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Using diamond-mined sediment discharges to test the paradigms of sandy-beach ecology

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ABSTRACT

The prevailing view of sandy-shore ecosystems is that they are controlled largely by physical conditions, particularly particle size, slope and wave regime, but it is rarely possible to test this view by experimentally manipulating these attributes. We report a unique opportunity to accomplish this because large-scale alteration of these properties has taken place on the Namibian coast, associated with diamond mining. Elizabeth Bay diamond mine, near Lüderitz, started modern operations in 1991. Since then, 30.8 million tonnes of sediment with a particle size (<1.4 mm) coarser than the native beach sand have been discharged as slurry onto the beach as part of the treatment process. The physical and biological effects of this were monitored on seven occasions between 1993 and 2012, spanning three phases: (1) an initial pre-upgrade phase (1994–2004) with discharges of moderate intensity; (2) doubling of discharges during upgrade of the mine (2005–2008); (3) temporary cessation of mining (2009–2011). These vicissitudes resulted in both spatial and temporal physical changes, including massive beach accretion (350–620 m), overall increases in mean sand particle size and slope and decreases in Dean's Parameter, east-to-west gradients in beach slope, wave height and erosion, and changes in the beach state from dissipative towards reflective conditions. Alteration of physical conditions led to significant macrofaunal changes, with the community structure in the centre of the bay opposite the discharge points shifting from a state dominated by sand mussels to one dominated by peracarid crustaceans, accompanied by reductions in diversity, biomass and abundance. Grossebucht, which lies nearby and is not mined, provided comparative reference samples: physical conditions there changed little, and biotic communities were constant, significantly more diverse and had greater abundances and biomasses than at Elizabeth Bay. The changes in physical conditions and ensuing biological responses confirmed the prevailing paradigm that sandy beaches are physically driven, with diversity, abundance and biomass all declining at places and times where sediment particle size and beach slope increased due to sediment inputs.

1. Introduction

A central paradigm of sandy beach ecology is that the composition, biomass and abundance of the fauna are dictated largely by physical conditions, rather than being biologically controlled (McLachlan et al., 1993; Defeo and McLachlan, 2005). Evidence for this comes largely from comparative and correlative studies because it is rarely possible to experimentally manipulate physical attributes on a scale appropriate to testing this paradigm. In this paper we report the long-term effects of altering the physical properties of a sandy beach due to large-volume deposition of sediments associated with diamond mining on the coast of Namibia. These operations constitute a unique opportunity to explore the responses of beaches and their infauna to artificial manipulation of the habitat equivalent to a large-scale experimental perturbation.

Worldwide, sandy beaches are subject to a range of anthropogenic impacts, including recreational activities, beach grooming, pollution, harvesting, introduction of alien species, coastal development and engineering, mining and climate change (reviewed by Brown and McLachlan, 2002; McLachlan and Brown, 2006; Defeo et al., 2009). More specifically, coastal and marine diamond mining, which is of central importance for the economy of southern Namibia, has unavoidable ecological consequences. To investigate the long-term effects of mining on physical conditions and

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invertebrate macrofaunal communities, the responsible mining company, Namdeb Diamond Corporation, launched a coastal biological monitoring programme at Elizabeth Bay (south of Lüderitz), where intense terrestrial mining has been associated with the release of waste sediments that are discharged onto the beach.

The beach was first sampled in 1993 and 1994 (McLachlan, 1996), and our paper analyses six periods of monitoring, covering 1994–2012, to evaluate the effects of these sediment discharges on the physical and biological conditions. The discharged sediments are termed 'fines', but in reality are coarser than the native beach sands and, because of the enormous volumes involved, have accreted the beach substantially, and altered the particle size, slope and wave climate. Over the course of this study, the intensity of mining (and therefore discharges) fluctuated with operations passing through three phases. In the initial (pre-upgrade) phase up to 2004, mining took place at moderate intensity, but following an upgrade of the mine, discharges doubled in 2005–2008, before ceasing in 2009–2011 because of the global economic downturn. We could therefore examine physical and biological responses under these three different intensities of mining, and compare them with those at a control site where no mining takes place.

Although primarily designed to assess the impacts of diamond mining on the Elizabeth Bay beach, the data constitute a powerful means of examining current concepts about the operation of sandy beaches and the ways in which the composition, structure and diversity of biotic communities are dictated by physical conditions. A such, they address what Defeo et al. (2009, p. 1) identify as a top priority in their review of threats to sandy beaches, namely "long-term field experiments and monitoring programmes that quantify the dynamics of key ecological attributes on sandy beaches".

Our sampling was designed to test the following hypotheses. (1) Deposition of sediments would accrete the beach and lead to coarser particle size, steeper slope and more reflective conditions. (2) Abundance, diversity and biomass of the macrofauna would diminish in response. (3) Intensification of deposition would increase and spread these effects, while cessation would lead to recovery of both physical and biological conditions towards the original states.

2. Methods

2.1. Study area

Elizabeth Bay (Fig. 1) is one of only three log-spiral bays on the arid southern Namibian coastline. Such bays act as deflation zones for sands and gravels being redistributed northwards along the coastline by swell-induced littoral drift (Rogers and Bremner, 1991; Corbet, 1993). At Elizabeth Bay, the annual transport of natural sediments of Orange River origin through the south eastern corner of the bay is about 1.4 million tonnes (CSIR, 2001). Aeolian deflation forms diamondiferous deposits relatively close to the surface, which are accessible through open-cast mining. In 1924, the first recovery plant was erected at Elizabeth Point, but ceased operations in 1948 (Schneider and Miller, 1992). Interest revived in the 1980s, and the current Elizabeth Bay Mine opened in 1991.

Processing both terrestrial and marine diamondiferous ores involves separation of the undersized tailings or 'fines' (particles <1.4 mm), which constitute 70–75% of the processed sediments, and which are discharged onto the beach as a sediment-slurry. The discharged material has a median grain size of 150–900 μm, and a clay proportion of 0.2–6.0%. The finer components disperse offshore in turbid plumes while the coarser fractions accrete on the beach.

The history of mining and volumes of discharges are summarised in Table 1. Important highlights include upgrade of the processing plant in 2004, and cessation of discharges in April 2009. Mining operations began again in 2012, and although tailings discharges had not yet resumed, a seawall of overburden material stripped from the back beach was under construction near the eastern corner of the bay, cutting off tidal coverage of the upper beach to allow mining in its lee.

Elizabeth Bay is south-facing and about 4.5 km in length, with a rocky promontory, Elizabeth Point, forming the western arm. Rocky shores flank the eastern shoreline. Historically, the beach was fine grained, ranging from low-energy dissipative in the sheltered western corner, through medium-energy intermediate to high-energy intermediate in the centre of the beach, and high-energy dissipative at the eastern end of the bay (McLachlan, 1996). Grossebucht (Fig. 1) lies outside the Elizabeth Bay Mining Licence Area, and served as a comparative 'reference' area as it has never been mined, and experiences only limited disturbance in the form of vehicles gathering kelp wrack. Grossebucht is similar to Elizabeth Bay in being a south-facing bay, but is smaller (1.5 km long) and well-protected behind a rocky point to the west, and consequently experiences lower wave energy than Elizabeth Bay.

2.2. Sampling

Sampling began in 1993 with surveys of a southern and a central site in Elizabeth Bay (McLachlan, 1996). In 1994, sampling expanded to include three more sites in Elizabeth Bay, and two reference sites at Grossebucht. Subsequent surveys took place in 2004 (prior to the upgrade of the mine), 2008 (at the time of peak mining), and in 2010, 2011 and 2012 (after mining and deposition of fines were suspended). Mining activities resumed in 2012, in the form of seawall construction in the eastern corner of the bay near site E2. Sampling sites were located in approximately the same locations each time, but as Elizabeth Bay beach had accreted substantially since the initial surveys, positions were adjusted offshore accordingly. Sampling was restricted to Autumn (March–April) to avoid potential seasonal differences. Fig. 1 and Table 1 summarise sampling years and localities.

Data on beach accretion 1990–2010 were derived from unpublished surveys by the South African Council for Scientific and Industrial Research (CSIR) and WSP Coastal Engineers. Beach gradient, particle size, wave height and frequency (which are used to define beach morphodynamic state) were measured or sampled within half an hour of low tide at each sampling site. Effluent-line crossings and surf-zone width were also measured (though not reported in the paper), and used to determine exposure rating (McLachlan, 1980).

During each sampling event at each site, the following physical and biological data were collected. Surface sediment samples (250 ml) were collected from the high, mid and low shore (respectively Stations 1, 5, and 10 – see below), and dry sieved and weighed to determine sedimentary composition. GRADISTAT Version 4 (Blott and Pye, 2001) was used to calculate mean particle diameter, settling velocity, sorting and skewness. Wave height (m) was visually estimated as the maximum height difference between the wave trough and the highest point before spilling over. Beach morphodynamic state was assessed using Dean's Parameter (Ω), calculated as $\Omega = H_b/(T_b \times W_s)$, where H_b is the wave height (cm), T_b the wave period (s), and W_s the sand fall velocity (cm s^{-1}). Beach width was measured as the distance (m) between the low tide waterline and the drift line. Beach gradient was calculated as the height difference between the first and last sampled stations (h) divided by the beach width between them (w): h/w, expressed as a decimal. Exposure Index was calculated according to McLachlan (1980) on a 20-point scale spanning 1 (very sheltered) to 20 (very exposed).