# SPECIALIST STUDIES – SECTION C

# C2.7 Plankton Report

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### **1** INTRODUCTION

The environmental effects of dredging marine pelletal phosphate on the Namibian continental shelf have been investigated and included in a previously conducted Environmental Impact Assessment (NMP, 2010). Received comments on this *inter alia* pointed out that insufficient attention had been paid to zooplankton and ichthyoplankton that occupy the area. To address this, a literature review of the available information pertaining to plankton in the central Namibian region was commissioned by NMP to summarise the existing knowledge on the distribution and biology of these groups.

The proposed mining area is situated within the Benguela upwelling system off Namibia on the west coast of Africa. The Benguela is a unique system and is one of the most dynamic and productive ecosystems in the world, playing a major role both ecologically and economically in Namibia. It supports a large suite of species, including phytoplankton, zooplankton and ichthyoplankton, that all play an important role in the trophic dynamics of the region, supporting important fish resources. The purpose of this review is to provide information on the suite of phytoplankton, ichthyoplankton and zooplankton species and ecology in the northern Benguela Current continental shelf waters encompassing the proposed mining site off central Namibia.

## 2 PROJECT DESCRIPTION AND REGIONAL OVERVIEW

A detailed project description with all relevant technical data is provided in the general EIA. Below is a brief summary of the proposed mining project.

The Mining Licence Area (MLA) is located approximately 60 km offshore of the central Namibian coast (Figure 1). Within the MLA, there are two initial target sites. SP-1 is the primary target site where dredging will commence, and is located in the north of the MLA. It covers an area of 172 km<sup>2</sup>, in water depths of 190-235 m. SP-2 is the same size as SP-1, but lies further south and slightly further offshore in water depths of 245-285 m. A further candidate area has been identified (SP-3), which is 88 km<sup>2</sup> in extent in water depths of 235-270 m.



showing surface and near-surface currents, frontal zones, upwelling cells, major areas of freshwater input and bathymetry. The dashed blue ellipse indicates the study site off central Namibia, and the solid red ellipse indicates the position of the Mining Licence Area (MLA). (SEC = South Equatorial Current; BOC = Benguela Oceanic Current; BCC = Benguela Coastal Current; SAC = South Atlantic Current; AgC = Agulhas Current; ABF = Angola-Benguela Front; STG = subtropical gyre; ACC = Antarctic Circumpolar Current) (Redrawn from Hardman-Mountford *et al.* 2003).

The main oceanographic features of the study area are shown in Figure 1. The oceanographic environment in the south east Atlantic, off the west coast of southern Africa, is dynamic and in many ways, unique, where it is primarily defined by the Benguela Current (including the Benguela Oceanic Current and the Benguela Coastal Current). As already explained in detail in the EIA report and related appendices, the Benguela Current flows equatorward and is one of the four major eastern boundary currents of the world, forming the eastern boundary of the South Atlantic subtropical gyre (e.g. Weeks *et al.* 2004). It extends from Cape Agulhas (35°S) to approximately Namibe, Angola (15°S) out to a depth of approximately 500 m off the west coast of southern Africa. As with other eastern boundary currents, it is dominated by the occurrence of coastal upwelling, generated by equatorward winds causing the offshore (Ekman) transport of surface water. It is unique in that it is bordered by warm water systems in both the northern and southern regions - the Angola Current system in the north and the Agulhas Retroflection area in the south (Shannon 1985). Another

characteristic of the Benguela Current region is the extensive and for the most part, permanent oxygen minimum layer at 100 – 500 m depth (Ekau and Verheye 2005).

The Lüderitz upwelling cell, which may be the strongest, perennial, locally wind-driven, coastal upwelling region of any region in the world lies between 27°S and 24°S (Figure 1) (Hardman-Mountford *et al.* 2003). The upwelling at this site is strong throughout the year, but a short quiescent period can occur during autumn and a slight maximum can occur during spring (Shannon and Pillar 1986). Although this feature is spatially and temporally variable, it effectively divides the Benguela Current system into southern and northern regions (Shannon 1985). The central Namibian sub-region, between Lüderitz and Walvis Bay, forms a transitional zone between the Lüderitz upwelling cell and the northern Benguela, and is characterized by slightly lower upwelling intensity than that off the coast of Lüderitz (Shannon 1985). It is this region that is the main focus of this review and forms the study area, as the prospective mining site is located on the northern edge of the Lüderitz upwelling cell, south of Walvis Bay, between 24.1° and 24.3°S latitude (Figure 1).

# **3 BIOLOGICAL OCEANOGRAPHY**

#### 3.1 SEASONALITY

#### 3.1.1 Phytoplankton

Off the coast of Lüderitz, there is a plentiful supply of nutrients to the surface waters, due to the perennial occurrence of intense upwelling causing water column mixing where the nutrient rich bottom water is brought to the surface. However, light is a limiting factor in the growth and production of phytoplankton, as the intense upwelling also results in the surface water replacing the bottom water. Phytoplankton cells are removed from the surface waters and therefore are not within the euphotic zone long enough to photosynthesize and create production. This results in low biological productivity in the vicinity of the Lüderitz upwelling cell and a reduced seasonal signal in this productivity, where a constant chlorophyll-*a* minimum is recorded in this area (Shannon *et al.* 1984; Demarcq *et al.* 2007).

Further north, on the northern border of the Lüderitz upwelling cell, there is a decrease in upwelling intensity, which results in more developed seasonality in the temperature of the water and the formation of thermoclines in the upper water column, with an increase in stratification in autumn (February to March) (Hardman-Mountford *et al.* 2003). This increases biological production. The seasonal effect in water temperature is reinforced by the seasonal warming of the northern Benguela waters during autumn due to the intrusion of equatorial waters, and is especially prominent in the areas on the northern boundary of the Lüderitz upwelling cell (Campillo-Campbell and Gordoa 2004). This seasonality in the physical conditions is reflected in the seasonal fluctuations in phytoplankton biomass (Figure 2).



Figure 2: Latitude by month plots of (a) sea surface temperature and (b) surface chlorophyll-*a*. The plots show a) Coastal sea surface temperature(°C), where the width of the coastal strip is considered to be 20 km and b) Coastal surface chlorophyll-*a* (mg.m<sup>-3</sup>), where the width of the coastal strip is considered to be 50 km. The two red lines indicate the northern and southern boundaries of the proposed phosphate mining site off central Namibia. (Redrawn from Harman-Mountford *et al.* 2003)

The Mining Licence (ML 170), located at 24.0°S to 24.5°S latitude, should experience low surface water temperatures and low phytoplankton biomass in the austral winter/spring with both metrics increasing in the summer/autumn period. Biomass and productivity is generally higher and more extensive in the late summer and autumn months, when there is a reduction in upwelling and an increase in thermocline development, and thus sufficient nutrient and light availability. In

continental shelf waters north of 25°S, highest chlorophyll-*a* concentrations were found to occur from November through to March (Campillo-Campbell and Gordoa 2004). The increase in chlorophyll-*a* concentration was coupled with a seasonal increase in the offshore extent of the phytoplankton distribution (Demarcq *et al.* 2007). Offshore of Walvis Bay in particular, an increase in chlorophyll-*a* concentrations occurs between January and May, with a peak occurring in May during intermediate upwelling activity (Shannon *et al.* 1984). During this period, phytoplankton biomass increases significantly in the beginning of the quiescent phase when nutrients are readily available, and then stabilizes as nutrients are utilized and become more limited.

During periods of increased upwelling in winter and early spring, from June to September, chlorophyll-*a* concentrations are reduced (Campillo-Campbell and Gordoa 2004; Demarcq *et al.* 2007). Phytoplankton concentrations are particularly reduced in September (Shannon *et al.* 1984).

Overall, a strong seasonal signal in terms of phytoplankton biomass and distribution, with an increase during the summer and early autumn months, off the coast of central Namibia has been shown. This is strongly related to certain physical parameters, where the upwelling present in the region plays an especially important role. More than one peak in chlorophyll-*a* concentration during these months may occur.

#### 3.1.2 Zooplankton

The short-term temporal variation in zooplankton distribution is linked to the availability of phytoplankton prey and so is related to the hydrographic conditions within the area (Shannon and Pillar 1986). The area off the coast of Lüderitz is characterized by the presence of perennial upwelling, while the area slightly further north, off the coast of Walvis Bay, is characterized by a more seasonal occurrence of coastal upwelling (Verheye et al. 1992). In this area and extending north of Walvis Bay zooplankton biomass has been found to peak during more quiescent periods from December through to May (Shannon and Pillar 1986; Verheye et al. 1992), coinciding with maximum phytoplankton production. More specifically, Unterüberbacher (1964) identified two peaks in zooplankton biomass in the Walvis Bay region: a primary peak occurring during summer from November to December, and a secondary peak occurring in autumn from March to June. Hansen et al. (2005) looking at the abundance of the dominant copepod species off Walvis Bay, reported similar distributions with the four most abundant copepod species (Metridia lucens, Calanoides carinatus, Rhincalanus nasutus and Centropages brachiatus) displaying a primary peak in abundance between October and December, and a minimum during September. This pattern appears to extend to euphausiids where highest abundances have been reported between January and March (Barange and Stuart 1991).

These seasonal patterns are however complicated by interspecies differences, changes in distribution patterns in response to upwelling, as well as some interannual variability. Timonin *et al.* (1992) found the seasonal variation in zooplankton biomass to have a spatial element. During quiescent conditions, zooplankton biomass increased further offshore on the shelf-break, while during and immediately after upwelling, zooplankton biomass increased closer inshore. In the study conducted by Hansen *et al.* (2005) from February through to December 2000, although the above mentioned seasonal patterns were shown for most copepod species, there was also a spatial element to the pattern, with inshore and offshore zones showing changes in species composition during active upwelling and quiescent phases. In contrast, Barange and Stuart (1991) found the

distribution patterns of the predominant euphausiids off Walvis Bay to remain relatively constant throughout the years from 1982 to 1984.

Overall, a seasonal signal in zooplankton biomass in central Namibian waters is apparent, and may be linked to seasonal variations in upwelling and phytoplankton availability. This pattern however has a spatial element for certain species, with higher zooplankton abundance occurring during quiescent phases further offshore, and increased zooplankton production during and immediately after active upwelling within inshore waters. To a certain extent, there may also be an interannual difference in the seasonality patterns displayed by zooplankton communities. Further south off the coast of Lüderitz, where the upwelling is more perennial, and there is less phytoplankton production and therefore less food availability, little seasonality in zooplankton biomass or distribution has been demonstrated.

#### 3.1.3 Ichthyoplankton

The productive waters off the coast of Namibia support many fish species, some of which are commercially important, supporting large pelagic and demersal fisheries within the area (O'Toole 1977a; Crawford *et al.* 1987). Ichthyoplankton, or the eggs and larvae of fish, form a relatively minor component of the plankton assemblage within Namibian waters but are an important consideration in light of the large commercial fisheries. Information on ichthyoplankton allows for information on spawner biomass or recruitment to be extrapolated, and for ecological processes related to the fisheries to be investigated (Shannon and Pillar 1986).

As a result of the commercial importance of the fish stocks off the coast of Namibia, regular cruises have been conducted within the area since approximately the 1970s. These include the SWAPELS cruises that were conducted between 18 and 24°S, collecting quantitative information on the eggs and larvae of commercially important species such as anchovy and sardine (O'Toole 1977a; Shannon and Pillar 1986), and in recent years, these cruises have been augmented with a variety of other investigations in the same area, including surveys conducted by the Ministry of Fisheries and Marine Resources, Namibia (MFMR) (Lange 20013), as well as other ad-hoc research surveys (e.g. Olivar *et al.* 1992; Stenevik *et al.* 2001; Ekau & Verheye 2005; Giest *et al.* in press).

As with phytoplankton and zooplankton communities, the occurrence of intense coastal upwelling off the coast of Namibia has a large implication for the ichthyoplankton community present in the area (O'Toole 1977a). The seasonality that this upwelling displays, particularly further north where the influence of the perennial Lüderitz upwelling cell is less prominent, has an influence on the spawning habits of fish species in the area (Shannon and Pillar 1986). A seasonal signal in ichthyoplankton abundance and distribution off central to northern Namibia is thus shown.

Olivar (1987) conducted a study off the coast of central and northern Namibia, where *in situ* data on ichthyoplankton were collected during three cruises completed between 1979 and 1981. During these cruises, samples were collected off Walvis Bay, at approximately 23°S, slightly further north than the MLA. The data collected were compared between cruises, where some were conducted during the occurrence of intense upwelling, and others were conducted during quiescent periods. This allowed for the effect of upwelling, and by extension the seasonal effect, on ichthyoplankton distribution, abundance and diversity to be investigated. It was found that with the presence of upwelling activity off Walvis Bay during the winter and spring, there was a reduction in ichthyoplankton abundance and diversity. In contrast, with increasing water column stability,

ichthyoplankton abundance and diversity was found to increase. To a certain extent, this was species specific and was related to the spawning habits of the adults.

During the first two cruises, both conducted during periods of increased upwelling, similar ichthyoplankton assemblages were found (Olivar 1987). Larvae from the pelagic bearded goby *Sufflogobius bibarbatus* and the lantern fish *Lampanyctodes hectoris* were the most abundant. Both of these species are shown to spawn virtually all year round, and the larvae form an important component of the food web within the northern Benguela. The spawning of *S. bibartus* is known to peak during spring, while *L. hectoris* spawning peaks during spring and early summer (O'Toole 1977a; Shannon and Pillar 1986). The third cruise was conducted during a quiescent period, and the ichthyoplankton abundances were quite different. The larvae of horse mackerel *Trachurus trachurus capensis* were the most abundant. This species is known to spawn during summer and autumn, with a peak from January to March, primarily north of 22°S (Shannon and Pillar 1986; Geist *et al.* in press). The larvae of another goby, *Lesuerigobius sanzoi* and achovy *Engraulis capensis* were the next most abundant, with *L. sanzoi* spawning mainly in autumn and *E. capensis* spawning in summer and autumn (O'Toole 1977a).

Other species, specifically important commercial species, which show seasonality in spawning and thus result in seasonal signals in the abundance, distribution and community structure of ichthyoplankton off central Namibia are discussed below. The sardine *Sardinops sagax* spawns at least twice a year from August through to April, with spawning maxima in late winter to spring, and the other in late summer to autumn (King 1977; O'Toole 1977a; Shannon and Pillar 1986; Stenevik *et al.* 2001; Kreiner *et al.* 2011). This is related to environmental signals such as temperature and food (King 1977; Shannon and Pillar 1986).

The West Coast sole (*Austroglossus microlepis*) which is bycatch of the monkfish fishery in Namibian waters, and has a relatively short spawning season. A seasonal signal in larval abundance was shown off central Namibia, with a significant increase shown from early spring to early summer (O'Toole 1977b).

Hake, *Merluccius capensis and Merluccius paradoxus* eggs and larvae occur throughout Namibian waters, with *M. paradoxus* occurring in deeper waters, outside of the 400 m isobath, and *M. capensis* occurring more broadly from nearshore waters out to the 400 – 500 m isobaths (Sundby *et al.* 2001). Spawning of these species occurs from spring through to late summer (Shannon and Pillar 1986). *M. capensis* in particular displays peak spawning from October through to December, with a secondary peak during February/March during some years (Sundby *et al.* 2001). This pattern in ichthyoplankton production is consistent with the results of Olivar (1987), with an increase in hake eggs and larvae during more quiescent periods off central Namibia.

Overall, there is clear seasonality displayed in ichthyoplankton abundance and community structure off the coast of central Namibia, but this is relatively complex, and is largely species specific. In general environmental and hydrological factors drive changes in the spawning habits of species and distribution of eggs and larvae, and so affect the ichthyoplankton assemblages on a temporal scale.

#### 3.2 ALONG-SHELF DISTRIBUTION

#### 3.2.1 Phytoplankton

The main controlling features affecting the longshore distribution of phytoplankton in the Northern Benguela Current region are the Lüderitz upwelling cell and the Angola/Benguela Front (ABF) which is generally located between 14°-16°S (Meeuwis and Lutjeharms 1990). Shannon et al. (1984) showed that within the Lüderitz upwelling cell phytoplankton biomass was generally <5 mg.m<sup>-3</sup>, of chlorophyll-a. Further north, on the northern boundary of the upwelling cell, towards Walvis Bay in situ chlorophyll-a concentrations increased significantly, ranging between 3 and 10 mg.m<sup>-3</sup>. Brown et al (1991) demonstrated a similar pattern from in situ surface measurements of chlorophyll-a obtained between 1985 and 1989. At the northern extremity of the region the ABF separates the biologically productive waters of the Benguela Current from the more oligotrophic tropical waters of the Angola Current. In the frontal zone very tight gradients of phytoplankton biomass develop, ranging from >8 mg chlorophyll-a per m<sup>3</sup> south of 15°S to <3 mg/m<sup>3</sup> north of 14°S, with corresponding gradients in nitrate-nitrogen and phosphate-phosphorus (Wasmund et al., 2005). Between these two features phytoplankton distribution can be variable but in general biomass increases with distance downstream (north) from the Lüderitz upwelling cell towards Cape Frio where this pattern may be interrupted by the Cape Frio upwelling cell (Barthomolae and van der Plas 2007).

The seasonal variation in upwelling that is seen off the coast of Namibia affects the along-shelf patterns in the physical environment, which in turn affect the along-shelf distribution of phytoplankton. The distribution expands and contracts as upwelling decreases and increases in intensity (Campillo-Campbell and Gordoa 2004). As mentioned previously, the lowest concentrations of chlorophyll-*a* occur within the Lüderitz upwelling cell. Concentrations increase northwards from this, with moderate phytoplankton concentrations occurring mid-way along this gradient off the coast of Walvis Bay ((Campillo-Campbell and Gordoa 2004; Demarcq *et al.* 2007).

An anomaly in the above pattern was found to occur during February-March 2002. High chlorophylla concentrations were found to occur off the coast of Lüderitz (Barlow *et al.* 2009). During this particular period there was very low wind stress and so the occurrence of intense upwelling was limited. This allowed for a significant increase in primary production, with ample nutrient and light supply.

Overall, there is therefore a strong spatial variation in the along-shore distribution of phytoplankton within the region off the coast of Namibia, for the majority of the time. This is strongly dependent on the prevailing physical conditions, and so changes with a significant change in the occurrence of upwelling. This is represented diagrammatically in Figure 2.

#### 3.2.2 Zooplankton

The along-shelf distribution of zooplankton in the northern Benguela is closely related to the hydrology within the area and the corresponding phytoplankton distribution (Timonin *et al.* 1992). In general, zooplankton biomass increases in a northerly direction from Lüderitz to Walvis Bay due to the suboptimal conditions for zooplankton development caused by the intense Lüderitz upwelling cell. Fearon *et al.* (1986) (in Verheye *et al.* 1992) found zooplankton, specifically copepod, biomass to peak inshore slightly south of Walvis Bay, while Olivar and Barange (1990) (in Verheye *et al.* 1992)

found copepod abundance to increase south of 22°S, further offshore, on the midshelf (Figure 3). More optimal conditions for zooplankton development are present downstream from the Lüderitz upwelling cell and so higher abundances are found within the region between Lüderitz and Walvis Bay.



Figure 3: The along-shelf distribution of copepod abundance in the northern Benguela. Data were collected during the SNEC cruise in April 1986 using RMT-1x6 nets (200 μm mesh) in the upper 200 m (redrawn from Olivar and Barange 1990). The red ellipse indicates the position of the mining site.

In the study conducted by Barange *et al.* (1992) on euphausiid distribution, the Lüderitz upwelling cell was found to be a major boundary in zooplankton distribution, with abundance of euphausiid species increasing downstream (northwards) from the Lüderitz upwelling cell. However, it was found that the location of the boundary is variable, resulting in changes in distribution patterns of euphausiid species, particularly *Nyctiphanes capensis* and *Euphausia lucens*. Therefore, the along-shelf distribution of certain zooplankton species has a seasonal component.

#### 3.2.3 Ichthyoplankton

The prevailing currents and hydrological features off the central Namibian coast have an influence on the distribution of fish eggs and larvae in this area (O'Toole 1977a), where the ichthyoplankton of some species has been found to be remote from the known distribution of the adults (Olivar *et al.* 1998). On a larger scale, the intense, perennial Lüderitz upwelling cell forms a barrier to ichthyoplankton transport and distribution off the west coast of Africa, resulting in ichthyoplankton and fish populations within the southern and northern Benguela, to a large extent, being considered as separate populations (Cole 1999; Lett *et al.* 2007). This distribution is largely species specific, and the interchange of some larval species is probable (Shannon and Pillar 1986), however, in general, the presence of ichthyoplankton within the Lüderitz upwelling cell only occurs when there are environmental anomalies, such as an intrusion of warmer waters into the area (Cole 1999).

The spawning of most species occurs offshore of Walvis Bay and further north (Shannon and Pillar 1986; Hewitson and Cruickshank 1993). In this area, 43 different species of eggs and 53 different species of larvae have been identified, with majority of these occurring off the northern Namibian coast. There is a clear diversity and abundance gradient, in both eggs and larvae, decreasing from north to south, towards the Lüderitz upwelling cell (Ekau and Verheye 2005). After spawning occurs, relatively little is known about the egg and larval patterns within the northern Benguela, until they reappear as juveniles. Offshore transport of the ichthyoplankton assemblages most likely occurs (Hewitson and Cruickshank 1993). However, the eggs and larvae of the South African sardine S. sagax have been recorded to occur inshore off the coast of Namibia with concentrated abundances occurring south of 22°S (Hart and Marshall 1951 and Mathews 1964, in Shannon and Pillar 1986; King 1977; Stenevik et al. 2001). This abundance presumably decreases towards Lüderitz (Olivar 1987). King (1977) identified two major spawning centres of sardine off the coast of Namibia that corresponded with the two spawning peaks mentioned earlier. Spawning during late winter/spring was found to occur primarily off the coast of Walvis Bay, while the spawning during late summer/autumn was found to occur further north at approximately 20°S. In more recent years, the spawning patterns, and thus the distribution of S. sagax eggs and larvae have changed with the decrease in spawner biomass, where spawning has been recorded to occur further north than Walvis Bay between 20 and 21°S (Stenevik et al. 2001; Ekau and Verheye 2005), however, Kreiner et al. (2011) still identified the area off Walvis Bay as an important spawning area, for at least some parts of the sardine spawning season.

Similarly, the spawning of anchovy has been recorded to occur primarily north of Walvis Bay, at approximately 20°S, where majority of the egg and larval biomass is present, although less intense spawning does occur slightly further south than Walvis Bay (Shannon and Pillar 1986; Ekau and Verheye 2005). The horse mackerel *T. trachurus* also spawns off northern Namibia, with its southern boundary of spawning occurring at 22°S at approximately Walvis Bay. The majority of the egg and larval biomass of this species is found between 17° and 20°S (Ekau and Verheye 2005; Geist *et al.* in press). West Coast sole larvae have been shown to occur slightly further south than those of horse mackerel, with increased abundances occurring between 20.5 and 24.5°S (O'Toole 1977b).

The two species of hake that occur off the coast of central Namibia, *M. capensis* and *M. paradoxus,* have a much wider spawning distribution with eggs and larvae being found to occur from the Angolan border in the north, to at least 28°S, with the area between 22 and 25°S being the principal spawning area (Shannon and Pillar 1986; Olivar *et al.* 1988; Sundby *et al.* 2001). The larvae of the goby *S. bibarbatus,* as well as that of the lantern fish *L. hectoris,* that both form a large proportion of

the central Namibian ichthyoplankton biomass, are also distributed along much of the Namibian coast, with goby larvae being reported as far south as 28°S, with highest concentration occurring between 23 and 24.4°S (O'Toole 1977a), and lantern fish larvae occurring up to 19°S (Olivar and Rubies 1985 in Shannon and Pillar 1986).

It is therefore clear that there is varied along-shelf distribution of the ichthyoplankton fauna off the coast of central Namibia. In general, there is an increased abundance of ichthyoplankton further north of Lüderitz, where the majority of the larvae and eggs are found in northern Namibian waters, where the majority of the adults spawn. This is however, species specific.

#### 3.3 CROSS-SHELF DISTRIBUTION

#### 3.3.1 Phytoplankton

The process of coastal upwelling occurs primarily because of the interaction between coastal winds and the Coriolis Effect which results in the Ekman transport of surface water perpendicular to the direction of the wind and upwelling against the coastal margin. This type of upwelling dominates the majority of the Benguela ecosystem. Correspondingly, the increased primary production occurs primarily within inshore waters. Shannon et al. (1984) identified a narrow coastal zone, approximately 30 km wide, off the coast of Namibia where there was increased primary production. Further offshore, production was found to be reduced. Off Walvis Bay, Barlow et al. (2009) found productivity at inshore stations to be approximately double that of the productivity at offshore stations. Similarly, Campillo-Campbell and Gordoa (2004) found chlorophyll-a maxima to occur primarily close inshore. Chlorophyll-a patches, signaling the presence of phytoplankton, were found to exist further offshore, however these were not as dense or as extensive as those found closer inshore. Within this area off central Namibia, phytoplankton biomass decreased seawards with very low levels beyond 100 km offshore. This is particularly apparent during the winter months when primary production is already reduced due to the occurrence of more intense upwelling. There is thus also a seasonal aspect to the cross-shelf distribution of phytoplankton cells observed off the coast of central Namibia, where a coincident increase in the offshore extent of phytoplankton distribution occurs with the increase in chlorophyll-a concentration in summer and autumn due to the decrease in upwelling activity during this time (Demarcq et al. 2007).

The cross-shelf distribution of phytoplankton biomass displayed off the coast of central Namibia is likely to be the result of the dominance of different functional phytoplankton groups in inshore and offshore areas. The increased productivity closer inshore is as a result of the dominance of diatoms, while the decreased productivity further offshore is as a result of the dominance of smaller flagellates (Barlow *et al.* 2009).

Physical transport also plays an important role in the cross-shelf distribution of chlorophyll-*a* off central Namibia (Campillo-Campbell and Gordoa 2004). Patches with high chlorophyll-*a* concentrations have been found offshore of Lüderitz. The occurrences of these phytoplankton maxima may be due to the offshore transport occurring within the region due to the high rate of upwelling.

Overall, primary productivity is lower offshore. There are however exceptions to this, where chlorophyll-*a* maxima are found offshore in relation to the shelf break. In these cases, offshore transport of water seems to play an important role in the distribution of phytoplankton.

#### 3.3.2 Zooplankton

The cross-shelf distribution of zooplankton within the northern Benguela does not exactly match that of phytoplankton. The phytoplankton maxima occur closer inshore, while the zooplankton maxima occur further offshore (Shannon and Pillar 1986). During the study conducted by Timonin *et al.* (1992), it was found that during more quiescent phases, zooplankton abundance, particularly copepod abundance, peaked further offshore in the region of the shelf break/upper continental slope. Barange *et al.* (1992) conducted a study looking at the distribution of euphausiids within the entire Benguela ecosystem, using *in situ* data obtained from five South West African Pelagic Egg and Larvae Survey (SWAPELS) cruises and two Spanish Namibian Environmental Cruise (SNEC) surveys. These authors found that the longitudinal boundary of euphausiid distribution occurred at the shelf break at approximately the 200 m isobath. This longitudinal boundary was found to be most prominent north of 28°S, off the central Namibian coast.

#### 3.3.3 Ichthyoplankton

As with the distribution of ichthyoplankton in relation to all other variables, the cross-shelf distribution of eggs and larvae off the coast of central Namibia is strongly related to the environmental conditions, which not only influence spawning patterns of the adults, but also can cause transport of the eggs and larvae further offshore. Again, this is, to an extent, species specific (Olivar *et al.* 1992). Shelf structure and bathymetry also play an important role in the distribution of ichthyoplankton off the coast of Namibia (Olivar *et al.* 1992) and some species show cross-shelf distribution in line with that of their phytoplankton prey (Shannon and Pillar 1986). In general, egg and larval abundance and diversity off the coast of Namibia decreases further offshore, beyond the continental shelf (Ekau and Verheye 2005). Larval distribution inshore increases recruitment success of species.

Sardine spawning occurs inshore off the coast of central Namibia, with larval abundance occurring within 50 km of the shore, and highest larval abundance occurring between 30 and 50 km offshore (O'Toole 1977a). This distribution coincides with that of their diatom prey (Shannon and Pillar 1986). The cross-shelf distribution of *S.sagax* eggs and larvae is however, also heavily dependent on the wind activity in the region. During quiescent periods, sardine eggs and larvae are confined to the upper surface layer of the water column. When upwelling intensifies, this upper surface layer is moved offshore through Eckman transport and as a result, a large proportion of the eggs and larvae are column, caused by increased wind activity which is synonymous with intense upwelling, and causes an increase in the number of eggs and larvae in the subsurface layers which are moved inshore. This mechanism reduces the offshore loss of sardine eggs and larvae during periods of intense upwelling (Stenevik *et al.* 2001). Similarly, West Coast sole also spawn in close proximity to the shore, where O'Toole (1977b) found larvae no further than 16 km off the coast of central Namibia.

In contrast to sardine and West Coast sole, anchovy eggs are found further offshore, up to a distance of 120 km, off central and northern Namibia (Le Clus 1985 in Shannon and Pillar 1986). In a study conducted by O'Toole (1977a) over 85 percent of anchovy larvae collected were collected at distances greater than 30 km offshore, with highest concentrations occurring between 60 and 112 km offshore.

Horse mackerel and hake eggs are found further offshore than those of sardine, with the highest concentrations occurring on the outer shelf approximately 50 to 100 km offshore (O'Toole 1977a and Olivar and Rubies 1983 in Shannon and Pillar 1986). The hake, *M. capensis* spawns offshore at depths between 100 and 400 m (Sundby *et al.* 2001). The neutral or slightly negative buoyancy of the eggs and larvae, as well as cross-shelf transport, as a result of the upwelling subsurface circulation that is characteristic of the Benguela Current region, results in the presence of hake eggs and larvae close inshore, outside of the area of spawning (Sundby *et al.* 2001)

The goby *S. bibarbatus* was found to spawn further offshore, between the 100 and 200 m isobaths, while, further north of Walvis Bay the larvae of the lantern fish *L. hectoris* was also found offshore, between the 200 and 4000 m isobaths (Olivar *et al.* 1992). It was however interesting to note that in the study conducted by Olivar *et al.* (1992) *L. hectoris* larvae were found much closer inshore further south. This was probably partly due to the proximity of the 200 m isobath to the shore off Lüderitz. Additionally, although the species occurs up to depths of 3 000 m, adults are most abundant in waters shallower than 800 m, and so spawning probably occurs within these depths (Olivar *et al.* 1998). The presence of eggs and larvae of *L. hectoris* much further offshore is as a result of transport by upwelling filaments, especially within the region of the Lüderitz upwelling cell (Olivar *et al.* 1998). Overall, it would seem that the cross-shelf distribution of the eggs and larvae of species off the coast of central Namibia, depend heavily on the wind activity, the resulting vertical mixing of the water column, and the transport of different water layers due to upwelling. For successful recruitment, larvae of most species need to remain inshore, and so transport offshore by upwelling filaments is disadvantageous. Again, however, this is species specific.

#### 3.4 VERTICAL DISTRIBUTION

#### 3.4.1 Phytoplankton

In the water column, light decreases exponentially with depth, where the depth of the euphotic zone corresponds with the depth where there is 1% of the light that is present at the surface (Ryther 1956). In the region off the coast of central Namibia, because of the prominent presence of upwelling, the water column remains well mixed for majority of the year, resulting in the surface chlorophyll-*a* measurements being a good indication of the subsurface chlorophyll concentrations (Shannon *et al.* 1984; Brown *et al.* 1991). During quiescent periods off the coast of Namibia, from February to March, Shannon *et al.* (1984) found that the vertical distribution of phytoplankton was closely linked to the stratification of the water column. During these times, subsurface maxima occurring up to a depth of 20 m were common, however, the concentrations were rarely above 20% greater than those within the corresponding surface waters.

#### 3.4.2 Zooplankton

The maximum abundance of zooplankton within the northern Benguela primarily occurs within the surface layers, however, there is also an increase in biomass from approximately 200 m downwards (Verheye *et al.* 1992, Timonin *et al.* 1992). In the latter study it was found that, at 25°S, between Lüderitz and Walvis Bay, zooplankton concentrations peaked at the surface at 500 mg.m<sup>-3</sup>, and then decreased. There was a secondary peak within the 200 to 700 m depth at 100 to 200 mg.m<sup>-3</sup>. This is shown in Figure 4. The presence of the oxygen minimum layer in the Benguela current region has a significant impact on the vertical distribution of zooplankton off the coast of Namibia. The bimodal vertical distribution shown by majority of the zooplankton species within the area is possibly as a



result of this layer of hypoxic water, where species actively avoid the low oxygen waters between the surface layers and 200 m depth (Auel and Verheye 2007).

Figure 4: Vertical distribution of zooplankton biomass at 25°S (redrawn from Timonin et al. 1992).

These vertical distributions do however depend on species, where some zooplankton species such as the copepods *Calanoides carinatus* and *Rhincalanus nasutus* show a more homogenous vertical distribution (Timonin *et al.* 1992). Season also has an important impact on vertical distribution, where a more homogenous distribution is shown during periods of increased upwelling and water column mixing. The vertical distributions of some species are complicated by ontogenetic migration where certain life stages occupy different depths of water (Timonin *et al.* 1992).

Additionally, some zooplankton species, such as many euphausiids, copepods and jellyfish, display diurnal vertical migration (Barange *et al.* 1992; Brierley *et al.* 2001; Postel *et al.* 2007), where they are present in the upper water column layers at night, and then sink to deeper layers during the day. These members of the zooplankton community play an important role in the pelagic ecosystem. This migration forms scattering layers where dense concentrations of plankton are found. These layers are easily identified from echo-sounder backscatter because of the strong acoustic signal that they produce. Within the NMP MLA off central Namibia, such acoustic scattering layers have been found, and are clearly shown for two periods in Figures 5 and 6.



Figure 5: ADCP beam attenuation through the upper water column from -10 m to -100m at site 15 of the marine ecology verification survey.

Measurements were taken from 8 June 2013 to 26 July 2013 at site 15 within ML 170 off central Namibia. The high levels of backscatter can be seen to cycle on a daily basis, indicating the diurnal vertical migration of a large amount of the zooplankton community within the area.





Measurements were taken from 2 August 2013 to 13 September 2013 at site 15 within ML 170 off central Namibia. The high levels of backscatter can be seen to cycle on a daily basis, indicating the diurnal vertical migration of a large amount of the zooplankton community within the area.

The presence of these scattering layers within the MLA indicates that there is a large zooplankton community within the area that undergoes diurnal migration. The dredging activities have the potential to affect the migration of the zooplankton communities through an increase in turbidity from sediment plumes decreasing light availability. Wallace *et al.* (2010) found that the presence of sea ice in an Arctic fjord influenced the diurnal migration of various zooplankton specie, through shading, thus having an effect on the acoustic scattering layer in that area. With the increase in sea ice coverage, and therefore a decrease in light availability, zooplankton migrations were asynchronous and occurred randomly, while zooplankton migrations at an ice-free site were more synchronized, occurring diurnally. Sediment plumes may have a similar effect on zooplankton communities in the area of the MLA, and this must be considered, although other properties such as food availability and zooplankton species composition also have an influence on migration behaviour. This underlines the importance of the requirement for monitoring of the turbidity within the region during mining, especially in terms of turbidity plume extent and duration and concomitant effects, if any, on diurnal migration patterns.

#### 3.4.3 Ichthyoplankton

The upwelling off the coast of central Namibia, and especially that further south off the coast of Lüderitz, results in a well-mixed water column for the majority of the year. This results in the majority of the ichthyoplankton assemblage to be widely distributed within the upper 200 m of the water column for much of the year (Olivar *et al.* 1992). This does, however, seem to be species specific and involves the influence of many other mechanisms where ontogenetic stage, movement ability, buoyancy and other factors may play a role.

Newly spawned sardine eggs are distributed just below the upper mixed layer off the coast of central Namibia, but the eggs are buoyant and so travel rapidly into the surface layers, resulting in the

majority of the eggs and larvae being distributed in the upper 60 m of the water column during more stable periods (Stenevik *et al.* 2004; Ekau and Verheye 2005). In a study conducted by O'Toole (1977a), 75 percent of the total number of sardine eggs collected from thirty net hauls over a period of three days occurred in the upper 20 m of the water column. As a result of upwelling, these surface layers are transported further offshore, resulting in the gradual loss of eggs and larvae (Stenevik *et al.* 2001). During periods of increased upwelling, the transport of the eggs and larvae offshore is increased. However, because of the vertical mixing of the water column, more eggs and larvae are transported to depth and so there is a greater chance of their transport inshore (Stenevik *et al.* 2001). During increased upwelling, there is therefore a higher abundance of sardine eggs and larvae below 20 m (Stenevik *et al.* 2004). Vertical migration is an additional mechanism that acts on the vertical distribution of sardine larvae in particular, especially the larger larvae, and is therefore an important consideration in their vertical distribution.

Similarly, anchovy larvae also show vertical migration, which occurs on a daily basis (Stenevik *et al.* 2007). On average, the majority of anchovy larvae off the coast of central Namibia are distributed below 25 m, which is below the offshore moving Ekman layer (Stenevik *et al.* 2007). This prevents losses offshore, and increases the chances of recruitment success.

*S. bibarbatus* larvae were found off central Namibia at depths between 20 and 60 m, while hake eggs and larvae have been found slightly deeper between 20 and 150 m and *L. hectoris* larvae have been found throughout the water column, but in slightly larger larvae (< 5 mm), concentrations increased below 90 m depth (Olivar *et al.* 1992).

#### 3.5 CHARACTERISATION OF SPECIES AND FORMS PRESENT

#### 3.5.1 Phytoplankton

In general, phytoplankton community structure varies with water temperature in a regular and predictable pattern. Micro-phytoplankton  $(20 - 200 \ \mu\text{m})$  such as the larger diatoms dominate at lower temperatures, while smaller flagellates dominate at intermediate temperatures and smaller pico-phytoplankton are most abundant at high temperatures (Bouman *et al.* 2003; Barlow *et al.* 2009). This is area specific, to a certain extent. Within the central Namibian waters, phytoplankton communities are generally dominated with diatoms and, to a lesser extent, dinoflagellates (Shannon and Pillar 1986; Heymans and Baird 2000a; Barlow *et al.* 2009). Diatoms are best able to compete for available nutrients and light and thus can develop dense blooms immediately after an active upwelling phase and the beginning of a quiescent phase. Dinoflagellates can grow more efficiently at lower nutrient concentrations in comparison to diatoms, and so dominate during the more quiescent phases (Sakko 1998). Diatoms tend to dominate the more inshore areas, while dinoflagellates along with flagellates are more important further offshore (Shannon and Pillar 1986, Barlow *et al.* 2009).

Shannon and Pillar (1986) reviewed several floristic studies undertaken in the northern Benguela from the 1950s to the 1980s. Off the coast of central Namibia the majority of the studies found diatoms to outnumber any other group of phytoplankton, followed by dinoflagellates which comprised about 4% of the phytoplankton assemblage in this area. Within the diatom group, the species *Chaetoceros* spp., *Rhizosolenia* spp., *Planktoniella sol, Nitzschia* spp., and *Asterionella glacialis (A. japonica)* were found to be the most common (Hart and Currie 1960, in Shannon and Pillar 1986). Other studies have found *Delphineis karstenii, Thalassiosira* spp., *Coscinodiscus* spp.,

Actinoptychus spp., Leptocylindrus spp., Coscinosira polychorda, Thalassionema spp., and Thalassiothrix spp. also to be present, with some species blooming during favourable conditions (Schuette 1980, Kollmer 1962, 1963, Pieterse and van der Post 1967 and Hulburt 1976, all in Shannon and Pillar 1986). Within the dinoflagellate group, *Peridinium* spp. and *Ceratium* spp. were found to be the most important (Shannon and Pillar 1986). Dinoflagellate blooms occur during quiescent periods during summer when there is a well-developed thermocline and water column stratification is at its highest. For example, this is demonstrated by the occurrence of red-tide blooms within the northern Benguela.

#### 3.5.2 Zooplankton

The productive Benguela current ecosystem is typically low in species diversity in comparison with the more tropical Agulhas current region, but supports much larger populations (Shannon and Pillar 1986). Within the central Namibian region off Walvis Bay, copepods are numerically dominant, comprising 70 to 85% of the zooplankton community (Timonin *et al.* 1992; Hansen *et al.* 2005). Specifically *Paracartia spp.* are important in nearshore habitats, while *Centropages brachiatus, Calanoides carinatus* and *Metridia lucens* are more abundant further offshore over the continental shelf (Timonin *et al.* 1992; Hansen *et al.* 2005). *Rhincalanus nasutus* is also a dominant species within Namibian waters (Timonin *et al.* 1992; Hansen *et al.* 2005).

Euphausiids are common in the Benguela ecosystem, and form an important component of the food web. Their ability to form aggregations makes them important prey for fish species within the area. Barange *et al.* (1992) found that *Nyctiphanes capensis* was the dominant euphausiid species on the inner shelf north of Lüderitz, while *Euphausia hanseni* was the dominant species on the shelf-break in this region. These authors and Pillar *et al.* (1992) also documented the presence of *Euphausia lucens* off Walvis Bay, especially during the maximum upwelling period between June and November, although this species is more characteristic of the euphausiid community further south. *Thysanoessa gregaria* and *Nematoscelis megalops* are less abundant, but also play an important role in the community structure of euphausiids in central Namibian waters, particularly further offshore and on the shelf-break (Pillar *et al.* 1992).

Other species also occur within the northern Benguela, specifically off central Namibia. Within the chaetognath group, Venter (1969) (in Shannon and Pillar 1986) reported the occurrence of ten species off the central Namibian region. *Sagitta friderici* was the most common of these, constituting 90% of all chaetognath species recorded in the inshore areas of the region, while further offshore *S. tasmanica* was the most common chaetognath, representing 70% of this group. In a more recent study, Bohata and Koppelmann (2013) recorded 17 chaetognath species in waters off Walvis Bay. To a certain extent, species composition depended on the distance offshore, with species richness and diversity increasing with distance offshore. Nevertheless, in that study, it was found that *S. serratodentata* and *S. tasmanica* dominated all stations sampled. Cladocera including *Podon polyphemoides* and *Evadne noidmanni* also occur and are abundant throughout the year in the northern Benguela (Unteruberbacher 1964). Thaliaceans (salps and doliolids) have also been found to occur in waters off central Namibia (Olivar 1987; Shannon and O'Toole 1999).

Some cnidarian species are becoming dominant within the northern Benguela (Lynam *et al.* 2006), where jellyfish, considered to be a part of the plankton, are found along the entire length of the Namibian coast, and are especially common in central Namibian waters (Flynn *et al.* 2012; Gibbons, in Midgley 2012). *Chrysaora fulgida* and *Aequorea forskalea* have been recognized as the dominant

cnidarian taxa in the central Namibian region (Lynam *et al.* 2006; Gibbons, in Midgley 2012). The increase in cnidarian abundance is thought to be as a result of various anthropogenic effects, including increased fishing in the area, as jellyfish biomass off the coast of central Namibia has increased since the collapse of the Namibian pelagic fisheries in the 1960s and 1970s (Gibbons, in Midgley 2012). This results in a reduction in the mean trophic level of species landed, and thus allows for the proliferation of many cnidaria due to the abundance of food that was once consumed by the fished species (Lynam *et al.* 2006). The implication of an increase in jellyfish abundance is not only an increase in competition for food with pelagic fish species, many of which are commercially important, but also jellyfish have the potential to severely reduce recruitment of these pelagic fish species by preying on large numbers of ichthyoplankton (Flynn *et al.* 2012). Overall the increase in jellyfish abundance therefore has a potential negative effect on pelagic fish populations.

There is a variety of zooplankton species that characterize the northern Benguela and occur offshore between Lüderitz and Walvis Bay, within the project region. These species all show spatial and temporal variation dependent on various biotic and abiotic drivers. Some of these species, such as the jellyfish could have detrimental effects on other components of the ecosystem in central Namibian waters, as their numbers increase.

#### 3.5.3 Ichthyoplankton

Central and northern Namibian waters support several large commercial fisheries, and so the presence of sardine *S. sagax*, hake *M. capensis* and *M. paradoxus*, horse mackerel *T. trachurus*, and anchovy *E. capensis*, eggs and larvae are important in terms of supplying recruits to these fisheries (Lange 2003). Although these species are of commercial importance, their eggs and larvae off the coast of central Namibia are outnumbered by the eggs and larvae of the goby *S. bibarbatus* and the lantern fish *L. hectoris* (Olivar 1987). Other species that may contribute to the observed ichthyoplankton assemblage off the coast of central Namibia include the round herring *Etrumeus whiteheadi*, the mackerel *Scomber japonicus*, the west coast sole *Austroglossus microlepis*, snoek *Thyrsites atun*, the lightfish *Maurolicus muelleri*, and the frostfish *Lepidopus caudatus* (Shannon and Pillar 1986).

#### 3.6 LONG-TERM VARIABILITY

The Benguela ecosystem is inherently a highly dynamic system. Changes in the physical environment occur at a variety of different spatial and temporal scales. Both intra- and inter-annual variability has been shown to occur (Shannon *et al.* 1992). The variation in the physical environment and the resulting changes in productivity within the northern Benguela do however seem to be more stable over more extended periods of time. Demarcq *et al.* (2007) show that there is a presence of interannual variation in phytoplankton biomass, but this is not very significant. The spatial patterns in chlorophyll-*a* distribution shown seem to hold true for the majority of the time, and also do not show a significant amount of interannual variability. There is a constant low phytoplankton biomass within the region of the Lüderitz upwelling cell where environmental conditions are not favourable for phytoplankton growth year-round.

Changes to the physical environment within the Benguela do however occur. These changes occur at a longer time scale, and typically are more inter-decadal in nature and may have significant effects on the productivity of the region. Characteristically warm oligotrophic water invades the system and upwelling reduces. These warm water occurrences are termed "Benguela Niños" because of their

similarity to the El Niño Southern Oscillation (ENSO) events that occur within the Pacific (Shannon *et al.* 1992). Such events have occurred approximately once a decade within the northern Benguela region, off the coast of central Namibia, in the vicinity of the proposed mining area. Shannon *et al.* (1992) investigated the changes in the Benguela ecosystem during the 1980s, and although these authors recorded the change in physical conditions during 1984, a change in phytoplankton biomass was not observed. These data were however very patchy, and so a variation in primary productivity with a significant change in environmental conditions due to an inter-decadal event would most likely be present, with Benguela Niños probably resulting in a reduction in the abundance of phytoplankton (Shannon *et al.* 1992).

During a study of zooplankton dynamics off the coast of Namibia, Timonin et al. (1992) recorded interannual variation in zooplankton community succession, which was attributed to interannual variation in the intensity of upwelling. However, the interannual variability in zooplankton abundance and distribution is not only influenced by environmental forcing, and is in fact much more complex than this. There is a variety of reasons that can explain variability in zooplankton biomass and zooplankton community composition over several years. Environmental conditions such as the intensity of upwelling not only affects the abundance of forage items, but also affects their dominant size. This has an influence on zooplankton abundance within the northern Benguela. It has been found that zooplankton biomass remains low with the occurrence of a high abundance of smaller phytoplankton species, presumably because the zooplankton species present within the northern Benguela are unable to feed on smaller particles (Shannon et al. 1992). Additionally, the presence of predators has an influence on the interannual variability in zooplankton populations within the northern Benguela, where grazing by species such as anchovy can decrease zooplankton abundance (Cury and Shannon 2004). The fluctuation in predator abundance thus will have a topdown effect on zooplankton populations and so may be partly responsible for interannual variability in zooplankton communities within the northern Benguela.

The occurrence of Benguela Niños which are more interdecadal in nature also have a significant effect on zooplankton abundance and distribution (Shannon *et al.* 1992). The occurrence of warmer water with a higher salinity and unusual oxygen concentrations results in a change in zooplankton community structure (Shannon and Pillar 1986). It was found that there was a notable increase in a warm water copepod, *Nannocalanus minor*, and a decline in some cool water copepods, predominantly *Paracalanus parvus*, as a result of the Benguela Niño event that occurred in 1963 (Shannon and Pillar 1986). This indicates the long-term variability of zooplankton within the region.

Similar to phytoplankton and zooplankton, the ichthyoplankton assemblages off the central Namibian coast also show long-term variability in abundance, distribution and diversity, associated with changes in environmental conditions (Cury and Shannon 2004). With the anomalous movement of water bodies during certain years, the transport of eggs and larvae can be affected, causing interannual variation in ichthyoplankton abundance and distribution. Cole (1999) recorded unusually high recruitment of clupeoids in 1987 in the northern Benguela, caused by the unusual northward transport of eggs and larvae from the southern Benguela. This was as a result of an anomalous intrusion of warmer water from the southern Benguela into the northern Benguela, suppressing the upwelling activity off Lüderitz.

Similar to phytoplankton and zooplankton populations, the ichthyoplankton assemblages within the northern Benguela change with the occurrence of a Benguela Niño. Fluctuations in the spawner

biomass have been recorded in the northern Benguela as a result of a Benguela Niño event, and thus, this affects the ichthyoplankton biomass (Shannon *et al.* 1992).

In addition to long-term variability as a result of changes in environmental conditions, the overexploitation of many of the commercial fish stocks off the coast of Namibia has influenced long-term variability in ichthyoplankton abundance and community composition, and has resulted in regime shifts (Cury and Shannon 2004). During the late 1970s there was a collapse of several of the major commercial fish stocks, including hake and pilchard, in Namibian waters due to overexploitation (Lange 2003; David, in Midgley 2012). Since then, these populations have shown significant fluctuations (Shannon *et al.* 1992; Heymans *et al.* 2004). Presently, the Namibian sardine and anchovy stocks remain depleted due to insufficiently cautious management coupled with environmental anomalies (Payne *et al.* 2001; David, in Midgley 2012), while there has been a gradual increase and improvement in the state of the hake stock (Payne *et al.* 2001), resulting in it presently being the most valuable commercially exploited fishery in Namibia (David, in Midgley 2012). Horse mackerel catches have also improved, making it the largest fishery by volume in Namibian waters (David, in Midgley 2012). Due to a fluctuation in the abundance of these species, it can be assumed that the overexploitation results in a fluctuation in their eggs and larvae within the northern Benguela, causing severe long-term variation in the ichthyoplankton in the ecosystem.

#### 3.7 IMPORTANCE OF PLANKTON IN THE FOOD WEB

Overall the northern Benguela upwelling system supports a productive ecosystem that sustains a number of living resources which are exploited for commercial gain (Heymans and Baird 2000a). The functioning of this ecosystem is complex, and is impossible to analyse fully, however, it is important to consider the various interactions between trophic groups to draw more holistic conclusions about ecosystem properties and functioning, and therefore the potential effects on the functioning of the ecosystem as a result of the phosphate dredging project (Heymans and Baird 2000b). Previous research has used a variety of models to estimate the trophic flows within the northern Benguela upwelling system (Hutchings *et al.* 1991; Heymans and Baird 2000a; Heymans and Baird 2000b; Shannon and Jarre-Teichmann 2000). All models highlight the importance of phytoplankton, zooplankton and ichthyoplankton in the functioning of this system. This is an important consideration in the development of the MLA off Walvis Bay, as an effect on one group or species has the potential to affect other trophic levels, which could include valuable commercial resources.

Within the northern Benguela upwelling system, phytoplankton is the only primary producer and the phytoplankton  $\rightarrow$ zooplankton  $\rightarrow$ pelagic fish  $\rightarrow$ demersal fish energy flow pathway was shown to dominate (Heymans and Baird 2000a). The importance of phytoplankton in the functioning of the ecosystem was noted by Shannon and Jarre-Teichmann (2000), where a reduction in total phytoplankton production resulted in insufficient production to support the consumers within the ecosystem. This indicates the importance of phytoplankton, zooplankton and ichthyoplankton (ichthyoplankton would form a part of the zooplankton in this case) in the Benguela system, where the upper levels of primary and secondary consumers are entirely dependent on the planktonic communities within the area for healthy ecosystem functioning. The primary consumers included mesozooplankton and macrozooplankton, consisting primarily of copepods and euphausiids (Hutchings *et al.* 1991), and jellyfish (Heymans and Baird 2000a). The fish community was found to consist of a variety of pelagic and demersal fish already mentioned in this review.

It must however be noted that most of the production and consumption estimates used in these models were obtained from inshore waters where phytoplankton biomass is higher than that offshore between the 200 and 500 m isobaths (Hutchings *et al.* 1991). The MLA extends from the 200 m to the 300 m isobath, and so the production and consumption in the system within this region may differ slightly, where the abundance of the various phytoplankton, zooplankton and ichthyoplankton communities are seemingly less pronounced.

### 4 SUMMARY

- The phosphate <sup>1</sup>Mining Licence area (between 23.8° and 24.5°S) is approximately 60 km offshore of the central Namibian coast, and the target <sup>2</sup>mine site area is between 24.1° and 24.3°S, on the northern edge of the Lüderitz upwelling cell, in water depths between 190 and 300 m.
- The oceanographic environment off Namibia is dynamic, and in many ways unique. It is primarily defined by the Benguela current upwelling system and supports a productive ecosystem with a high abundance of phytoplankton, zooplankton and ichthyoplankton species. The distribution of these species differs with spatial and temporal variation affected by the occurrence of upwelling, where the perennial upwelling cell off Lüderitz plays a particularly important role.
- Within the Lüderitz upwelling cell species abundance is low, but the area further north off the central Namibian coast where the proposed mining site is located, forms a transitional zone between the southern and northern regions of the Benguela ecosystem, and so the influence of the Lüderitz upwelling cell is slightly reduced, resulting in increased species abundances.
- This species abundance, however, tends to decrease further offshore, which is important considering that the proposed mining site is located 60 km offshore.
- Although species abundance is greater off central Namibia, the species present in the vicinity of the mine site area are ubiquitous in the region.
- Phytoplankton communities in the area are dominated by diatoms and majority of the species found are found elsewhere in the world's oceans. The diatoms occur primarily within inshore waters, with biomass decreasing steadily seawards. The phytoplankton species found within the vicinity of the mining site are, therefore, not only ubiquitous but also occur within the mining site in decreased abundances in comparison to inshore waters.
- Zooplankton communities in the central Namibian region are dominated by copepods, which again, are not unique to the area. In contrast to the phytoplankton, the zooplankton is found slightly further offshore, where abundance peaks on the shelf-break at depths of approximately 200 m. The proposed mining site is located in water depths of 180- 300 m, and so an increased abundances of zooplankton will be present. However, the species present here will not be unique to the area.
- Central Namibian waters support several commercial fisheries, with sardine, anchovy, hake and horse mackerel being particularly important. The ichthyoplankton of these species found off central Namibia plays a pivotal role in recruitment to the fisheries, and are especially important

<sup>&</sup>lt;sup>1</sup> The Mining Licence area (MLA) is 2230 km<sup>2</sup>.

<sup>&</sup>lt;sup>2</sup> The mine site area (Sandpiper-1) is 176 km<sup>2</sup> of which up to 60 km<sup>2</sup> is proposed to be mined during the 20 year mining licence period

in the light of the current depleted state of the sardine and anchovy fisheries. Generally, however, fish off the Namibian coast spawn in inshore waters north of Walvis Bay. Therefore, the proposed mining area off central Namibia is not within any important spawning or nursery grounds, particularly for the commercially important species.

- All of the species mentioned play an important role as producers or primary consumers within the northern Benguela upwelling system, resulting in the higher trophic levels relying on planktonic communities for healthy ecosystem functioning. This however, may be more pronounced in more inshore waters where plankton communities are more prolific.
- Overall, although the waters off central Namibia are productive and support large communities of species, the proposed mining site does not occur within any identifiably important area of phytoplankton, zooplankton or ichthyoplankton growth and development.

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