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Estuarine refugia and fish responses to a large anoxic, hydrogen sulphide, "black tide" event in the adjacent marine environment

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ABSTRACT

The fish fauna of the Berg River Estuary was sampled from the mouth to 40 km upstream using a small-meshed seine-net before (summer 1993), during (summer 1994) and after (summer 1996) a low-oxygen, hydrogen sulphide "black tide" event that caused a mass mortality of fish in St Helena Bay. These data were compared to determine how the species composition, abundance and distribution of the fish fauna of the Berg River Estuary differed before, during and after the event as well as to ascertain which species, if any, found refuge in the estuary. The overall catch-per-unit-effort of 1637 fish.haul^{-1} during the event was almost double the 932 fish.haul^{-1} and 643 fish.haul^{-1} in the years before and after respectively. All the fish recorded alive in the estuary during the event were species known to have some degree of estuarine association. No representatives of the purely marine species found dead on the adjacent shoreline were recorded live in the estuary during the event. Of the 10 estuarine-associated species sampled, 5 extended their range and/or modal peaks of abundance further upstream during the event. One species, *Liza richardsonii*, was abundant enough to examine its size distribution in different breaches of the estuary. Large/adult fish were concentrated further upstream than small/juvenile fish, which appeared to be unable to escape tidal currents and were concentrated at the edge of the low-oxygen front. Collectively this circumstantial evidence indicates that (1) fish used the Berg Estuary as a refuge from low-oxygen conditions in the marine environment during the "black tide" event, and (2) the ability to secure refuge in the estuary was restricted to species described as "estuarine-associated" or "estuarine-dependent".

1. Introduction

Estuaries provide refuge to fish from adverse conditions in the marine environment, the most extreme of which may lead to mass mortalities. Globally, fish kills or mass mortalities have several possible causes, including disease, extreme or abrupt changes in temperature, salinity or turbidity, hypoxia or anoxia and harmful algal blooms (Hanekom et al., 1989; Hallegraeff, 1995; Whitfield, 1995; Cyrus and McLean, 1996; Pitcher and Calder, 2000; Ward et al., 2001). On a long-term geological time scale, volcanic eruptions, earthquakes and meteorite impacts have also been responsible for extirpations of fish, but only in conjunction with shorter-term extreme salinity changes, thermal shock and harmful algal blooms (Zinsmeister, 1998). In general, fish kills arising from natural or anthropogenic causes are most frequent and severe in confined habitats such as estuaries, fiords or bays (Heil et al., 2001).

The global increase in the frequency and occurrence of harmful algal blooms is, aside from increased awareness, often attributed directly or indirectly to anthropogenic influences such as introductions via ballast water, eutrophication, pollution, the intensification of aquaculture and accelerated climate change (Hallegraeff, 1992, 1995; Burkholder et al., 1995; Pitcher and Calder, 2000). Harmful algal blooms may be either toxic or non-toxic, and their effects may be immediate or manifested in the long-term (Pitcher and Calder, 2000). Toxic algal blooms poison fish directly or indirectly via bio-accumulation through progressive trophic levels (Kane et al., 1998; Pitcher and Calder, 2000). Non-toxic blooms cause fish mortalities through anoxia or hydrogen sulphide poisoning arising from algal decay, hypoxia arising from nighttime algal respiration, mechanical damage or blocking of gills and smothering due to the precipitation of dead organic material (e.g. Brown et al., 1979; Horstman, 1981; Morrison et al., 1991; Hallegraeff, 1995; Collard and Lugo-Fernández, 1999). Both toxic and non-toxic blooms may, especially when recurrent, alter or destroy ecosystems over time (Pitcher and Calder, 2000).

Most mass mortalities of fish in southern African estuaries result from a combination of low salinities (<3) and low water temperatures

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(<14 °C) whereas most in the sea result directly or indirectly from toxic and non-toxic harmful algal blooms (see Whitfield, 1995, 2005; Pitcher and Calder, 2000 and Cockcroft, 2001 for reviews). This said, fish kills along the South African coastline have largely been due to adverse conditions arising in estuaries or their adjacent catchments and more recently due to anthropogenic influences associated with urban areas and mining activity such as eutrophication, increased silt loads, discharge of untreated effluent and ill-conceived flow and estuary mouth manipulation (Morant and Quinn, 1999). In general, fish in the marine environment appear to be less susceptible to adverse conditions than those in the relative confinement of estuaries. The 1988 Orange River floods diluted coastal waters causing mass mortalities of shallow-water invertebrates and kelps (Branch et al., 1990). No mortalities of intertidal fish were recorded, probably due to their escape to deeper more saline waters, whereas freshwater fish washed out of the river eventually succumbed to osmotic shock (Morant and O'Callaghan, 1990). In comparison, a flood-associated mass mortality of fish in the Sundays estuary on the east coast of South Africa was mostly due to gill clogging by suspended sediments but also due to osmoregulatory stress and reduced dissolved oxygen levels (Whitfield and Paterson, 1995). However, estuarine-independent marine species on the Tsitsikamma east coast regularly evade upwelling-induced thermal shock by finding refuge in warmer estuarine waters (Hanekom et al., 1989).

Estuaries provide refugia for estuarine-dependent and estuarine-independent marine species. Even so, obligatory estuarine-dependence may be a life-history bottleneck for many fish species as they are generally more vulnerable to physico-chemical stress and fishing within estuaries than would be the case outside estuaries. Therefore, the negative effects resulting from the unstable and unpredictable nature of estuaries need to be outweighed by the benefits of estuarine-dependence, such as access to rich food resources and the ability to find refuge in estuaries from adverse, sometimes lethal conditions in the sea.

During summer, the prevailing southerly winds along the west coast of South Africa cause upwelling of nutrient-rich bottom water and the development of dense phytoplankton blooms that provide a vital source of food for fish and other marine organisms. These blooms are usually of short duration as they are soon dispersed offshore by the onset of another southerly blow. Towards autumn the southerly winds are less frequent and the blooms may persist for a week or more and sometimes turn the water brown, red, orange, green or purple in colour (Pitcher and Calder, 2000). These blooms may be toxic but in most cases are not.

In March 1994, a strong southeasterly followed by a week of windless days facilitated the development of a non-toxic "red tide" in St Helena Bay. Calm conditions persisted and the bloom began to decay, bacterial decomposition reducing oxygen levels in the water and turning the sea black with the production of hydrogen sulphide. Marine life died either from suffocation or hydrogen sulphide poisoning and approximately 1500 t of fish were washed up on the shore (Matthews and Pitcher, 1996). The anoxic water extended a short way into the Berg River Estuary and local fishers reported catching fish struggling on the surface in the vicinity of the mouth. Further up the estuary, larger-than-average commercial catches of the southern mullet (*Liza richardsonii*) were reported and fisheries compliance officers had to be reinforced in number to cope with an influx of illegal gillnet fishers.

Fortuitously, an unrelated study addressing altered freshwater flows was carried out in the Berg River Estuary in 1993, the year prior to the low-oxygen event there, provided data before the event that could be compared with data gathered during and after the event in 1994 and 1996 respectively (Bennett, 1994), allowing comparison of the species composition, abundance and distribution of the fish assemblage of the Berg River Estuary during these three times. In doing so, it could also be established which fish found refuge in the estuary as a means of escaping the lethal effect of anoxia in the sea. The life-history characteristics that allowed particular groups to employ estuaries to escape the low-oxygen 'black tide' event could also be ascertained.

2. Methods

2.1. Study area

The Berg River falls within the cool temperate winter rainfall zone of South Africa. It is 294 km long and drains a catchment of approximately 4000 km^2 with a mean annual runoff of 693×10^6 m^3 (Bennett, 1994; Harrison, 1997; Morant et al., 2001). The Berg River Estuary (32°46′S, 18°09′E), one of only three permanently open estuaries on the west coast, flows into the Atlantic Ocean at Laaiplek in St Helena Bay (Fig. 1). The estuary, including floodplain wetland, is approximately 3615 ha in area and meanders over an extensive floodplain; tidal effects are measurable 69 km upstream (Day, 1981; Slinger and Taljaard, 1994; Turpie et al., 2002). Much of the lower 15 km comprises mudflats and saltmarsh but the final 4 km are dredged to maintain a harbour for purse-seine boats and an entrance to the Port Owen Marina. The original mouth closed with harbour construction and a new mouth was excavated and stabilized with concrete approximately 1 km to the north. In the process, the old channel became a blind-arm that is gradually silting up.

2.2. Sampling

The fish assemblage of the Berg River Estuary was sampled at 32 sites from the mouth to Kersefontein, 40 km upstream (Fig. 1), during the summer months of February and March, before (1993), during (1994) and after (1996) a low-oxygen, hydrogen sulphide event that occurred in the adjacent sea. The 1993 sampling was part of a broad multidisciplinary study addressing the freshwater requirements of the Berg River Estuary (Bennett, 1994).

Fish were sampled using a 30-m long, 2-m deep, 12-mm stretched-mesh seine-net with 50-m hauling ropes. The net was set parallel to the shore from a 3 m-long rowing boat and hauled shorewards by 5–10 persons. Mean area swept was 320 m^2. Salinity was measured using a handheld refractometer, water clarity with a Sechii disk and temperature with a standard mercury thermometer. Dissolved oxygen (DO) levels were not sampled during 1993 but were measured during 1994 and 1996. During 1994, limited surface and bottom water samples were taken at 5 sites from the mouth to approximately 8 km upstream, whereas in 1996 surface and bottom water samples were taken at all 32 sites. Water samples were analysed for oxygen using the Winkler titration method. All fish caught in each seine haul were identified, counted, and their total lengths measured. In the instance of large catches, the haul was sub-sampled and a minimum of 100 fish of each species measured.

Species composition and abundance of fish washed up on the beach adjacent to the Berg Estuary mouth during the low-oxygen event were estimated by walking along ten 25-m long by 2-m wide transects and counting and identifying all fish seen. All fish caught in the estuary or washed up on the beach were categorized in terms of their dependency on estuaries according to the five-category classification scheme originally proposed by Wallace et al. (1984) and refined by Whitfield (1994), based on life-history characteristics (Table 1).

2.3. Data analysis

Catch-per-unit-effort data (*cpue*, number of fish per haul) were partitioned among ten 4-km reaches and analysed using Plymouth