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Effects of sediment discharge from Namibian diamond mines on intertidal and subtidal rocky-reef communities and the rock lobster *Jasus lalandii*

Andrea Pulfrich [a,b,*], George M. Branch [a]

[a] Marine Research Institute, Zoology Department, University of Cape Town, Private Bag, Rondebosch 7701, South Africa
[b] Pisces Environmental Services (Pty) Ltd, PO Box 31228, Tokai 7966, South Africa

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ABSTRACT

Extensive terrestrial diamond mining occurs on the southern coast of Namibia, and at Elizabeth Bay near Lüderitz sediment tailings totalling about 2 million tons.yr^{-1}, have been discharged onto the beach. We report here on monitoring spanning 2004–2012 to assess (1) the impacts of increased tailings discharges following an expansion of the mine in 2005, and (2) recovery after discharges halted in 2009. Sampling covered three levels of wave exposure, and compared impacted sites with comparable unmined reference sites. Benthic communities were quantified on both intertidal and subtidal reefs, and kelp densities and rock-lobster abundances, lengths and sex ratios on subtidal reefs.

Prior to intensification of mining, deposition of tailings significantly influenced intertidal communities only at sheltered localities where wave action was insufficient to disperse them. Following the mine expansion, effects spread to both semi-exposed and exposed sites. After mining was suspended, recovery of the biota was limited, even three years later.

Reductions of intertidal diversity and grazers, proliferation of macroalgae, and increased dominance by filter feeders were recorded at the impacted sites and were persistent, but the affects of wave exposure on community composition generally exceeded those of mining discharges.

On subtidal reefs, tailings deposition reduced predators and grazers, increased filter feeders and ephemeral green algae, and decreased all other algae, possibly driven by light reduction due to plumes of suspended fine sediments. Increased discharges post-2005 also substantially influenced bathymetry, wave and current regimes, transforming 2 km of previously wave-exposed rocky coastline into a semi-exposed sandy beach. Tailings discharge appeared to influence community composition in four ways: (1) inundation and blanketing; (2) increased suspended particulate materials; (3) indirect top-down ripple effects, and (4) light reduction.

Throughout the period 2004–2007, tailings-deposition had no detectable effects on the sex ratio, sizes or density of rock lobsters, but following suspension of mining activities, densities in 2010–2012 at impact sites exceeded those at reference sites. High natural variability in the abundance of rock lobsters may mask mining impacts, but the data strongly indicate an absence of any negative effects on rock lobsters.

1. Introduction

How ecosystems respond to physical disturbance is of central interest in determining both human impacts and how natural ecosystems operate (Littler et al., 1983; McLachlan, 1996; Airoldi, 2003). In this paper, we report on physical disturbance of rocky reefs in the form of sediment deposition associated with diamond mining in Namibia.

At Elizabeth Bay, 30 km south of Lüderitz, diamonds have been mined since 1908. Current activities began in the 1980s, and Elizabeth Bay Mine opened for full operational production in 1991 (Schneider and Miller, 1992). Mining involves the removal of overburden, and sedimentary tailings resulting from diamond extraction are pumped onto the beach through a large-diameter pipeline as a slurry, which carries suspended particles with a

* Corresponding author. Pisces Environmental Services, PO lBox 31228, Tokai 7966, South Africa.
E-mail addresses: apulfrich@pisces.co.za, andrea.pulfrich@gmail.com (A. Pulfrich).

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median grain size spanning 150–900 μm, and a clay content of 0.2–6.0%. The discharged tailings comprise two components: a finer component that remains suspended and disperses offshore in turbid water plumes, and a coarser fraction that accretes on the beach and adjacent rocky shores, advancing the shoreline, particularly around the discharge point. The concentration of accretion at a single point has been mitigated by the introduction of alternative discharge points, smoothing the impacted shoreline to resemble its original form (McLachlan, 1996). The coarse and fine fractions that are discharged are collectively termed 'fines' in mining terminology, but we employ the word 'tailings' to avoid confusion with the geological connotation of 'fines', which relates to silt and clay (Warrick, 2013).

When Elizabeth Bay Mine was commissioned, the Namibian Ministry of Fisheries and Marine Resources expressed concerns about the possible impacts of increased turbidity and tailings deposition on living marine resources in the area, particularly the commercially-harvested rock lobster *Jasus lalandii*. In response, a coastal biological monitoring programme was launched to examine the long-term effects of the tailings-deposition on the composition of rocky intertidal and subtidal communities in the vicinity of Elizabeth Bay and on the rock-lobster population. Because wave action profoundly influences the composition and dynamics of rocky reefs (Menge, 1978; Denny, 1988; Bustamante and Branch, 1996a,b; Blamey and Branch, 2009), comparisons were made at three levels of wave action, always ensuring that reference and impact sites were matched at equivalent wave intensities. Monitoring began in 1993 and was initially conducted annually until it was suspended in 1998, and by that stage revealed that the biotic communities of rocky intertidal habitats within Elizabeth Bay were strongly impacted at sheltered sites, less so at semi-exposed sites, and negligibly at exposed sites (Pulfrich et al., 2003a).

The processing plant at Elizabeth Bay was expanded in 2004 and went into full production in June 2005. The expansion increased the annual discharge of tailings from 1.6 million tons in 2004 to 2.3–2.9 million tons in 2007–2008. In April 2009, in response to the global economic downturn, mining activities were placed on hold, and no discharges took place from March 2009. To determine the effects of the mine expansion and record any recovery after cessation of discharges, monitoring was resumed in 2004, and has since spanned low-intensity discharges during pre-expansion conditions (2004–2005), intensified tailings deposition during the expansion (2006–2008), and post-mining responses (2009–2012). This paper summarizes the results of this monitoring.

There are four potential influences of tailings deposition on rocky-substratum communities, which depend on whether one is considering the coarse deposited fraction or the fine suspended element: (1) blanketing by the coarse fraction, which directly depletes all or some groups, reducing community diversity; (2) alteration of supplies of both coarse and fine particulate materials with potential effects on suspension-feeders; (3) ripple effects in which depletion of higher trophic levels would influence lower trophic levels; (4) diminution of light by suspended fine materials, with effects on subtidal primary producers. On the grounds of two fundamental ecological concepts, namely the effects of disturbance on community diversity (Connell, 1978) and top-down ripple effects vs. bottom-up supply-driven control of community composition (Menge and Branch, 2001), we advanced six hypotheses about the effects of mining-related sediments on intertidal and subtidal communities. First, we predicted that the discharge of higher volumes of tailings into the sea at Elizabeth Bay would alter hydrodynamic conditions, increasing beach accretion (as predicted by CSIR, 2002). Second, the net effects of tailings were predicted to reduce species richness and diversity. Third, we forecasted that species at top trophic levels (predators and grazers) would decline, leading to an increase in intertidal ephemeral foliose algae, in turn causing a decline in encrusting algae; that filter feeders would increase due to the enhancement of suspended materials, and that subtidal algae would decline due to a reduction in light penetration. Fourth, as discharges intensified with the mine expansion, escalation and spread of mining effects were expected. Fifth, the magnitude of wave effects on intertidal community composition was anticipated to exceed that of discharges. Conversely, after the suspension of mining in 2009, amelioration of discharge effects was forecast. Lastly, based on past surveys (Pulfrich et al., 2003a), the tailings-discharges were expected to have no negative affect on rock lobsters. These hypotheses were advanced *a priori* and tested with the data. However, an additional mechanism emerged during the study that we had not anticipated, namely habitat conversion at a landscape scale from rocky communities into completely sand-inundated shores.

The deposition of tailings constitutes a manipulation of sediment budget on an extraordinary scale, and is of broader interest than just the effects of mining discharges, because it allows a general exploration of the responses of rocky shore communities to physical disturbance.

2. Materials and methods

2.1. Study area

Elizabeth Bay comprises a 4-km long beach, with a rocky promontory, Elizabeth Point (located at the E-Bay Point sites in Fig. 1), flanking the western arm, and rocky shores backed by sand dunes forming its eastern shoreline. To the north, the coast predominantly comprises rocky shores exposed to strong wave action, punctuated by numerous small bays and sandy beaches (Fig. 1).

Persistent southerly to south-easterly winds produce coastal upwelling, and the strongest upwelling cell on the entire west coast is centred off Lüderitz (Shannon, 1985). Inshore waters are naturally turbid (CSIR, 1998), with levels of particulate inorganic matter covering 5–20 mg l^{-1}. The Orange River, 230 km south of Elizabeth Bay, contributes substantially to the coastal sediment budget, with a mean annual input of ~17 million tons, but episodic floods boost this to 64 million tons (Bremner et al., 1990). Northward littoral drift transports an average of 0.45 million tons per annum into Elizabeth Bay (Smith et al., 1994).

2.2. Survey approaches

No pre-mining baseline data exist for the rocky shore communities in Elizabeth Bay, but two pre-expansion surveys (2004 and 2005) made it possible to collect a form of 'Before-After' data as proposed by Green (1993) and Underwood (1993). In this case, however, the 'baseline' environment in the bay was already impacted by existing mining perturbations, and does not constitute a pristine condition. Because of this, comparisons with non-impacted 'reference' sites (equating to 'controls'), matched to ensure equivalent levels of wave exposure, were the most valid means of assessing impacts.

Impacted and reference sites were chosen to span (a) exposed shores on the open windward side of rocky headlands, (b) semi-exposed shores, also on the open coast but protected by extensive forests of the kelp *Laminaria pallida* that buffer waves, and (c) sheltered shores, protected from direct wave action because of their position in bays on the leeward side of headlands. Independent validation of the categorisation of wave intensity appears in Blamey and Branch (2009).

Eight intertidal sites were surveyed. In Elizabeth Bay, two sheltered sites (North Jetty and South Jetty), one semi-exposed site