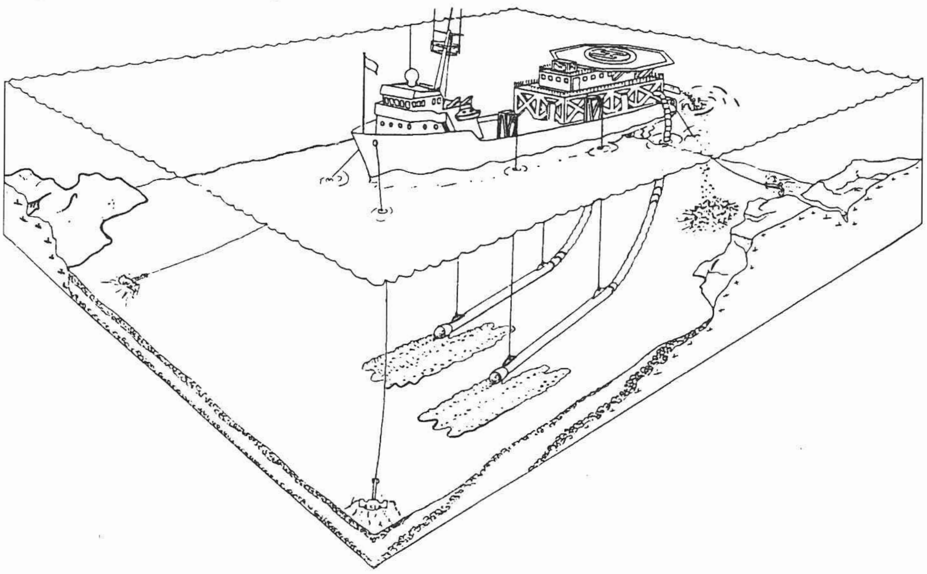
Results and discussion

Attempts to simulate the discharge of tailings with a change in draft of less than 2 m failed, as the tailing's jet did not reach the sea floor during convective descent. The simulations are then terminated as the plume reaches a level of neutral buoyancy. This negative result indicates the importance of introducing tailings at sub-surface depths and at pressure, if a sediment slurry jet and an associated minimisation of the mixing zone is desired. The fundamental effect of discharging tailings as a sediment slurry rather than as a collapsing cloud, containing sediment grains settling out individually, is to greatly increase the rate at which sediment settles to the sea floor. The results thus indicate that if, as in the case in the Benguela operation, tailings are discharged a few metres above surface, the sediment plume will reach a level of neutral buoyancy, and minimisation of the mixing zone will not be achieved.

Snapshot simulation

The modelled plumes sink rapidly, reaching the depth of dynamic collapse, 5 to 7 m above the sea floor, within 2 minutes after end of discharge. The dynamic collapse phase in turn ends 1 to 2 minutes later, 0.5 to 1 m above the sea floor. The timing and depths of these events is not sensitive to changes in the ambient current regime. During the descent phase, seawater is entrained, increasing the volume of the tailings plume, and thereby diluting the concentration of suspended solids. In the simulations, maximum concentrations of, in general about 100 mg/l near discharge, is diluted to maximums of less than 50 mg/l further down the water column. As the depth of dynamic collapse is reached, concentrations of suspended solids increase dramatically, and just above the sea floor, maximum concentrations of up to 10 660 mg/l are reached. The effect of a stronger current is to dilute the concentration of suspended solids in the plumes, and thereby also increase the absolute size of the plume. In the fast current simulations, the maximum concentrations of suspended solids during the convective descent phase are generally about 20 per cent less than in the normal current simulations. Maximum concentrations during dynamic collapse are, however, essentially the same in the two current regimes. Natural background values for suspended solids on the South African west coast generally vary between 1 to 5 mg/l, but values as high as 44 mg/l have been reported.[34] The results of the snapshot simulations imply that the concentration of suspended solids will, within a distance of a few hundred metres, be diluted to less than 10 mg/l, which thus is comparable to background values expected for the area. Thus, the simulation results imply that the area of influence of the tailings plume will be no more than about 300 x 300 m or 90 000 m^2, representing less than 0.03 per cent of the two concession areas.

Figure 2. The mining method.



Source: BHP-Benguela, 1996.

In the deeper areas a substantial part of the mined sediment is Orange River-derived mud, which may contain significant amounts of organic matter, nutrients, and possibly also trace amounts of heavy metals and pesticides derived from the Orange River catchment. During mining, anoxic sediment tailings will be suspended, and toxic trace metal-contaminants which may previously have been bound in the sediments as metal sulphides, can then enter the dissolved phase.[35] Hence, there may be a risk of heavy metals and or pesticide pollution. Modelled tailings plume concentrations of silt were often about 1000 mg/l in the bottom waters. The background concentrations of Zinc in Orange River-derived sediments is 25.7 ug/g, and in surface sea water off the Orange River 3.7 ug/l.[36] If, for example, ten per cent of the Zinc in the plume enter the dissolved (" phase, this would lead to concentrations of about 29 g/l Zinc in the bottom waters which, would exceed the Water Quality Guidelines for the South African Coastal Zone of the South African Water Research Commission.[37]

Sedimentation simulation

The long-term simulations of sedimentation pattern are done at "normal" (20 cm/s) current conditions. In all simulations, the gravel fraction settled no more than 30 m from the point of disposal. The sand fractions also settled rapidly, with all sand settling no more than 60 m from the point of disposal. Neither the gravel nor the sand fractions should therefore smother the sea bed of unmined areas to any great extent. A substantial part of the silt and clay fractions did not settle out during the simulations, implying that part of these finer fractions is maintained in suspension and transported away as a turbid plume. However, the results of the snapshot simulation (above) imply that the concentrations of suspended solids carried away from the mining area are rapidly diluted to concentrations of the same order of magnitude as natural background values. The smothering effect of these finer fractions is therefore not likely to be significant. A consequence of the coarser fractions remaining within the mined areas, whereas at least part of the finer fractions is carried away, is that mining will not only disturb stratigraphy, but will also cause a change of the particle size distribution of the mined areas' sediment. However, investigations directly south and north of the mining area show that the sea floor above wave base is very dynamic: gravels (diameter 2 mm) are moved at depths of up to 30 m during average wave conditions, whereas medium cobbles (diameter 10.5 mm) may be moved at similar depths during storm conditions.[38]

Consequently, in the shallow ore bodies, the changes in particle size distribution as well as the excavation hollow are likely to be only short-term phenomena. Conversely, in the deeper areas where the ore bodies are covered by a mud drape the excavation hollow and the change in particle size distribution may persist for a longer time.

Table 2. Summary of Monitoring Programme needed to adequately assess the significance of impact of marine diamond mining off the Namaqualand coast

	Parameter	Location	Frequency
Oceanographic Monitoring	Wind	vessel	daily
	Wave	fixed buoy	daily
	Current	fixed buoy	biweekly
	TS-Profiles	vessel and ref. stn's	
Tailings monitoring	BOD	at discharge	sign. change in sed. character
	Particle size dbn	at discharge	sign. change in sed. character
Water quality monitoring	DO (bottom)	vessel and ref. stn's	biweekly
	NO_3 (surface)	vessel and ref. stn's	biweekly
	PO_4 (surface)	vessel and ref. stn's	biweekly
	Turbidity (surface midwater, bottom)	vessel and ref. stn's	biweekly
Sediment monitoring	Particle Size dbn	all ore bodies[1]	before /after mining
	Nutrient content	all ore bodies[1]	before /after mining
	Org. mtrl. content	all ore bodies[1]	before /after mining
	Toxic substances	all ore bodies[1]	before /after mining
Biological monitoring	Macrobenthos	all ore bodies[1]	before/after mining

Note: 1. Monitoring of deeper areas should be prioritised.

Recommendations for environmental management

According to the South African Council for the Environment's policy for coastal zone management, the impacts of marine mining should be monitored, and where possible minimised, especially with respect to suspended sediment levels.[39] Furthermore, the South African Water Research Commission's guidelines state that the extent of the mixing zone (zone of influence or impact) should be kept to a minimum.[40] Following the above recommendations, the objectives of the remainder of the paper is twofold: first to draw up a monitoring programme aimed at increasing the understanding of the natural environment and the impact of mining, and second to provide management guidelines which may help to mitigate the primary environmental impacts of mining: turbidity, smothering and contamination toxicity. These recommendations will focus on the Benguela Concessions' operation but should be applicable, with minor modifications, to most marine diamond operations off the South African coast.

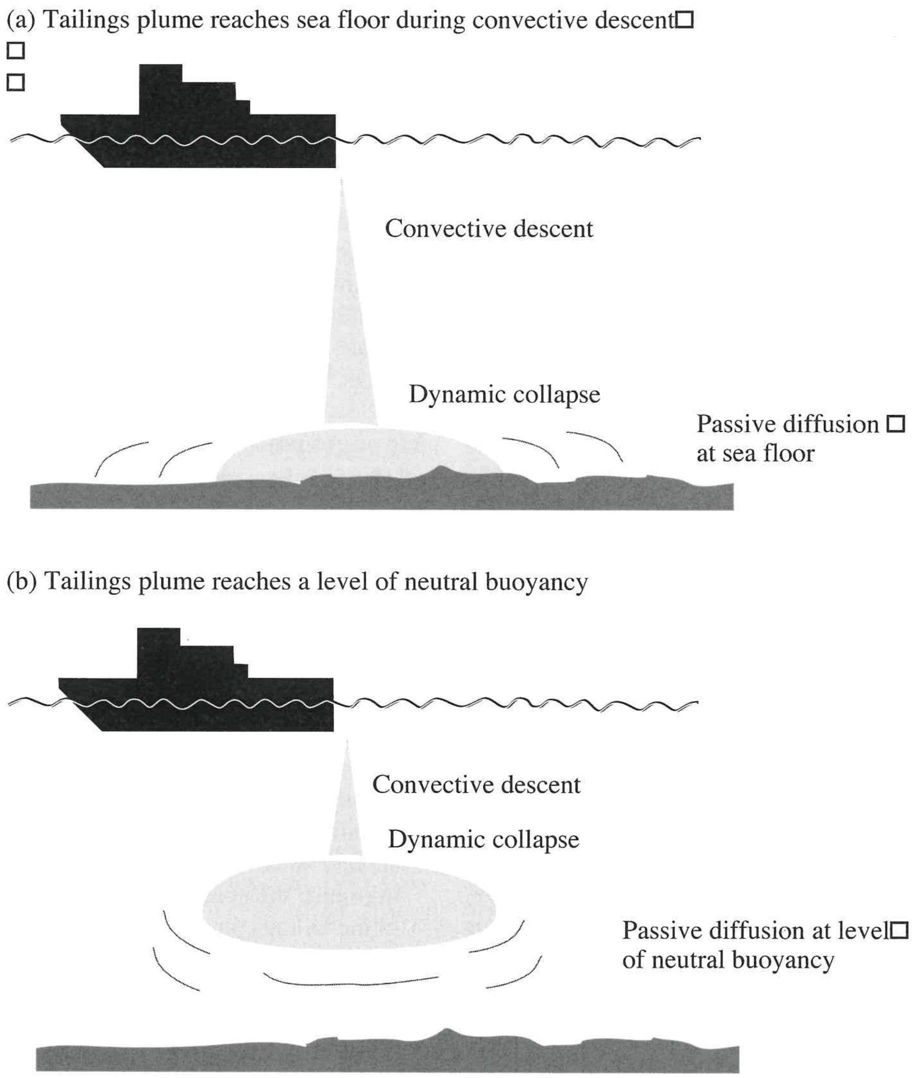
Environmental monitoring

In a variable system such as the Benguela, it may be difficult to separate the impact of mining from that of natural variability, and therefore the collection of base line scientific data against which the significance of impact may be assessed is of vital importance. Consequently monitoring should include pre-mining base line studies as well as the continuous monitoring of critical parameters.[41] It is suggested that monitoring of the various factors listed below should be done from the mining vessel, from a fixed buoy and, from three reference stations. Two of the reference stations should be situated a few kilometres south and north of the mining location and at similar depths, so as to investigate to what extent the influence of the tailings plume is spread northward and southward by the northward surface, and the southward bottom currents respectively. The third reference station should be positioned well away from the mining area (more than 5 km from the vessel), also at a similar depth, so as to investigate natural fluctuations in the parameters that are being measured, and to provide a basis for comparison. Below follows a summary of what should be monitored, and at what frequencies monitoring should be done (see also Table 2).

Oceanographic monitoring

Data on winds, wave heights and periods as well as current regimes are important in allowing rational explanations for events occurring in the ocean environment. These factors may change rapidly and daily monitoring is therefore suggested. Wave and ocean current data can be obtained from a fixed buoy station whereas, an anemometer may easily be installed on the ship. Temperature and salinity profiles should be taken in order to build up a fuller understanding of the water column structure and changes to it. These factors undergo seasonal changes as well as are strongly influenced by periodic upwelling events. Biweekly moni-

Figure 3. Idealised discharge from the mining vessel.



Source: Johnson, 1990.

toring by use of a salinity-temperature-depth sensor at all three reference stations and from the vessel is suggested.

Tailings monitoring

The particle size distribution and water solid ratio of the discharged slurry should be investigated as these strongly affect both the dynamics and concentration of suspended solids, of and in the tailings plume. The biological oxygen demand of the tailings should also be determined regularly. Additionally the possible presence of heavy metals in the Ferrous Silicone used in processing should be investigated. Should initial investigations indicate high concentrations of harmful elements, leaching experiments should be conducted in order to investigate the extent to which these may be available for uptake by biota.

Water quality monitoring

Oxygen concentration in the bottom waters, concentrations of the major nutrients in surface waters (NO and PO), and the concentration of suspended solids throughout the P water column, should be determined both at the three reference stations and at the vessel, so as to monitor natural variations as well as the possible impact of mining. These factors, like temperature and salinity, undergo seasonal changes as well as are strongly influenced by upwelling events. Biweekly monitoring at all three reference stations and from the vessel is therefore suggested. A field study of the spatial dynamics of the tailings plume should be undertaken in order to address the shortcomings and/or validate the modelling approach used in this study. It is suggested that a number of drogues, anchored at different depths, may be used as means of tracking the sediment plume and that concentrations of suspended solids in the plume may then be measured over a period of at least 12 hours.

Sediment surveys

Grab samples of sea bed sediment should be taken before and after mining in order to investigate composition (particle size analysis), organic matter and nutrient content (NO_3, NO_2, NH_4 and PO_4) in order to assess the possibility of oxygen depletion and eutrophication during mining, and to investigate how sediment have changed once mining is completed. Additionally, samples of Orange River-derived mud should be analysed for heavy metals and/or pesticides.

Biological surveys

Biological surveys should be undertaken before and after the mining of an area. Due to the suspicion that deeper areas may rehabilitate more slowly than shallow areas, surveys of the deep areas should be prioritised. A previous study has shown that the analysis of soft-bottom macrobenthos (>1000 um) is a useful way of investigating the biological effects of marine diamond mining.[42] Chemical tests of bivalve tissue may also be undertaken. These filter feeders may magnify small ambient concentrations of heavy metals and pesticides in their tissue, thus giving an early indication of possible contamination and/or toxicity impacts.[43]

Management of the mining operation

The direct removal and disturbance of benthic habitat (i.e. the sea floor) during mining, is unavoidable. Other impacts may, through careful management, be kept at a minimum.

- The practice of discharge tailings at sub surface depth and at pressure (so called Submarine Tailings Disposal or STD) appears to be an effective way of minimising the mixing zone and consequently focuses sedimentation on a smaller area. Additionally, STD will minimise the spatial and aerial extent of the tailings plume and thus limit the potential impact of increased turbidity. In a STD operation, the discharge should ideally be made on the sea floor. Modelling indicates, however, that a discharge at pressure, at no more than two metres below sea level, will produce a rapidly descending tailings jet, and thus reduce the size of the mixing zone, as well as limiting the smothering of unmined areas.
- The results of the monitoring programme should continuously be scientifically analysed and the findings used, whenever possible, to improve the environmental management of the mining operation
- It is important to ensure that an area is mined out during one single visit as the recolonisation of benthic fauna and flora adversely affected by mining can then proceed uninterrupted.
- Should the monitoring programme reveal that during conditions of especially strong currents, significant areas of the sea floor are smothered, mining under those conditions should be curtailed.
- Should the analysis of the trace chemistry of Ferrous Silicone reveal significant concentrations of harmful events, the flushing of Ferrous Silicone into the sea during processing should be minimised.

Conclusion

This study indicates that the most significant impacts of marine diamond mining on the physical environment are likely to be:

- Direct disturbance of sediments caused by excavation
- Increased turbidity,
- Seabed smothering,
- Changed particle-size distribution of mined areas due to the selective entrainment of fine sediment fractions.

Additionally, eutrophication, oxygen depletion, and contamination and toxicity effects due to the suspension of nutrients, organic material and heavy metals and or pesticides may be of importance when mining ore bodies overlain by Orange River-derived mud. The potential for oxygen depletion of the water column must be regarded as being of particular concern because of the naturally low levels occurring in the area. The combination of these naturally low levels and further reduction through mining could be damaging to the environment. The long-term impact of mining is dependent on sediment dynamics of the sea floor, hence the depth at which mining is done. In shallower areas, where the sea floor is in a natural state of change due to wave induced sediment transport, the impact of mining is not likely to be severe. Conversely, below wave-base the impact of mining is more likely to persist. Numerical modelling of the tailings plume indicate the following:

- A tailings discharge at sub-surface depths and at pressure will greatly increase the rate at which the sediment settles to the sea floor, whereas disposal discharge above the sea surface will lead to a slower rate of settling. Sub-surface tailings disposal will consequently limit the extent of the mixing zone (the area of impact) as well as limit the area affected by the tailings disposal.
- The maximum concentration of suspended solids (turbidity) reached in the upper water column will be between 50–100 mg/l. Close to the sea floor maximum concentrations are predicted to vary between 1 000 to 10 000 mg/l. Concentrations of suspended solids are affected by the sediment composition of the mined material, the ambient current regime and the depth of mining.
- During mining, the sediment plume-mixing zone, if defined as the area with a loading of TDS of more than 10 mg/l, is predicted to be less than 300 x 300 m.
- During normal current conditions, the gravel and sand fractions will settle within 60 m of the point of disposal. The silt and clay fractions will, to a greater extent, be carried away from the mined areas, corroborating the conclusion that the particle size distribution of the mined sediments will change. The results of this study indicate that marine diamond mining at the scale investigated should not have a major impact on the physical environment. However, due to the lack of data on the pre-mining and eventual post-mining environments, further work needs to be done to properly assess the significance of the impacts that are identified. By following the recommendations for Environmental Management and Monitoring, the impacts of the marine diamond mining operations will be kept to a minimum, and valuable data will be obtained that may improve the understanding of these impacts.

Notes

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1. Lundin and Lunden, 1993; Els, 1995; Viles and Spencer, 1995; Clark, 1996
2. Miller, 1995
3. Bartlett, 1987; Robinson, 1994; Miller, 1995
4. Robinson, 1992
5. Crawford et al., 1987; Armstrong and Thomas, 1989; Barkai and Bergh, 1992
6. Jackson and Lipshitz, 1984
7. De Decker, 1986
8. Rogers, 1977
9. e.g. see Kirkley et al., 1992 for a review
10. De Decker et al., 1991
11. De Decker et al., 1991
12. Shannon, 1985
13. Crawford et al., 1987; Jury, 1991; Shannon and Anderson, 1982
14. Stander, 1964; De Decker, 1970; Chapman and Shannon, 1985; Dingle and Nelson, 1993
15. De Decker, 1970; Nelson, 1989
16. Branch and Griffiths, 1988
17 De Decker, 1986
18. e.g. Blomqvist, 1982; Persson, 1983; Naturvårdsverket, 1985; Ellis, 1987; Charlier and Charlier, 1992; Hobbs, 1993; Gajewski and Uscinowicz, 1993; Ellis et al., 1995; Garnet and Ellis, 1995
19. Ellis, 1987
20. Ellis, 1987
21. CMS, 1994; CSIR, 1995 and Savage, 1996
22. BHP-Benguela, 1996
23. Dr. S. Smith (MD Benguela Concessions Ltd.), personal communication
24. Dr. S. Smith (MD Benguela Concessions Ltd.), personal communication
25. BHP-Benguela, 1996
26. BHP-Benguela, 1996
27. BHP-Benguela, 1996; Woodborne, 1987
28. Rogers and Bremner, 1991; De Decker, 1986
29. Rogers, 1977; Rogers and Bremner, 1991; De Decker, 1986
30. e.g. CMS, 1995 and CSIR, 1995
31. Johnson, 1990
32. Dr. P. Shroeder (US Army Engineers Waterways Experiment Station), personal communication
33. Johnson and Holliday, 1978
34. G. Bailey (Sea Fisheries Research Institute in Cape Town), personal communication; Zoutendyk, 1995
35. Libes, 1992
36. Chapman and Shannon, 1985
37. Water Research Commission, 1992
38. De Decker, 1986; Woodborne, 1987
39. Council for the Environment, 1991
40. Water Research Commission, 1992
41. Ellis, 1987
42. Savage, 1996
43 Libes, 1992

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