A PRELIMINARY EXAMINATION OF SELECTED BIOLOGICAL LINKS BETWEEN FOUR EASTERN CAPE ESTUARIES AND THE INSHORE MARINE ENVIRONMENT

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ABSTRACT

The coastal transition zone (CTZ), which links the terrestrial and marine environments, has been identified as a region of high biological diversity and elevated production. Results of studies conducted in the northern hemisphere indicate that the links between estuaries and the adjacent marine environment is critical to ecological functioning within the CTZ. This study assessed the influence of selected estuaries with different hydrodynamic characteristics on the adjacent marine environment along the south-eastern coastline of southern Africa. Four estuaries were examined, including two permanently open systems, the fresh water deprived Kariega and fresh water dominated Great Fish, and two temporarily open/closed estuaries (TOCE), the Kasouga and East Kleinemonde.

Results of the study indicated that outflow of estuarine water from the Great Fish Estuary contributed to a plume of less saline water being evident within the adjacent marine environment. The plume of water was associated with increased zooplankton biomass and particulate organic matter (POM) and chlorophyll-*a* concentrations. Adjacent to the Kariega Estuary, no evidence of fresh water outflow into the marine environment was observed. However, in the sea directly opposite the mouth of the estuary an increase in zooplankton abundance and biomass was evident. Results of numerical analyses indicated that the increase in zooplankton abundance observed adjacent to the mouth of both permanently open estuaries could not be attributed to the export of zooplankton from the estuary, but rather the accumulation of marine species within the region. The mechanisms responsible for this accumulation were not determined, but it was thought to be associated with increased food availability in the estuarine frontal zone. A similar, but less dramatic biological response was also observed in the marine environment adjacent to the two TOCEs. It is suggested that the increase in biological activity within these regions could be ascribed to seepage of estuarine or ground water through the sand bar that separates these estuaries from the sea.

Results of stable carbon isotope analyses indicated that both the Great Fish and Kariega estuaries exported carbon to the nearshore marine environment. The area influenced by estuarine derived carbon was dependent on the volume of estuarine outflow to the marine environment. Adjacent to the fresh water dominated Great Fish Estuary, estuarine derived carbon was recorded up to 12km from the mouth, while adjacent to the fresh water deprived Kariega, estuarine derived carbon was only evident directly opposite the mouth.

The recruitment of macrozooplankton (> 2cm) into the fresh water deprived Kariega Estuary was in the range recorded for other permanently open southern African estuaries with higher fresh water flow rates. This indicates that the mechanisms which allow estuarine dependent larvae to locate and enter estuaries are not related to fresh water inflow.

In conclusion, this study has demonstrated that despite their small size relative to European and North American systems, South African permanently open and temporarily open/closed estuaries also influence biological activity within the adjacent nearshore marine environment.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

The Coastal Transition Zone (CTZ) has been defined by Schaefer (1972) as “the sea and the land adjacent to the interface, encompassing that region where terrestrial activities importantly impinge on the marine environment, marine resources and marine activities and where marine activities importantly impinge on the environment, resources and activities of the land”. The CTZ is an important area both anthropogenically and biologically. Levin *et al.* (2001) consider the CTZ as biologically important as it is an area of intense interactions resulting in enhanced species richness, biodiversity and productivity. Costanza *et al.* (1997) describe the CTZ as being a “keystone” habitat, providing both ecosystem and human services out of proportion to its areal extent. The provision of ecosystem services out of proportion of the CTZ’s areal extent is well demonstrated by Liu *et al.* (2000) who have determined that the CTZ provides approximately 20% of the world’s oceanic production, yet represents only ≈8% of the earths total surface area. Costanza *et al.* (1997) state that globally, coastal habitats contribute ecological services with a total economic value of US$12.568 trillion per year, with estuaries providing economic services that amount to a global total of US$0.411 trillion per year. Due to the limited surface area of estuaries, on a per hectare basis, the ecological services they perform contribute the greatest economic value out of any ecosystem on the planet, at a global average of US$22 832 per hectare per year (Costanza and Daly, 1992; Costanza *et al.*, 1997). The areal extent of the CTZ is dependent on a variety of factors, including the width of the continental shelf and local hydrography, as well as the size and hydrodynamics of adjacent estuaries.

In terms of human services, different authors have considered the CTZ important due to high anthropogenic use of this zone (Bruton, 1988; Vitousek *et al.*, 1997; Talley *et al.*, 2003). Vitousek *et al.* (1997) and Talley *et al.* (2003) have calculated that approximately 60% of the world’s human population, a total of 3.8 billion people, live within 100km of the coastline. The high densities of humans within the coastal regions of the world can be related to several factors, including the provision of bulk transportation services, production of energy (previously hydrocarbon sources and currently renewable electricity), the abundance of food resources and in more recent times, the recreational potential of the zone (Talley *et al.*, 2003). Pauly and Christensen (1995) analysed the consumption of the ocean's primary productivity by fisheries and determined that globally, 8% of the total primary productivity was used. However, when coastal shelf systems were viewed in isolation, approximately 35% of shelf primary productivity was used by human fisheries. This study did not consider estuarine and fresh water fisheries that would have contributed to productivity used within the CTZ. Exploitation of the CTZ is very high, and therefore an understanding of the ecological and biotic links within this zone is urgently required (Levin *et al.*, 2001; Talley *et al.*, 2003). Estuaries are considered critical as a link between the interactions occurring in the CTZ and particularly between the sea and fresh water aquatic habitats (Costanza *et al.*, 1997; Levin *et al.*, 2001; Gillanders and Kingsford, 2002).

It has long been hypothesised that due to the direction of flow through estuaries being predominantly seaward, the net transport of material, particularly phytoplankton and detrital biomass is similarly in a seaward direction (Dame and Allen, 1996; Roegner and Shanks, 2001). Odum (1968; 1980) proposed the "outwelling hypothesis", which states that estuaries (and associated habitats) have a greater rate of production than consumption and decomposition. As a result, excess production will be exported to the nearshore marine environment. This hypothesis has been examined in terms of a variety of components of estuaries (different forms of carbon, nitrogen, phosphorus, sediments and metals) throughout the world (Black *et al.*, 1981; Boto and Bunt, 1981; Miller and Shanks, 2004; Newton and Stephen, 2005; Dean *et al.*, 2005), and in South Africa (carbon and particulate matter: Baird *et al.*, 1987; Winter *et al.*, 1996; inorganic nutrients: Baird and Winter, 1989; Winter and Baird, 1991). The general trends resulting from these studies have been inconclusive, with the primary finding being that the degree of interaction between estuaries and the sea appears to be reliant on the fresh water flow rates entering the specific estuary.

Several international studies have investigated links between estuaries and the marine environment in terms of larval and adult export/connectivity and chlorophyll-*a* export (Sanchez-Velasco *et al.*, 1996; Roegner, 1998; Roegner and Shanks, 2001; Dale and Prego, 2003; Espinosa-Fuentes and Flores-Coto, 2004). Sanchez-Velasco *et al.* (1996) and Espinosa-Fuentes and Flores-Coto (2004) identified an estuarine larval fish community in the marine environment adjacent to Terminos Lagoon, a permanently open estuarine lagoon on the southern Gulf of Mexico. Both of these studies identified a shifting larval community offshore of the lagoon that was dependent on the fresh water flow rate through the system. Similarly, Roegner (1998) identified a continuous seaward flow of chlorophyll-*a* from the Eel River in Nova Scotia, with the rate of chlorophyll-*a* export into the adjacent marine environment being proportional to the magnitude of fresh water flow into the system. In contrast, a study on the South Slough arm of Coos Bay (west coast of the United States) found that there was a continual import of marine derived chlorophyll-*a* into the estuary (Roegner and Shanks, 2001). Finally, Dale and Prego (2003) identified a seasonal nature in nutrient fluxes between the Chupa Estuary and the White Sea, with low autumnal flow rates resulting in an influx of nutrients and higher summer flow rates resulting in nutrient export. The importance of fresh water flow cannot, therefore, be underestimated in terms of connectivity within the CTZ.

When considering the biological connectivity of estuaries and the marine environment, a large number of studies have focused on the ichthyofauna, and to a lesser extent, invertebrate use of estuaries as nursery areas. Several authors (Wicker *et al.*, 1988; Vance *et al.*, 1998; Herzka *et al.*, 2001; Gillanders *et al.*, 2003; Herzka, 2005; Able, 2005) have reviewed available studies on fish and invertebrate species that enter estuaries during their juvenile phases and accumulate biomass in these systems before leaving to the marine environment. Very few studies have, however, attempted to quantify the export of biomass by these fauna from estuaries to the marine environment. Deegan (1993) investigated a single estuarine-dependent fish species in an attempt to identify the estuarine-marine transfer of nutrients and energy by fish migration. The study demonstrated that due to the use of Fourleague Bay as a nursery area, Gulf Menhaden were responsible for exporting between 5 and 10% of the system’s primary production.

In addition to the movement of biotic material between estuaries and the marine environment, the influence of estuarine water entering the marine environment needs to be considered. The zone of interaction between estuarine and marine water is termed an “estuarine front” (Largier, 1993; Jasinska, 1993; Gillanders and Kingsford, 2002). Estuarine fronts may occur in the adjacent marine environment or the lower reaches of an estuary and are considered highly productive zones due to the continual supply of nutrients and well oxygenated water to these areas (Largier, 1993). The temporal and spatial scales of estuarine frontal systems vary depending on the fresh water flow rates of the adjoining estuary and river (Gillanders and Kingsford, 2002). For example, the Amazon River provides 200 000$m^3.s^{-1}$ of water to a frontal system extending for over 120km offshore and 500km along the coast (Curtin, 1986). Alternatively, in the Burdekin River in Australia, which is characterised by low fresh water inflow rates (5$m^3.s^{-1}$), the front is occasionally within the estuary or extends, at most, 0.3km directly offshore (Thorrold and McKinnon, 1992).

Despite these large spatial variations in estuarine frontal systems, O’Donnell (1993) and Largier (1993) consider these areas to be of importance for inshore marine productivity. Largier (1993) noted that despite some estuarine fronts being short lived, their recurrent periodic nature allowed biota such as zooplankton and nekton, with longer reproductive cycles, to congregate in the region where the frontal system develops and benefits from the increased productivity that occurs. The higher trophic levels either actively enter the frontal regions to exploit the increased levels of primary and secondary productivity within these features, or are passively transported into the frontal region due to convergent surface flows (Largier, 1993). Estuarine frontal systems have been considered important, not only due to the localised area of higher productivity and increased food availability, but due to the benefits of deposition of detritus, particulate organic matter and sediment to deposit feeders on continental shelves, and as a cueing system to allow fish and invertebrates to navigate to estuarine nursery areas (Gillanders and Kingsford, 2002; Gillanders *et al.*, 2003).

The international literature, therefore, indicates contrasting results when considering estuarine to marine transport and interaction, with the volume of biological matter moving between these environments largely being dependent on the mouth status and the magnitude of fresh water outflow from these systems.

1.1.1 Estuaries and the CTZ in South Africa

Pritchard (1967) defined an estuary as “a semi-enclosed body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage”. This definition is limiting for South African estuaries due to two phrases, “a free connection with the open sea” and “sea water measurably *diluted* with fresh water”. Many South African systems are under natural conditions separated from the sea for varying periods of time and several systems may have hypersaline conditions or be completely marine due to high rates of evaporation or low fresh water inputs (Day, 1980). As a result, Day (1980) suggested a revised definition that would include South African systems with low fresh water flow rates (whether naturally or due to anthropogenic influences) and those that close from the sea for varying periods. Day’s (1980) definition states that: “An estuary is a partially enclosed body of water which is either permanently or periodically open to the sea, and within which there is a measurable variation of salinity due to the mixture of sea water with fresh water derived from land drainage”.

This definition identifies 258 bodies of water along the South African coastline as estuaries (Whitfield, 2000). Despite the inclusion of a broad range of geomorphological and physico-chemical characteristics, Whitfield (1992a) devised a classification system which allows grouping of southern African estuarine systems based on their physiographical, hydrographical and salinity characteristics into five basic estuarine classes. The five classes are estuarine bays, river mouths, estuarine lakes, permanently open systems and temporarily open/closed estuaries (otherwise known as intermittently open/closed estuaries). Permanently open estuaries are those systems that retain their connectivity to the sea at all times, while temporarily open/closed estuaries (TOCEs) are separated from the marine environment, forming small lagoons at different times and for varying periods throughout the year (Whitfield, 1992a).

The marine borders of the CTZ along the South African coast are relatively narrow due to the boundary currents along both the east and west coast of the country. Along the northern half of the Eastern Cape coastline the continental shelf is narrow, allowing the Agulhas Current to meander between 20 and 30km offshore (Lutjeharms, 1998; Lutjeharms, 2005), restricting the influence of any terrestrially derived constituents within this region. Temporal patterns within the CTZ are dominated by annual seasonal changes, with the biological cycles being strongly linked to the seasonal patterns in temperature and rainfall (Costanza *et al.*, 1997; Levin *et al.*, 2001). The degree of interaction between the terrestrial and marine zones of the CTZ in southern Africa is also strongly linked to the seasonal rainfall patterns as many of the estuaries in this region rely on rainfall to maintain a link to the marine environment (Whitfield and Bruton, 1989; Whitfield and Wooldridge, 1994; Whitfield and Lubke, 1998).

1.2 MANAGEMENT IMPLICATIONS

As discussed earlier, estuaries and the CTZ are important in biological terms due to the services they provide to surrounding communities (Costanza *et al.*, 1997; Vitousek *et al.*, 1997; Talley *et al.*, 2003). Lamberth and Turpie (2003) attempted to demonstrate the economic importance of fisheries within southern African estuaries. They estimated that estuarine based fisheries landed a total catch valued at approximately R433 million per year (US$62.75 million), and inshore marine fisheries targeting estuarine dependent fish species totalled an additional R490 million (US$71.01 million) per year. The total value of estuarine and estuary-dependent fisheries during the 2002 financial year was estimated to have been approximately R1.251 billion (US$181.30 million) (Lamberth and Turpie, 2003). Other estuarine dependent fisheries including the estuarine and offshore based penaeid prawn fishery, which is estimated at a total value of R10 million (US$1.45 million) per year (De Villiers *et al.*, 1999) were not considered in this study. In addition to the recreational and commercial fisheries on southern African estuaries, due to the impoverished nature of the region, the CTZ, and estuaries in particular, provide important resources for subsistence to communities living close to the shore (Breen *et al.*, 2004).

Southern Africa is considered a water-poor region, with a mean annual runoff of ≈450mm.yr^{-1}, approximately half the world average of 860mm.yr^{-1}, coupled with relatively high evaporation rates (DWAF, 2004a). Additionally, there are no large or navigable rivers in the region and the total river runoff in the country equates to less than half the flow of the Zambezi River in Mozambique (DWAF, 2004a). To meet the increasing demands for fresh water, water managers are considering constructing additional impoundments along the major river systems in the sub-region (DWAF, 2004a). However, the National Water Act of 1998 (Act 36) established the requirement that all river systems should be considered in terms of two Water Reserves, a basic human needs reserve and an ecological reserve. The ecological reserve relates to "the water required to protect the aquatic ecosystems of the water resource", including river systems, estuaries and the marine environment. South African water managers have been slow to acknowledge that estuaries are a legitimate user of water and prior to the National Water Act of 1998, water running into estuaries was considered wasted (Burman, 1970; Morant and Quinn, 1999).

Despite this legislation, water supplies to estuaries are under increasing threat. South Africa's economy is growing at a relatively high rate of 4.2% per annum (Reuters, 2006), which is associated with increased water use in the industrial and agriculture sectors (Reddering and Rust, 1990; Cooper *et al.*, 1999). Furthermore the provision of basic sanitation services and potable water to segments of the population that were disadvantaged under the previous dispensation has exacerbated the increased demand for fresh water (ETU, 2002). In addition to the threat of reduced fresh water runoff into the CTZ, current global climate trends threaten intertidal wetland areas due to sea level rise and corresponding decreases in the areal extent of intertidal wetlands as well as the tidal gradients within these systems (Warwick *et al.*, 1996).

As a result of increased demands for fresh water, a number of national programmes have been initiated to assess water requirements of natural ecosystems, including rivers and estuaries. To date, limited work has investigated the potential influence of fresh water on the marine nearshore environment. Should fresh water flow into the marine environment be seen to influence the nearshore productivity or ecology, then the ecological reserve would have to be calculated to accommodate this. To date there is one report linking fresh water flow rates to offshore productivity. The DWAF (2004b) report demonstrated that fresh water flow rates of rivers into the marine environment along the east coast of South Africa (KwaZulu-Natal) affected the productivity of the adjacent Thukela Banks, with high flow rates providing good recruitment to the adjacent linefishery, while years of low flows corresponded to poor recruitment into the fishery. More studies are required on the effect of fresh water inflow into the marine environment, and particularly the nearshore environment, to allow water managers to adequately understand the effect of reduced river runoff.

1.3 ESTUARINE-MARINE INTERACTIONS

To date, South African estuarine research has examined the physico-chemical environment and general ecology of these systems, including specific components of the flora or fauna (e.g. the ichthyofauna: Cyrus and Blaber, 1987; Whitfield, 1996; zooplankton: Wooldridge and Erasmus, 1980; Froneman, 2004a; or macrophytes: Wortmann *et al.*, 1998; Colloty *et al.*, 2001), ecological interactions within individual estuaries (Schlacher and Wooldridge, 1996a), comparisons between different systems (Vorwerk, 2000; Vorwerk *et al.*, 2001; Perissinotto *et al.*, 2003; Thomas *et al.*, 2005) and in more recent times, the river-estuary interface (Whitfield and Wooldridge, 1994; Grange and Allanson, 1995; Grange *et al.*, 2000; Whitfield and Wood, 2003). The current research has highlighted dissimilarities between estuaries with different flow rates and therefore the importance of fresh water flow rates in determining the structure of these systems.

High fresh water flow rates are considered important in forming structured salinity gradients within estuaries, which, in combination with higher turbidity, is considered a crucial cue to estuarine dependent marine species (Cyrus and Blaber, 1987; Cyrus and Blaber, 1992; Harris and Cyrus, 1996). The biological community structure within estuaries has been strongly related to these varying salinity and turbidity regimes that are associated with fresh water inflow (Grange and Allanson, 1995; Ter Morshuizen *et al.*, 1996a and b), indicating the importance of flow rates to the structuring of these communities.

Several authors have debated the influence of fresh water flow rates and the resultant physico-chemical cues in aiding fish larval recruitment into South African estuaries (Beckley, 1985; Bennett, 1989; Whitfield, 1989a and b; Whitfield, 1996; Harris and Cyrus, 1996; Whitfield, 1998; Vorwerk *et al.*, 2001; Harris *et al.*, 2001; Bell *et al.*, 2001). It is currently uncertain which physico-chemical variable fish larvae use to locate an estuarine nursery area, with some authors indicating turbidity preferences amongst larvae, while others indicate salinity gradients and olfactory cues as driving forces for larval recruitment (Cyrus and Blaber, 1987; Whitfield, 1989a; Whitfield, 1998). However, most authors agree that fish larvae do congregate in the surf zone adjacent to estuaries, with a distinctly estuarine recruiting community existing in this area (Whitfield, 1989a; Harris *et al.*, 2001; Cowley *et al.*, 2001). Accumulations of estuarine dependent marine larvae have also been recorded adjacent to the mouths of TOCEs (Whitfield, 1989a; Harris and Cyrus, 1996), where the larvae remain awaiting a recruiting opportunity such as a breaching or overtopping event (Cowley *et al.*, 2001; Bell *et al.*, 2001; Kemp and Froneman, 2004). Most of the current studies agree that the fish larval accumulations in the surf zones adjacent to estuaries are for recruiting purposes, but authors have generally not considered the potential of feeding aggregations as the degree and sources of primary productivity adjacent to South African estuaries is currently unknown.

In conjunction with structuring the physico-chemical environment and fish communities within estuaries, fresh water inflow has been identified as promoting production within these systems. Froneman (2000; 2001a) recorded lower primary production (18.1 – 37.7mg C $m^{-3}.d^{-1}$) and chlorophyll-*a* concentrations (1.12 – 2.13mg chl-*a* m^{-3}) in the fresh water deprived Kariega Estuary than had been recorded in neighbouring fresh water dominated systems such as the Great Fish Estuary by other authors (Table 1.1). The low production in the Kariega Estuary has been confirmed by several authors (Grange and Allanson, 1995; Grange *et al.*, 2000) and attributed to very low fresh water inflow reducing the nutrient availability within this system. Similar results have been recorded within TOCEs, with Froneman (2002a) and Gama *et al.* (2005) both recording higher chlorophyll-*a* concentrations in these systems during high riverine flow rates. Thomas *et al.* (2005) similarly related the high chlorophyll-*a* concentrations in the TOC Mhlanga and Mdloti estuaries, along the east coast of southern Africa, to high base flows and nutrient concentrations entering these systems due to waste water treatment works in their catchments.

The abovementioned relationship between fresh water inflow and primary production has been identified as having a secondary effect on the zooplankton biomass within estuaries. Froneman (2002a), Kibirige and Perissinotto (2003) and Nozias *et al.* (2001) have identified a substantial increase in the zooplankton biomass within TOCEs during flood phases relative to closed or overwash phases. The large increase in zooplankton was primarily associated with the coincident increase in food (phytoplankton) availability as well as temperature and salinity changes. Reduced fresh water inflow has also been demonstrated to cause a shift in the phytoplankton cell size, to smaller phytoplankton species (Froneman, 2000; Froneman, 2001a; Gama *et al.*, 2005). The smaller phytoplankton cells are reportedly not available to copepods (dominant zooplankton group) for grazing and as a result can affect the abundance of these primary consumers in estuaries as well as reducing the abundance of secondary and tertiary consumers (Froneman, 2000; Kibirige and Perissinotto, 2003; Froneman, 2004b). In some instances the copepods within estuaries have been demonstrated to switch diets in these systems, and the food web changes from an autochthonous phytoplankton driven system to one that is driven by allochthonous detrital inputs and benthic algae (Froneman, 2001a and b; Perissinotto *et al.*, 2002).

Table 1.1: Water column chlorophyll-*a* values published for South African estuaries (after Adams *et al.*, 1999). PO indicates permanently open, while TOC indicates a temporarily open/closed system.

Estuary	**Chlorophyll-*a* (µg.l^{-1})**		**Mean Annual Runoff (x10^6 m^3)**	**Estuary Type**	**Reference**
	Minimum	**Maximum**			
Van Stadens	0.8	14.2	Unknown	TOC	Gama *et al.*, 2005
Maitland	7.29	138	Unknown	TOC	Gama *et al.*, 2005
Sundays	12	>100	202.26	PO	Hilmer and Bate, 1990; Hilmer and Bate, 1991
Kariega	1	8	5	PO	Allanson and Read, 1995
Kasouga	0.19	5.68	Unknown	TOC	Froneman, 2002a
Great Fish	0	210	224	PO	Lucas, 1986; Allanson and Read, 1995
Keiskamma	0	19	142.7	PO	Allanson and Read, 1995
Nyara	<0.01	4.1	Unknown	TOC	Perissinotto *et al.*, 2000
Mdloti	0.869	111	Modified 8Ml.d^{-1} Sewage Effluent	TOC	Thomas *et al.*, 2005
Mhlanga	0.732	303	Modified 20Ml.d^{-1} Sewage Effluent	TOC	Thomas *et al.*, 2005

Considering the amount of information available on the impact of fresh water on estuaries and its coincident ecological importance, the relative lack of information on the effect that estuarine or fresh water has on the marine environment is surprising. It is generally accepted that there is a paucity of information in South Africa on links within the CTZ and particularly those biological links between estuaries and the sea (Fennessy *et al.*, 1997; SANCOR, 2003; NRF, 2003).

In terms of biomass, several authors support the "outwelling" theory and have hypothesised a net export from southern African estuaries due to the use of these systems as nursery areas for fish and invertebrates resulting in the emigration of juvenile/sub-adult individuals, which have accumulated biomass within estuaries, to the marine environment (Cyrus and Forbes, 1996; Cowley *et al.*, 2001; Bell *et al.*, 2001; Bernard and Froneman, 2005). Of particular importance commercially are the penaeid prawns, which Forbes *et al.* (1994) and Forbes and Demetriades (2005) have identified as requiring an estuarine phase during their juvenile development. Reducing the ability of the penaeids to use estuaries would have disastrous consequences for the fishery on the adjacent Thukela Banks (Forbes *et al.*,1994; Cyrus and Forbes, 1996; Fennessy *et al.*, 1997). Alternatively, some studies have indicated a substantial import of biomass during overtopping events into TOCEs and the use of this imported biomass by a variety of predators in the estuary (Froneman, 2004a; Kemp and Froneman, 2004).

To date there has been a single South African study investigating the influence of estuarine water on the biology in the nearshore marine environment. Harris *et al.* (2001) investigated the changes in the ichthyoplankton communities along the ocean-estuarine gradient in the nearshore environment adjacent to Lake St Lucia (north-east coast of South Africa) and demonstrated distinct communities related to each of these zones, which appeared to separate based on the turbidity occurring within each zone.

The productivity in the continental shelf waters off South Africa is generally considered to be fuelled by nutrient-rich water reaching the photic zone through upwelling (Brown and Hutchings, 1987; Richardson *et al.*, 2003). This appears to be on a pulsing basis with upwelling events being either wind-driven or occurring due to shear-edge eddies upwelling colder water at their cores (McMurray *et al.*, 1993; Lutjeharms *et al.*, 2000). Alternatively, in the marine inshore zone, Campbell and Bate (1998) suggested the productivity of diatoms in the surf zone adjacent to the Alexandria dunefields was sustained by groundwater seepage from dune aquifers. Fennessy *et al.* (2000) suggested that adjacent to the Thukela River, the inshore phytoplankton productivity was limited due to the highly turbid nature of the estuarine water flowing from this system. However, the high density of rocky inshore invertebrates along the coast adjacent to the Thukela River was ascribed to the high concentration of terrigenous outputs from this system (Fennessy *et al.*, 2000). To date no studies have investigated the nearshore region, between the surf zone and the coastal ocean, to attempt to identify the source of biomass and productivity in this region.

1.4 OBJECTIVES

The influence of estuaries on the nearshore biology remains largely unclear. This study attempts to address the paucity of information available regarding the estuarine component of the CTZ in South Africa. The main objective of the study was to attempt to identify specific biological interactions between estuaries and the marine environment and to investigate the applicability of the outwelling hypothesis in terms of biological export or import from/to these systems. The study focused on specific physico-chemical and biological components, including water temperature, salinity, particulate organic matter, chlorophyll-*a*, the zooplankton community structure and the food web structure between estuaries and the marine environment.

1.5 THESIS STRUCTURE

This thesis is structured in such a way that each chapter is independent (i.e. deals with its own topic), although all the chapters are linked to one another in dealing with estuarine-marine links. Each chapter has its own brief introduction, the materials and methods used in answering the relevant questions, the results and a brief discussion. If the same materials and methods have been used in more than one chapter the initial mention of those methods will be referred to.

Chapter 2 – Study Area: A complete description of the study sites (i.e. specific estuaries) where the study was conducted is provided, including a detailed description of the Eastern Cape coastal zone.

Chapter 3 – The effect of two permanently open estuaries with contrasting fresh water flow rates on zooplankton in the adjacent nearshore environment: This chapter aims to identify links between the biology of two estuaries with contrasting fresh water flow regimes, the Kariega and Great Fish estuaries, and the adjacent nearshore environment.

Chapter 4 – The effect of temporarily open/closed estuaries on zooplankton communities in the adjacent nearshore environment: Chapter 3 examined the effect of permanently open estuaries on the zooplankton in the nearshore environment as these systems are more likely to have an impact due to the open condition of their mouths. This chapter deals with the effect of smaller estuaries on the zooplankton communities in the nearshore environment, to identify whether they have an impact despite the predominantly closed nature of their mouths.

Chapter 5 – The importance of estuarine derived carbon for the nearshore marine environment: A stable carbon isotope approach on two permanently open Eastern Cape estuaries: Chapter 5 examines the importance of estuarine derived carbon for the nearshore environment. The study was conducted in two permanently open estuaries with contrasting flow regimes, the Kariega and Great Fish estuaries.

Chapter 6 – Tidal import of macrozooplankton into a fresh water deprived, permanently open Eastern Cape estuary: This chapter presents the results of a study that documented the recruitment of macrozooplankton into the Kariega Estuary to identify diurnal and seasonal patterns of recruitment.

Chapter 7 – General Discussion: The final chapter discusses the results from the various experimental chapters in a combined format as well as comparing the results presented in the individual chapters to work conducted internationally. Finally, suggestions for future research on estuarine-marine interactions are provided.

CHAPTER 2

STUDY AREA

2.1 INTRODUCTION

This study was conducted in four estuaries along a 60km stretch of the Eastern Cape coastline, between the town of Kenton-on-Sea (33º 40′ 55.5″ S, 26º 40′ 27.9″ E) in the south-east and Fish River Mouth (33º 29′ 33.2″ S, 27º 08′ 11.9″ E) in the north-west (Figure 2.1). This area was selected due to the proximity of different estuaries with varying physico-chemical and hydrodynamic characteristics. The four estuaries studied included the Kariega, Kasouga, East Kleinemonde and Great Fish estuaries (Figure 2.1).

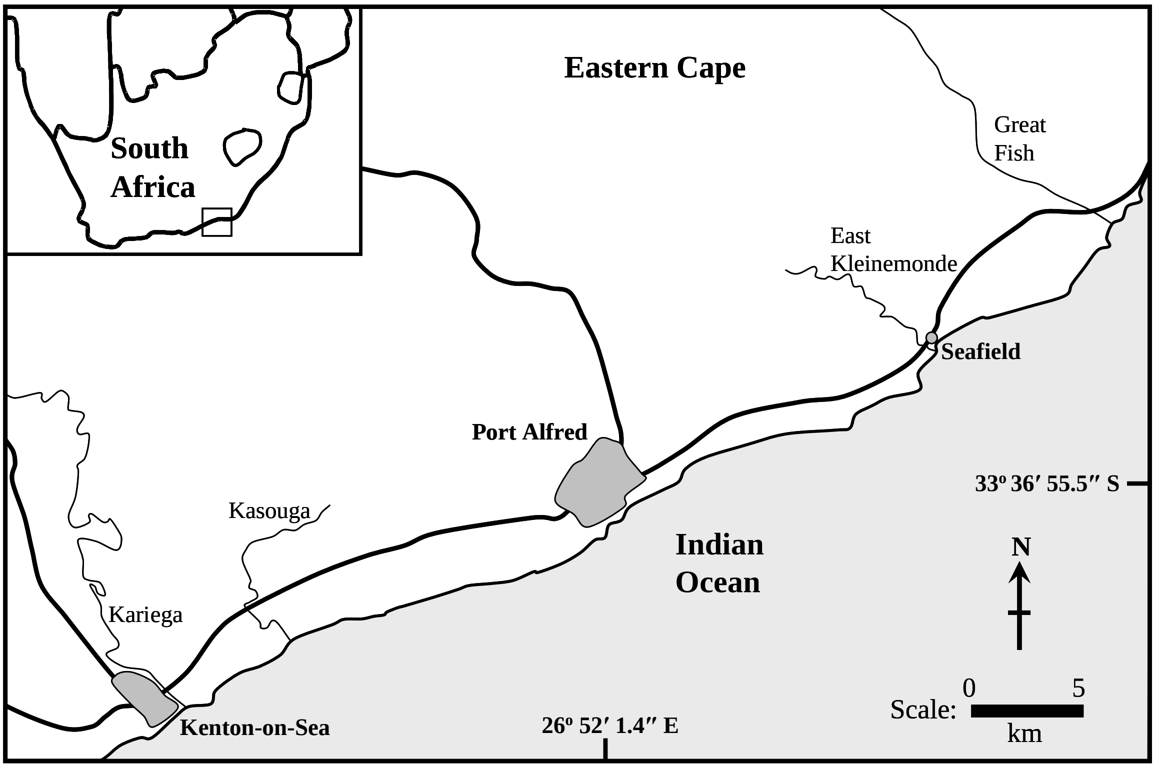


Figure 2.1: The study area showing the location of the four study estuaries along the Eastern Cape coast (adapted from Walton, 1984).

Three of the study estuaries, the Kariega, East Kleinemonde and Great Fish estuaries, were classified as being in a good condition by Whitfield (2000), indicating a moderate anthropogenic impact. The Kasouga Estuary, was classified as excellent, indicating minimal human impacts. All four systems are affected by the narrowing of their channels due to road bridges from the main coastal route (R72). In addition, all four estuaries have housing developments of varying sizes in close proximity to the lower reaches (Lubke, 1988; Whitfield, 2000). Land use in the catchments of these systems includes private game reserves and a variety of agricultural uses, mostly beef and pineapple farming.

This chapter provides a description of the coastline along the Eastern Cape and the estuaries studied. The methodology used to collect the physico-chemical data can be found in Chapter 3.

2.1.1 Climatic conditions

The climate in the Eastern Cape coastal zone is considered subtropical according to the Kopen system of climate classification (Lubke, 1988; Kopke, 1988; Lubke, 1998). The weather patterns in this region are primarily determined by the synoptic weather to the south and west, typically reaching the Eastern Cape one to two days after landfall on the west coast of South Africa (Stone, 1988).

The temperatures along the coastline typically range between 9.5ºC and 26.0ºC, with the minimum occurring in July and the maximum in February (Figure 2.2). Fluctuations in the air temperatures are reduced relative to the hinterland due to the regulating effect of the sea (Stone *et al.*, 1998). The maximum and minimum air temperatures recorded at Port Alfred from 1996 to 2005 were 38.5ºC (March 2003) and 1.9ºC (July 2002), respectively (as measured at 08h00, South African Weather Bureau records, *in litt.*). These temperatures can, however, be considered extremes (Stone, 1988; Stone et al.,1998).

The mean annual rainfall recorded at Port Alfred over the corresponding period was 604mm, with a maximum of 731mm in 1998 and a minimum of 396mm in 1999 (South African Weather Bureau records, *in litt.*). The rainfall observed in the coastal region demonstrates an autumn spring bimodal pattern (Figure 2.3), with a spring peak (Kopke, 1988). In addition to the annual pattern recorded, Grange *et al.* (2000)

have described a cyclical wet and dry climatic phenomena of between 12 and 20 years duration.

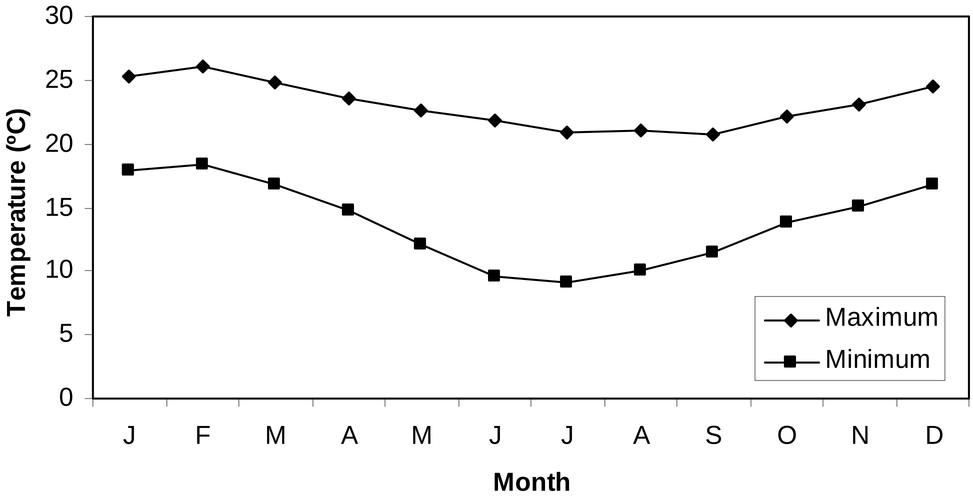


Figure 2.2: Daily air temperatures (ºC) averaged per month measured at Port Alfred between 1996 and 2005 (South African Weather Bureau records, *in litt.*).

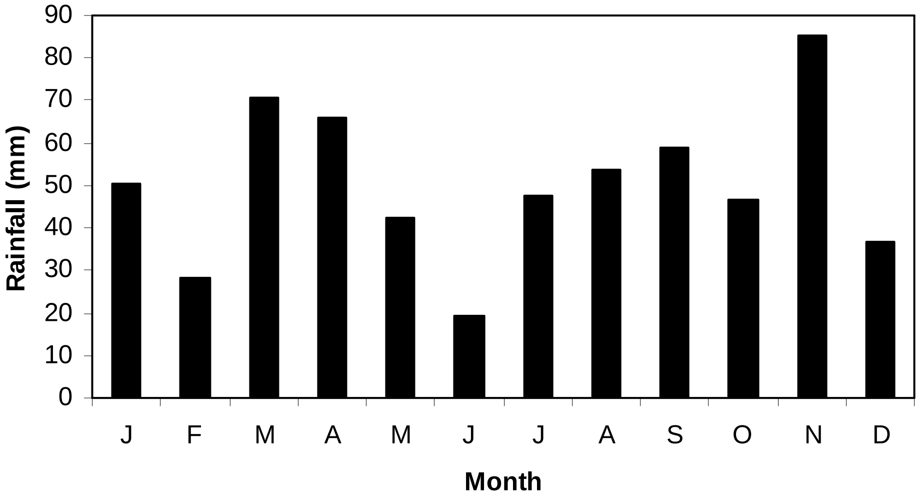


Figure 2.3: The mean monthly rainfall at Port Alfred between 1996 and 2005 (South African Weather Bureau records, *in litt.*).

2.1.2 Description of the coast

The 60km long coastline that forms the study area consists of sandy beaches and rocky headlands and promontories with a predominantly dune thicket vegetation type near the coast, and coastal grasslands or savanna further inland (Lubke, 1998). The sandy beaches are backed by large vegetated dunefields and separated by rocky headlands, which often extend into the inshore environment as reefs (Lubke, 1988).

The seafloor is predominantly sandy, with dune-rock and Aeolinite reefs in a patchy distribution to a depth of 50m. The continental shelf in this region is relatively narrow, with the 100m isoline approximately 25km offshore (Lutjeharms, 1998). The mean spring tidal range along the coastline is 1.61m and predominantly semi-diurnal with a small diurnal inequality (Mackay and Schumann, 1990).

2.1.3 Coastal hydrography

The area of the Eastern Cape coastline that incorporated the study estuaries is within the warm-temperate biogeographic region that is dominated by the Agulhas Current (Whitfield, 2000). This current system has two main sources of water, the South Equatorial Current and recirculation from the South West Indian Ocean subgyre, and extends from the tropics to the subtropical convergence (Lutjeharms, 2005).

The contribution from the South Equatorial Current arises on the east coast of Madagascar, where the water separates into the northern and southern East Madagascar Current (Figure 2.4). The northern branch rounds the tip of Madagascar and upon reaching the east coast of Africa splits again, contributing northwards to the Somali Current and southwards to the Mozambique Current in the Mozambique Channel (Lutjeharms, 2005). The southern arm of the East Madagascar Current and the Mozambique Current then converge at approximately 28ºS and flow in a southerly direction along the edge of the continental shelf (Payne and Crawford, 1989; Lutjeharms, 2005). Along most of the KwaZulu-Natal coast and the northern half of the Eastern Cape coastline this equates to a distance of 20 – 30km (Payne and Crawford, 1989; Lutjeharms, 1998).

In the region of Port Alfred, in the centre of the current study site, the Agulhas Current begins moving offshore due to the broadening of the continental shelf (Ross, 1988; Payne and Crawford, 1989). A system of mesoscale eddies form inshore of the current, especially when the core of the Agulhas has meandered offshore of the continental shelf (Lutjeharms, 1998). These eddies, in combination with wind-driven surface water movement, can result in the net movement of inshore water in a north-easterly direction (Ross, 1988; Lutjeharms, 2005). The Agulhas Current continues in a south-westerly direction along the outside edge of the Agulhas Bank until the force of the current can no longer be controlled and the system retroflects in an anticlockwise direction to form the Agulhas Return Current (Payne and Crawford, 1989; Lutjeharms, 2005).

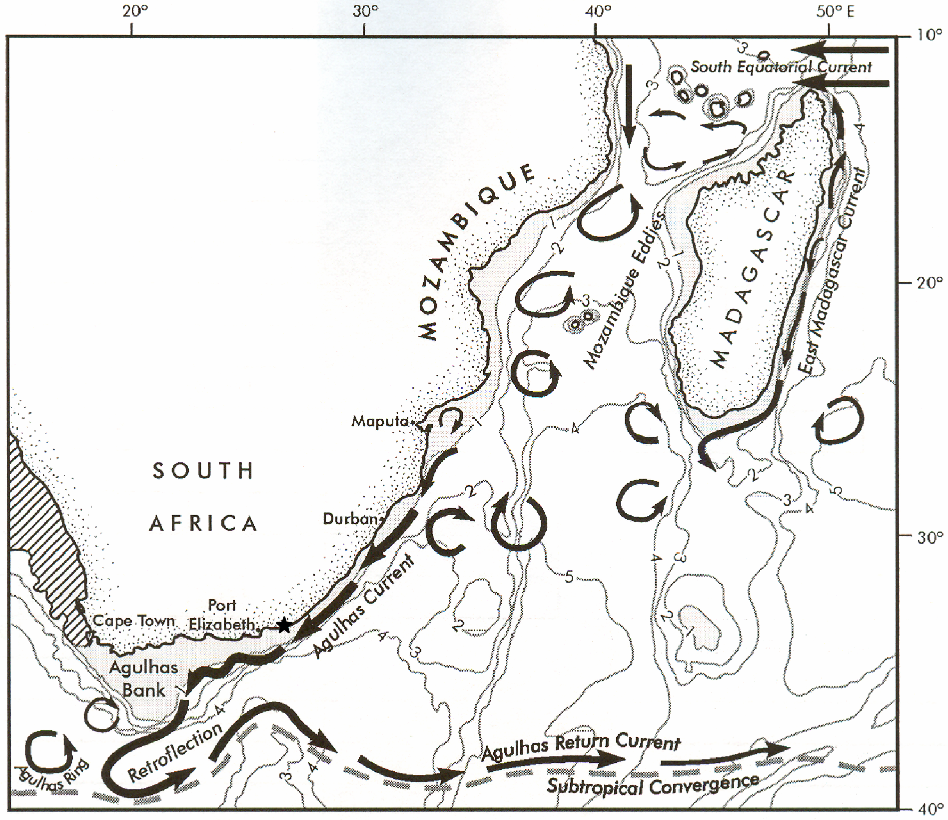


Figure 2.4: A general view of the Agulhas Current system showing its sources and the return current (after Lutjeharms, 2005). Contours represent depths (x 100m). The overlaid star indicates the position of Port Alfred.

Within the Agulhas Current system two regions of upwelling have been recorded, one off northern KwaZulu-Natal, where the continental shelf widens due to the Tugela Banks and one, of more relevance to this study, near Port Alfred, in the centre of the study area (Lutjeharms *et al.*, 2000). The presence of cold upwelled water was recorded in the Port Alfred region 45% of the time during a study covering a six year period and was suggested to be due to the widening of the continental shelf and the coincident moving of the Agulhas Current further offshore (Lutjeharms *et al.*, 2000). Both of these upwelling cells occur due to the widening of the continental shelf and the jet effect on the inshore edge of the current pulling deeper waters towards the surface.

Smaller recorded upwelling events in the coastal inshore zone include wind-driven and shear-edge eddy events (Lutjeharms, 2005). Wind-driven upwelling is caused when persistent easterly winds move surface waters causing upwelling of colder water that is already on the continental shelf to replace the surface waters (Schumann *et al.*, 1982). Intense shear-edge eddies occur along the continental shelf edge due to the passing Agulhas Current and these systems upwell cold water in their cores (Lutjeharms *et al.*, 1989a). All these upwelling events have a marked influence on the physical water bodies in the inshore zone, as well as the nutrients and biological primary productivity due to the upwelled water being several degrees centigrade cooler and having considerably higher nutrient concentrations than the surface waters (Lutjeharms *et al.*, 2000).

2.2 STUDY ESTUARIES

2.2.1 Great Fish Estuary

The Great Fish River Estuary (Figure 2.5) enters the sea at 33º 29′ 28″ S and 27º 08′ 06″ E (Vorwerk *et al.*, 2001) and is considered a permanently open estuary (Whitfield, 1992a). Land use along the east bank of the estuary is farmland, while a nature reserve is situated on the west bank. In the lower reaches a small camping site has been developed below the region where the main coastal road crosses the estuary (Vorwerk, 2000).

This system has a catchment size of 30 366km^2 producing a mean annual runoff of 525 x 10^6 m^3.yr^{-1} (NRIO, 1987). Prior to 1975, the system had a highly variable flow regime with extended periods of low flows resulting on occasion in mouth closure (Ter Morshuizen *et al.*, 1996a and b). However, in 1975 the flow rates were augmented by a transfer scheme from the Orange River system, resulting in near flood level flow rates reaching the estuary continuously (Ter Morshuizen *et al.*, 1996a and b). The Orange River transfer scheme was introduced by the South African Government to augment water supplies to the inland Eastern Cape farming districts. The average daily flow rate during the current study was 14.2m^3.s^{-1} (SD=16.5) with a range from 2.8m^3.s^{-1} to 137.2m^3.s^{-1} (Figure 2.6) (Department of Water Affairs and Forestry flow data, *in litt.*). The spring tidal prism is approximately 1.6 x 10^6 m^3, resulting in a tidal to river volume ratio of only 6:1 (Strydom *et al.*, 2002). The interaction between the tidal forcings and the high flow rates produce a distinct salt wedge to a distance of 10km from the mouth of the estuary (Ter Morshuizen *et al.*, 1996a and b; Strydom *et al.*, 2002).

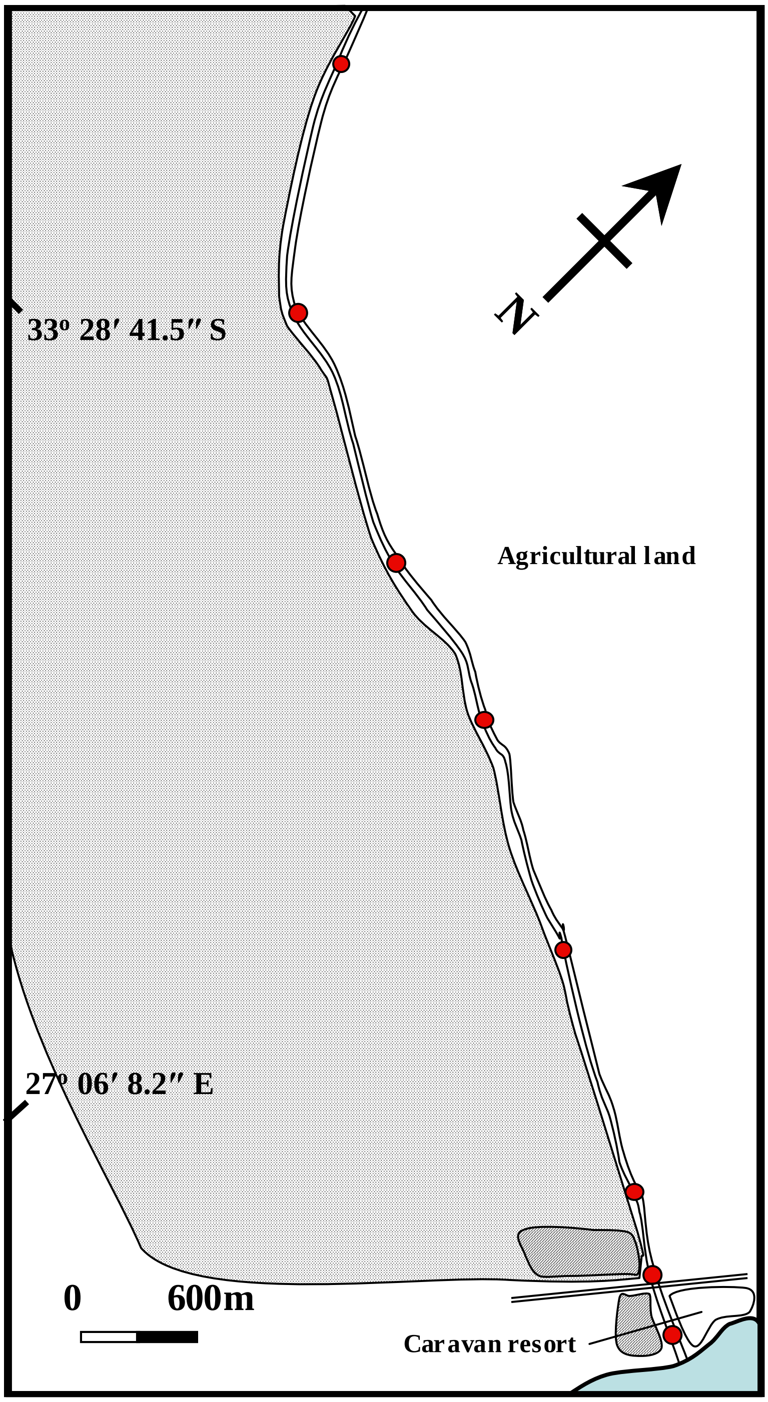


Figure 2.5: Map of the Great Fish River Estuary showing the sampling stations, salt marsh areas (hatched), protected areas (stippled) and road bridge (after Vorwerk, 2000).

The Great Fish Estuary is approximately 12km long with a width of 180m in the lower reaches and 50m in the head-waters (Vorwerk *et al.*, 2001). Large intertidal mudbanks are present throughout the system, resulting in an average depth of 1.37m; however, the maximum depth of the main channel can reach 6.4m. The large mudbanks are due to the system slowly silting up because of heavy sediment loads from the water transfer scheme and the erodible soils in the catchment (Ter Morshuizen *et al.*, 1996a and b).

Aquatic vegetation in this system is sparse, with no submerged macrophytes, most likely due to high turbidity. There are two large salt marshes on the west bank in the mouth region covering a combined area of 199ha, and reeds and sedges occur intermittently along the banks for the entire length of the estuary, covering a total of 16.6ha (Colloty *et al.*, 2001).

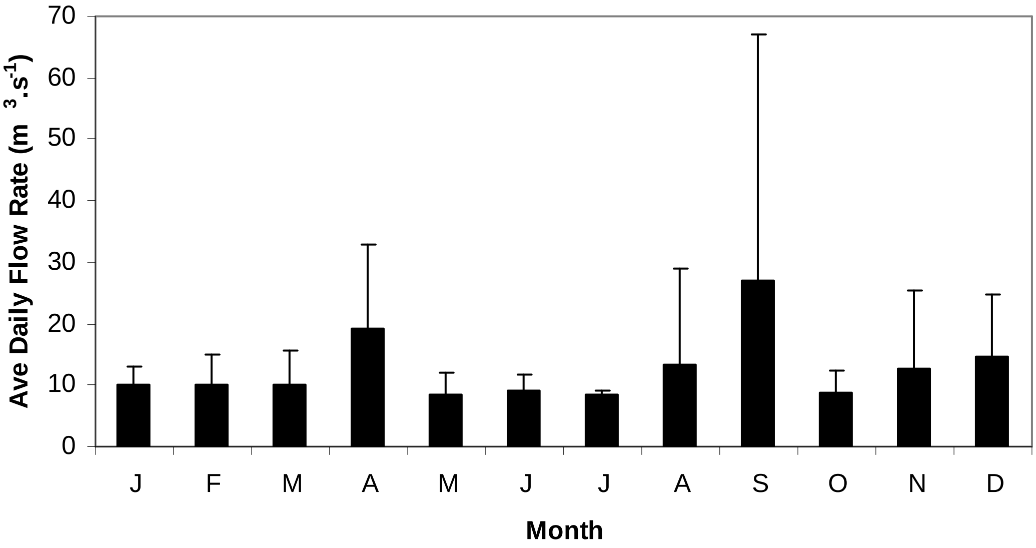


Figure 2.6: Average daily flow rate in the Great Fish River Estuary on a monthly basis (Error bars indicate standard deviation). The data are averaged across 2001 to 2005 (Department of Water Affairs and Forestry data, *in litt.*).

Harrison *et al.* (2000) considered the status of the ichthyofaunal community in the Great Fish to have an overall moderate rating, with each of the components of species diversity, presence/absence and percentage abundance all being moderate. The aesthetic rating that Harrison *et al.* (2000) awarded the estuary was moderate, with human impact evident on the east bank and in the lower reaches of the estuary. The water quality was considered good, with excellent trophic status and moderate suitability for human contact and aquatic health (Harrison *et al.*, 2000).

2.2.2 Kariega Estuary

The Kariega Estuary (Figure 2.7) is classified as a large permanently open estuary (Whitfield, 1992a) and is situated approximately 30km south-west of Port Alfred with the mouth meeting the sea at 33º 40′ 46.6″ S and 26º 40′ 57.9″ E. The town of Kenton-on-Sea is situated on the west bank in the lower reaches, with a few houses on the east bank and the coastal road (R72) crossing the estuary 600m from the mouth.

The main body of the estuary is approximately 15km long (Figure 2.7) before it reaches a highly constrictive causeway, above which the estuary continues for a further 3km. In the upper reaches the channel is 40 – 60m in width, while in the lower reaches the estuary widens to approximately 100m (Grange and Allanson, 1995), and the system has an average depth between 2.5 and 4m (Paterson, 1998).

The Kariega Estuary has a catchment size of 686km^2; however, due to the fresh water flow restrictions of three large dams, river flow is negligible (mean monthly flow during the study period was 0.011m^3.s^{-1}) for extended periods (Figure 2.8) and the system is marine dominated (Allanson and Read, 1995; Grange *et al.*, 2000). The anthropogenic influences are aggravated by a low rainfall to runoff conversion in the Eastern Cape of between 3% and 12% (Whitfield and Bruton, 1989).A 106:1 ratio of tidal prism volume to river volume (Grange *et al.*, 2000) indicates the major influence the marine environment exerts on this system. The marine dominance and low fresh water inputs result in a system that is well-mixed and has a uniform marine salinity through the middle and lower reaches, with hypersaline conditions occurring in the upper reaches (Allanson and Read, 1995; Paterson, 1998).

The major marine influence on the Kariega Estuary is evident by the deposition of marine sandy sediments up to 3.5km upstream, and a spring tidal prism of 1.9 x 10^{6}m^3 (Grange *et al.,* 2000). In addition, the continuing shallowing of the estuary in the lower reaches and the extension of the flood-tidal delta up the estuary is indicative of the tidal dominance (Ter Morshuizen, 1995).

The marine dominance in the estuary has led to eelgrass beds, *Zostera capensis*, occurring along the entire length of the estuary as a littoral band around the spring low tide level (Ter Morshuizen and Whitfield, 1994). The eelgrass beds vary in width from approximately 5.2m in the lower reaches to 3.3m in the upper reaches. Salt marshes are significant contributors to the aquatic vegetation, with salt marshes occurring in an intertidal band along most of the estuary length, which in conjunction with the four large salt marshes represent approximately 24% of the estuarine surface area (Taylor, 1987).

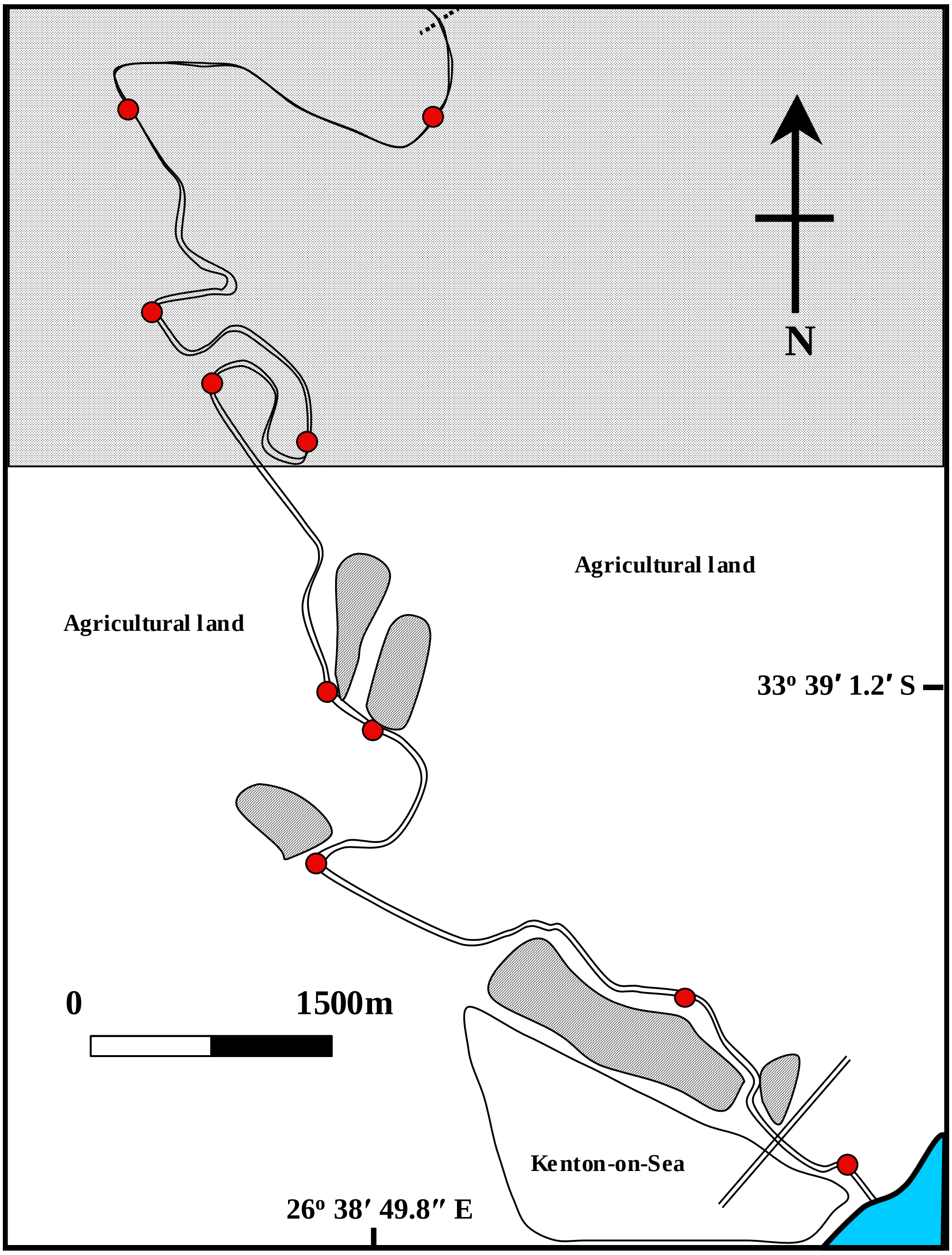


Figure 2.7: A map of the Kariega Estuary showing the study sites as well as salt marsh areas (hatched areas), conservation area (stippled) and road constrictions on the channel (after Paterson, 1998). Surrounding land uses are also indicated.

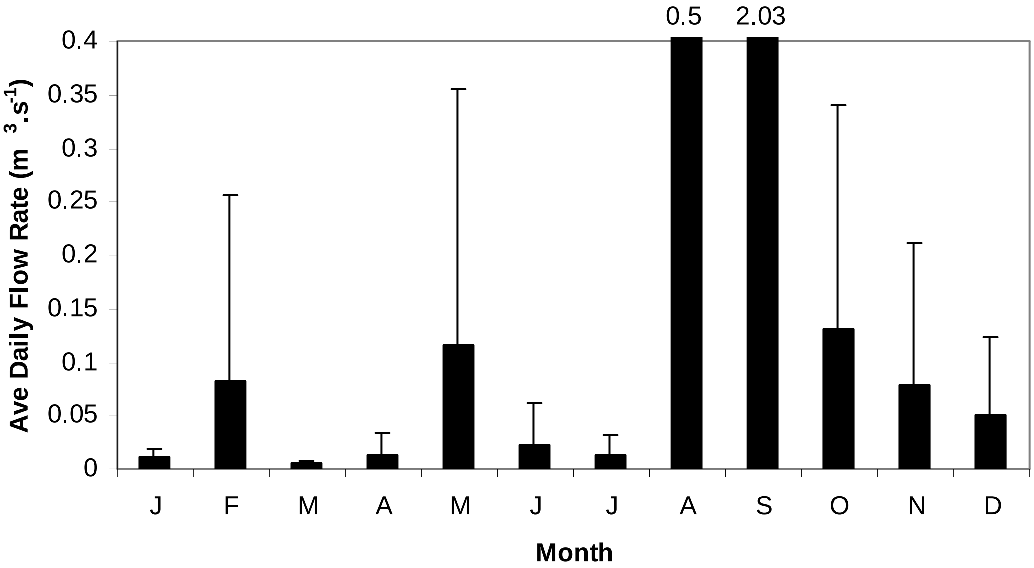


Figure 2.8: The mean average daily flow rate of the Kariega Estuary for each month in a calendar year (Error bars indicate standard deviation). Based on Department of Water Affairs and Forestry Data for 2001 to 2005.

In terms of the South African State of the Environment report for Estuaries, the Kariega was assessed as in a good condition in terms of the ichthyofaunal communities and water quality and in a moderate condition aesthetically (Harrison *et al.*, 2000). For the ichthyofaunal communities Harrison *et al.* (2000) considered the results for the three components they examined for the Kariega Estuary, namely the species richness, presence/absence and the percentage abundance of species, to be among the highest calculated for the warm temperate biogeographic region. Similarly when considering the three components used to assess the estuarine water quality, namely suitability for aquatic health, suitability for human contact and the trophic status, Harrison *et al.* (2000) considered all three components to be in a good to excellent range. The aesthetic characteristics of the estuary were rated based on various human use parameters such as litter and dams to flood plain land use, and the Kariega Estuary was considered to have a moderate aesthetic impact, scoring 8.5 out of ten.

2.2.3 Kasouga Estuary

The Kasouga Estuary (Figure 2.9) is located at 33º 39′ 17″ S and 26º 44′ 16″ E and lies approximately 20km from Port Alfred along the coastal road. This system is a temporarily open/closed estuary that remained isolated from the sea throughout the sampling period. The Kasouga was considered to be in an excellent condition and an important conservation and recreational estuary by Whitfield (2000).

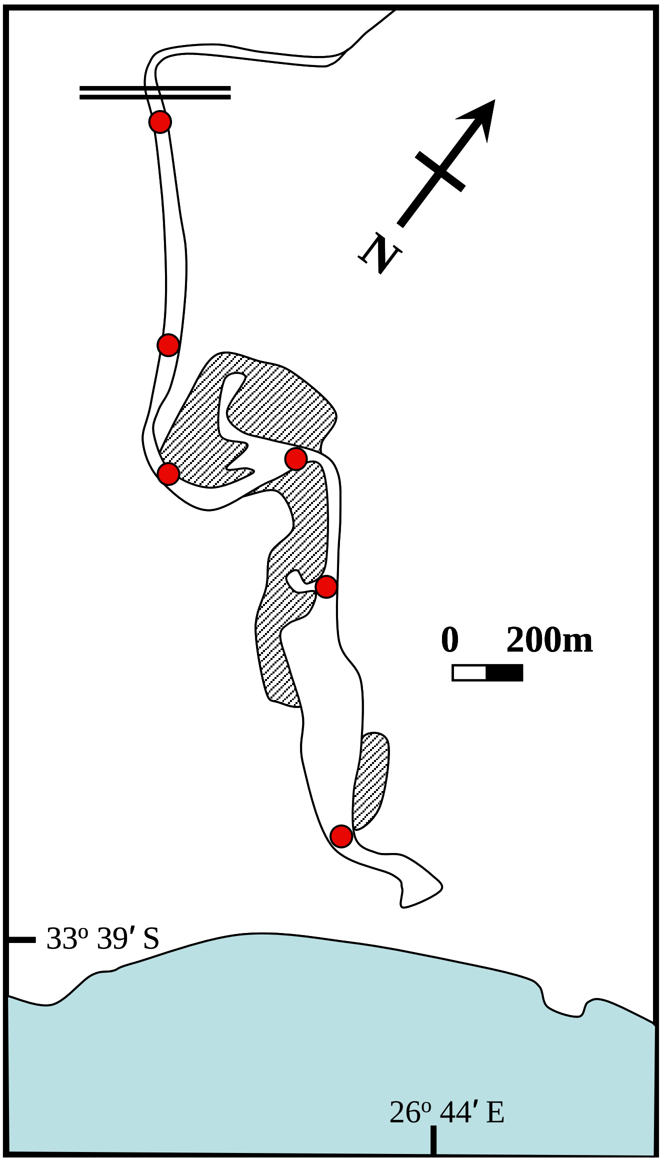


Figure 2.9: Map of the Kasouga Estuary, showing the sampling stations within the estuary, salt marsh areas (hatched) and the location of the R72 road bridge (after Tweddle, 2004).

The catchment area of this system is approximately 39km^2 (Froneman, 2002a and b) with limited anthropogenic alterations. There is a small residential development on the east bank of the estuary and cattle farming is the predominant activity (Tweddle, 2004). The streams and river valleys within the catchment are, however, in a relatively pristine state and undisturbed (Froneman, 2002b; Froneman, 2004a).

The estuary surface area is approximately 22ha excluding the salt marsh areas that are normally inundated during periods of high water levels (Froneman, 2004a and b). The system is navigable for 3km and varies in width between 10m and 150m (Froneman, 2002a; Froneman, 2004b). The average channel depth varies between 0.5m and 2m, with the depth being below 0.5m during breaching events (Tweddle, 2004).

The Kasouga Estuary contains large areas of aquatic vegetation, including large submerged macrophyte (*Ruppia* spp.) beds and salt marshes in the lower and middle reaches (Tweddle, 2004). In addition, there are extensive reed beds (*Phragmites australis*) along the west bank in the middle and upper reaches and occasional patches in the lower reaches (Tweddle, 2004).

The State of the Environment report for estuaries rated the Kasouga as good in all three components examined, namely the ichthyofaunal status, water quality and aesthetics (Harrison *et al.*, 2000). The three ratings for the ichthyofaunal community, namely, the species compositions, presence/absence and percentage composition, were all considered good. In terms of the water quality ratings, suitability for human contact and trophic status of the system were both considered good, while the suitability for aquatic health was moderate to good (Harrison *et al.*, 2000). The rating of the aesthetics of the system was considered good as the estuary is in a near pristine state.

2.2.4 East Kleinemonde Estuary

The East Kleinemonde Estuary (Figure 2.10) is a medium-sized temporarily open/closed system situated at 33º 32′ 42″ S and 27º 03′ 05″ E (Vorwerk, 2000). The lower reaches of this system are surrounded by the small township of Seafield and the coastal road (R72) bridge crosses the system approximately 500m from the mouth. The remainder of the catchment of the estuary is relatively pristine with agriculture, mostly beef farming, predominating (Cowley, 1998).

The estuary is approximately 3km long with a surface area of 17.5ha (Vorwerk *et al.*, 2001) and a catchment size of ≈46km^2 (NRIO, 1987; Badenhorst, 1988). The lower and middle reaches have a width of approximately 100m, while the upper reaches narrow down to 25m. The system has an average depth of 2.5m, with a shallow littoral area along most of the estuary (Cowley and Whitfield, 2002).

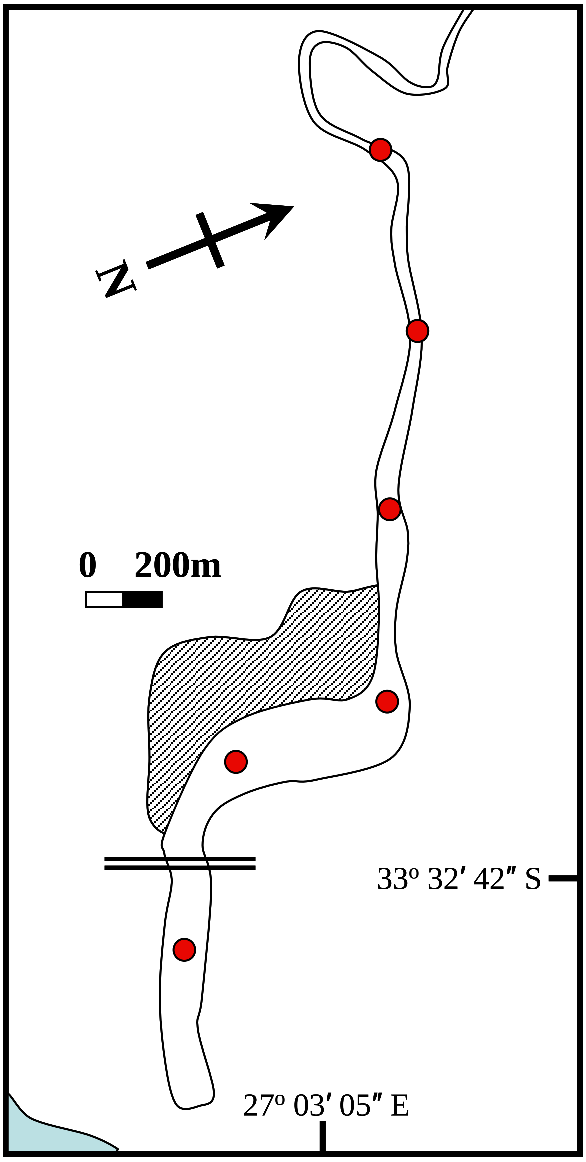


Figure 2.10: Map of the East Kleinemonde Estuary showing the sampling stations, salt marsh areas (hatched) and the coastal road (R72) bridge (after Vorwerk *et al.*, 2001).

Information is available on the mouth dynamics of this system, which indicate that it interacts with the sea frequently through mouth opening events and overwash events (Cowley, 1998; Cowley and Whitfield, 2001). The estuary is open to the sea 2.6% of the time, while overwash conditions were evident 25.6% of the time (Cowley, 1998). These marine interactions occurred frequently, with open mouth conditions occurring during every month, except March and July for the period 1993 – 1998 (Cowley and Whitfield, 2001; Cowley *et al.*, 2001).

Adams (1997) conducted a botanical survey in the East Kleinemonde Estuary, revealing two species of submerged macrophytes and a small salt marsh above the bridge on the west bank. The dominant species of submerged macrophytes was *Ruppia cirrhosa*, which occurred in a continuous band along both banks of the estuary, and the second species was *Halophila ovalis*. The salt marsh contained four different plant species in bands along the depth contours, namely *Sarcocornia perennis*, *Sporobolus virginicus*, *Sarcocornia decumbens* and patches of *Juncus kraussii* (Adams, 1997). There are also small stands of *Phragmites australis* along the entire length of the estuary, particularly in the lower and middle reaches.

Harrison *et al*. (2000) rated the species richness, presence/absence and percentage abundance of the fish species as good within the East Kleinemonde. Similarly, all the components of the water quality index were rated as good, including the suitability for aquatic health and human contact, and the trophic status of the system. However, the aesthetic rating for the estuary was considered moderate (Harrison *et al.*, 2000).

CHAPTER 3

THE EFFECT OF TWO PERMANENTLY OPEN ESTUARIES WITH CONTRASTING FRESH WATER FLOW RATES ON ZOOPLANKTON IN THE ADJACENT MARINE ENVIRONMENT

3.1 INTRODUCTION

Various biological matter, in the form of particulate matter as well as living organisms, are exchanged between estuaries and the sea, with the net fluxes being dependent on physical and biological processes within the estuary concerned and the adjacent coastal ecosystem (Dame and Allen, 1996). The exchange of material between estuaries and the sea can be classified into two categories, those that are the active result of organism behaviour or that which is passively driven by physical forces (Jansson, 1988).

Material and non-motile organism (such as phytoplankton) exchange differs between river dominated and tidally dominated systems. The net flux of material through a river dominated estuary is in a seaward direction due to the direction of water flow, while in a lagoonal or tidally dominated system the net material transport tends to be in a terrestrial direction (Postma, 1981; Kjerfve, 1989). This has been attributed to time-velocity asymmetry, where the peaks in both flood and ebb tidal flow are nearer to the low slack water, resulting in net landward transfer of material (Postma, 1967).

The exchange of larger organisms between estuaries and the marine environment is considered to occur in both a passive and active manner. Passive exchange occurs in forms of larvae that are not sufficiently developed to maintain their position in the water column. In the Wadden Sea, de Wolf (1973) observed barnacle larvae being passively transported upstream due to the flood-tidal domination of the currents. Similar arguments have been made by other authors (Biocourt, 1982; Stancyk and Feller, 1986) to explain the movement of a number of invertebrate larvae.

An alternative strategy is for invertebrate and fish larvae to either actively swim relative to currents, or migrate up and down in the water column to take advantage of tidal currents (Dame and Allen, 1996). An example includes *Rhithropanepeus harrisii* larvae (Sandifer, 1975) that move upward in the water column on the flooding tide and downward on the ebbing tide to maximise the use of the fast flowing surface currents and therefore maximise upstream transport in the estuary (Epifanio, 1988). Active swimmers include penaeid prawn postlarvae, which recruit into estuaries by swimming along the slower moving bottom waters (Edwards, 1977; Forbes *et al.*, 1994).

Several international studies have demonstrated the presence of offshore zooplankton communities occurring adjacent to estuaries (Sanchez-Velasco *et al.*, 1996; Espinosa-Fuentes and Flores-Coto, 2004), as well as the material transport of phytoplankton and particulate organic matter from these systems into the marine environment (Roegner, 1998; Dale and Prego, 2003). However, the applicability of these results to the South African environment is uncertain. As discussed above, physical characteristics and hydrodynamics appear to be the driving force in terms of biological transport between estuaries and the sea. Due to the relatively small size of South African estuaries, coupled with the high variability in flow rates, the applicability of the trends from the international literature to South African estuaries needs to be assessed.

Several studies in the South African literature have assessed the use of estuaries by various organisms at different stages of their life cycles, including fish and invertebrates (specifically the penaeid prawns). However, to date only one study has been conducted on a South African estuary to assess the influence of estuarine water on the inshore marine biology. Harris *et al.* (2001) examined the fish communities along a gradient from the St Lucia Estuary (east coast of South Africa) into the marine environment. This study did identify a continuum of fish communities between the estuary and the marine environment and attributed this to turbidity and salinity gradients. The St Lucia Estuary is, however, a temporarily open/closed estuary (TOCE), and is not necessarily representative of the permanently open estuaries along the South African coastline.

The aim of this chapter is to examine the biological connectivity of two permanently open estuaries with contrasting flow regimes and the adjacent marine environment. The aims of this study were:

1. Assess if the estuaries have an impact on the hydrography (including water quality parameters such as salinity, temperature and density) and biology (chlorophyll-*a* concentration and zooplankton) in the adjacent marine environment;
2. Determine the geographic extent of the influence of the two estuaries on the adjacent marine environment;
3. Establish whether the proximity of an estuary leads to the accumulation of zooplankton in the adjacent marine environment; and
4. Determine if there is a relationship between the river flow volumes entering the estuaries and the extent of the impact the systems have on the adjacent marine environment.

The two estuaries studied were the fresh water dominated Great Fish Estuary (see 2.2.1 in the previous chapter for details) and the Kariega Estuary, a tidally dominated estuary with very low fresh water flow rates (see 2.2.2 in the previous chapter for details).

3.2 MATERIALS AND METHODS

3.2.1 Sampling protocol

Estuarine samples were collected from ten stations within the Kariega Estuary and eight stations within the Great Fish Estuary, which were established approximately 1.75km apart (see Figures 2.5 and 2.7 for a diagrammatic representation of station positions). Offshore of the estuary mouth, 20 stations were occupied in a sampling grid of five transects that were ≈500m apart. One transect was established north-east of the mouth (upstream relative to the Agulhas Current), one opposite the mouth and three transects at ≈500m intervals south-west of the estuary (downstream relative to the Agulhas Current). The first station in each transect was occupied 250m offshore, with an additional three stations at ≈200m intervals (see Figure 3.1 for the grid details). The entire sampling grid was considered mobile, and could have been switched to sample the majority of stations north-east of the estuary mouth, however, wind conditions consistently allowed the sampling to occur as presented in Figure 3.1 (see section 3.3.1 below). The surveys were conducted on a seasonal basis (see Table 3.1 for sampling dates, tide times and types). The only survey that was not uniformly conducted on a tide between spring and neap was the March survey. Weather conditions and boat availability prevented sampling on the preferred tides.

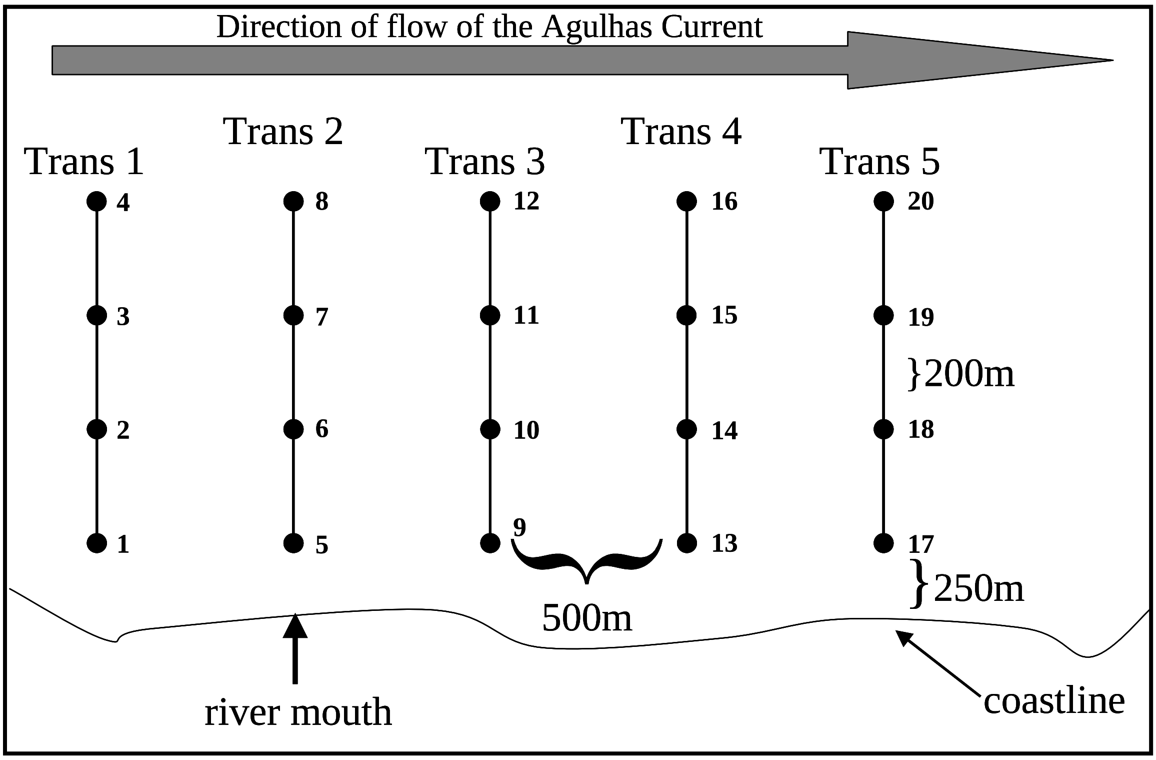


Figure 3.1: A stylised layout of the marine sampling grid used in the nearshore marine environment off the Kariega and Great Fish estuaries.

3.2.2 Physico-chemical parameters

Flow data for the water entering both estuaries prior to each sampling trip was obtained from the Department of Water Affairs and Forestry (DWAF) based on weirs close to the head of each system. Temperature and salinity measurements were taken at the surface and bottom (≈2m depth) for estuarine stations and at the surface and at 5m for the marine stations. The 5m depth for samples in the marine environment was used to target the low salinity water plume and the interface region between this plume and marine waters. Temperature and salinity were measured using a YSI 600XL water quality probe that had been calibrated for estuarine and marine waters. Salinity readings during December were measured using an optical refractometer due to technical problems with the YSI 600XL water quality probe.

Table 3.1: Listing of the dates on which sampling took place as well as the relevant tide times and types on those dates (Tide types and times given for the marine sampling day). Tide type is represented by a spring tide or a tide that is between spring and neap tide (mid).

Month	Estuary Name	Estuary		Marine		Tide Type	High Tide Time
		Date	Start Time	Date	Start Time		
June	Kariega	23/06/04	13H55	24/06/04	08H40	Mid	07H28
	Great Fish	23/06/04	08H35	22/06/04	08H40	Mid	05H58
September	Kariega	22/09/04	09H15	23/09/04	08H18	Mid	12H12
	Great Fish	22/09/04	13H57	21/09/04	07H45	Mid	08H14
December	Kariega	02/12/04	13H50	03/12/04	07H00	Mid	07H52
	Great Fish	02/12/04	10H10	01/12/04	08H15	Mid	06H20
March	Kariega	10/03/05	13H10	09/03/05	06H56	Spring	16H03
	Great Fish	10/03/05	08H55	08/03/05	07H40	Spring	15H25

3.2.3 Chlorophyll-*a* and particulate organic matter determination

Chlorophyll-*a* concentrations were determined for surface and bottom waters (or 5m depth for the marine stations, see Section 3.2.2 above for determination of sampling depth) for each station by collecting 200ml water samples. These samples were vacuum filtered (<5cm Hg) through GF/F filters which were subsequently extracted in 90% acetone for 24hrs in the dark at -20ºC. The chlorophyll-*a* concentrations were then determined using a 10AU-Turner fluorometer (using a 10-051 filter: wavelength=665nm) before and after acidification according to the method of Holm-Hansen and Riemann (1978).

The particulate organic matter (POM) concentration in the surface and bottom waters (or 5m depth for marine stations) for both estuarine and marine waters was determined for each station by collecting and filtering a 300ml water sample through a pre-weighed GF/F filter. The filter and filtered material were then oven-dried at 60ºC for a period of 24hrs prior to initial weighing on a Sartorius microbalance. The organic matter was subsequently burnt off at 500ºC for a period of 24hrs prior to re-weighing the filter. The POM was determined by calculating the difference between the post-60ºC and post-500ºC weights.

3.2.4 Zooplankton sampling

Due to logistical constraints in terms of safety at sea during night time hours, zooplankton samples were only collected during the daytime from the marine environment. For comparison purposes, the estuarine samples were similarly only collected during daytime. Three replicate zooplankton surface tows (depth≈0.5m) were conducted at each station using a WP-2 net with a 60µm mesh size and a 47cm mouth diameter. The net was fitted with a flow meter (General Oceanics) to allow volumetric standardisation of the samples. All samples collected were stored in 10% buffered formalin for later identification in the laboratory. For each replicate sample the zooplankton dry biomass was determined by filtering a 1/2 to 1/32 sub-sample, obtained using a Folsom plankton splitter, through a pre-weighed GF/F filter and then oven drying at 60ºC for a period of 24hrs. The samples were then weighed on a Sartorius microbalance and dry biomass calculated as the difference between the filter weight and the combined dry weight. Abundance and biomass values were expressed as ind.m^{-3} and mg dwt m^{-3}, respectively.

Where possible, zooplankton were identified to species level. All zooplankton were counted to allow for density estimates which were then averaged across the three replicate samples. The average community abundance data for each station was then entered into the PRIMER (Plymouth Routines in Multivariate Ecological Research version 5.2.4; Clarke and Warwick, 1994) software package for comparison between the stations. The data was transformed (log x+1) to minimise the effect of less abundant species and input into a group-averaged Bray-Curtis Similarity analysis from which a cluster diagram was generated. The SIMPER routine was then employed to identify which species were contributing to the differences between the groupings identified with the numerical analysis. The BIOENV routine in PRIMER was then used to try to identify correlations between the biotic and physico-chemical data (Clarke and Warwick, 1994).

For the purposes of comparing the marine to estuarine stations two diversity indices were used, Shannon-Weiner Diversity and Margalef's Richness Index. Margalef's Richness (d) was calculated using Equation 1 below and Shannon-Weiner Diversity (H') was determined employing Equation 2. Margalef's Richness is a measure of the number of species and a limited indication of the number of individuals of each species, while Shannon-Weiner Diversity incorporates equitability and is a more comprehensive measure as it indicates whether a community is dominated by a few individuals (Zar, 1996).

$$d = (S - 1) / (Log(N)) \qquad \text{(Eq. 1)}$$

Where d is Margalef's Richness, S is the total number of species and N is the total number of individuals (Clarke and Warwick, 1994).

$$H' = - \Sigma i\, pi\, (\log pi) \qquad \text{(Eq. 2)}$$

Where: H' is the resultant diversity, i is the sample number and pi is the proportion of the total count represented by the ith species (Clarke and Warwick, 1994).

3.2.5 Analysis

The contour plots of the various hydrological and biological parameters were produced in SigmaPlot (version 8.0). This software package processes regular spaced grid data into a two dimensional plot. Water density is presented as σ_t. The σ_t calculation is determined according to Fofonoff and Millard (1983) from the temperature and salinity data collected at the surface and at 5m depth.

Non-parametric statistical analyses were used as water quality data tends to have a log-normal distribution (Grange and Allanson, 1995). The differences between offshore surface and bottom (or 5m depth for marine stations) salinities, temperatures, POM and total chlorophyll-*a* concentration were tested using a two-tailed t-test in Microsoft Excel. Similarly, a t-test executed in Microsoft Excel was used to compare particular transects to the remaining sites as well as testing for seasonal variation. Significance was determined at a p-value of 0.05. Similarly, the non-parametric Spearman Rank Correlation was used to observe relationships between the various parameters measured. This was conducted on the average values for each parameter within the estuary and marine environment during each season.

3.3 RESULTS

3.3.1 Seas state, current and wind speed direction at the time of sampling

The swell size during all sampling surveys was less than 2.5m, causing moderate to slight sea states on all occasions (South African Weather Service, unpublished data). The depths below the sampling stations ranged from 3 – 5m for the inshore stations to 9 – 12m for the offshore stations. The longshore current in the swash and surfzones was in a south-westerly direction adjacent to both estuaries during all sampling surveys (personal observation). This occurs due to the location of rip currents adjacent to rocky promontories to the south-west of the sampling grids in the marine environment off both estuaries.

Based on observed wind speed and direction (South African Weather Service Data, Port Alfred Station), the wind on the evening prior to sampling and on the sampling date was predominantly an easterly or northerly wind (blowing towards the south or west) (see Appendix 1, Table A1.1 and A1.2). This resulted in surface currents that were westerly, permitting the establishment of the sampling grid as presented in Figure 3.1. The only sampling occasion when the wind was in a westerly direction was on 21 September 2004 (the Great Fish Estuary September sample), but the decision was made to keep the grid survey in its current alignment due to the visible turbidity plume (as supported by the density plume presented in Figure 3.4).

3.3.2 Physico-chemical and hydrological variables

Flow rates

The average daily flow rate in the Great Fish Estuary (Figure 2.8) demonstrated a bimodal pattern, with spring and autumn peaks. These peaks do not relate to the rainfall pattern within the catchment, with the water transfer scheme being the main source of fresh water to the estuary. The specific flow rates on the dates that sampling took place on the Great Fish demonstrated very low values for the September 2004 sampling trip (3.46 and $3.35m^3.s^{-1}$) and high values for the March 2005 samples (32.92 and $10.40m^3.s^{-1}$) (Table 3.2). Intermediate flow rates were recorded in September and December 2004.

Table 3.2: Flow rates ($m^3.s^{-1}$) for the days that sampling was carried out on the Great Fish and Kariega Estuary and in the adjacent marine environments. Data provided by DWAF.

	Great Fish		**Kariega**	
	Sampling the Estuary	**Sampling the Marine Environment**	**Sampling the Estuary**	**Sampling the Marine Environment**
June 2004	8.45	9.34	0.003	0.003
September 2004	3.46	3.35	0.003	0.003
December 2004	4.98	4.67	0.003	0.003
March 2005	32.92	10.40	0.005	0.005

The Kariega Estuary has a significantly lower flow rate ($p<0.05$; $t=2.8$) than the Great Fish as it is highly regulated due to the presence of numerous impoundments along the main channel and its tributaries. For ten months of the year, the average monthly flow rate for the last five years was less than $0.15m^3.s^{-1}$, with August and September being the only exceptions (Figure 2.6). Throughout the investigation, the mean flow rate of the Kariega River into the estuary was less than $0.005m^3.s^{-1}$ (Table 3.2).

Salinity

The surface salinity within the Great Fish Estuary ranged between 0 (practical salinity units) in the upper reaches during December to a maximum of 34.93 near the mouth during September (Table 3.3). Similarly, the bottom salinity ranged between 0.34 in March to a maximum of 34.93 during September (Table 3.3). A salt wedge was evident penetrating up the bottom waters of the estuary during all seasons (Figure 3.2).

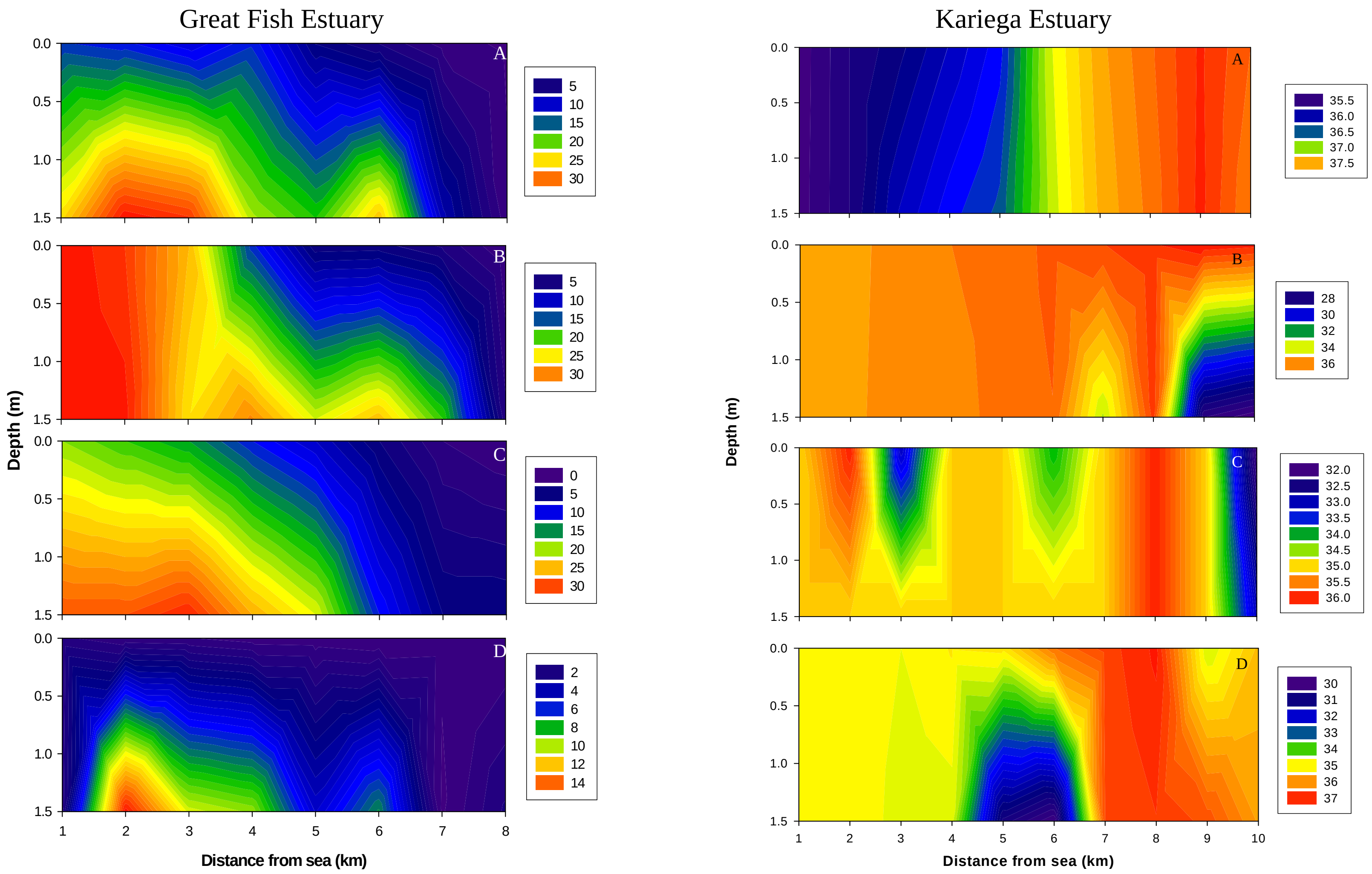


Figure 3.2: Salinity profiles (practical salinity units) for the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). Note the different scales on the contour plots.

Table 3.3: Salinity measurements (practical salinity units) for the surface and bottom waters within the Great Fish Estuary.

		June	September	December	March
Surface	Average	7.56	15.50	9.38	0.68
	Std Dev.	5.15	14.02	7.31	0.30
	Maximum	13.13	34.93	19.00	1.28
	Minimum	0.76	0.97	0.00	0.40
Bottom	Average	20.68	24.52	19.50	6.29
	Std Dev.	11.24	10.19	10.94	5.28
	Maximum	33.88	34.93	31.00	15.49
	Minimum	1.30	3.33	5.00	0.34

The salinities within the Kariega Estuary were significantly higher than those recorded in the Great Fish Estuary in both the surface waters ($p<0.01$; $t=-8.7$) and bottom waters ($p<0.01$; $t=-4.7$). The salinities in the Kariega Estuary demonstrated very little variation between surface and bottom waters, with the maximum variation at any one site being <4 (practical salinity units) (Figure 3.2). The difference between the averages for the surface and bottom waters was less than 1 in all seasons except September, where the bottom waters in the head of the estuary had a relatively low salinity of 26.5. This resulted in the average for the bottom waters being 2.5 units lower than that for the surface waters (Table 3.4).

Table 3.4: The average, maximum and minimum salinities (practical salinity units) measured in the Kariega Estuary during each season.

		June	September	December	March
Surface	Average	36.69	36.41	34.6	35.48
	Std Dev.	0.99	0.78	1.26	0.85
	Maximum	37.92	37.51	36	37.05
	Minimum	35.34	35.38	32	34.6
Bottom	Average	36.73	33.92	34.9	34.58
	Std Dev.	0.92	3.84	0.74	2.37
	Maximum	37.93	36.94	36	36.79
	Minimum	35.35	26.48	33	30

As expected the seasonal variation in salinities within the Kariega Estuary was extremely low (<6) due to the highly regulated nature of the river flow. The surface salinities fluctuated between a June maximum of 37.92 and a December minimum of 32, while the bottom salinities ranged between a June maximum of 37.93 and a September minimum of 26.48 (Table 3.4).

Marine salinities were recorded near the mouth within the Kariega Estuary, with a reverse salinity gradient occurring and hypersaline conditions being recorded towards the head of the estuary. Hypersaline conditions occurred from approximately 7.5km upstream and continued towards the head of the estuary during all seasons (Figure 3.2). An exception was recorded during the September and December surveys, with lower salinity water recorded at the highest estuarine station, although this did not penetrate downstream to any extent, and hypersaline conditions were still evident eight kilometres from the mouth (Figure 3.2). In addition, lower salinity water was recorded on three occasions lower downstream (two in December and one in March), at positions that coincided with the mouths of salt-marshes along the estuary (Figure 3.2).

The average surface and 5m salinities recorded in the nearshore environment adjacent to the Great Fish Estuary demonstrated little seasonal variation (Table 3.5). The minimum surface salinity was recorded in March (25.45), while the maximum was recorded during September (35.24). The maximum 5m salinity was 35.33 (June) and the minimum was 28 (December).

Although variable, spatial trends in the nearshore salinity adjacent to the Great Fish Estuary were evident, with the surface salinity values in transects two, three and four indicating a pool of significantly ($p<0.005$) lower salinity water (±26) than the remaining transects during all seasons (Appendix 2, Figure A2.1 – A2.4). Stratification of the water column was also apparent during three seasons, with significantly lower salinities recorded in the surface waters during June ($p=0.007$), September ($p=0.001$) and March ($p=0.008$) (Table 3.5).

Table 3.5: Salinity measurements (practical salinity units) for the surface and 5m waters in the nearshore environment opposite the Great Fish Estuary, including t-test results for comparisons between the values recorded for the surface and 5m waters (* indicates significant p-values).

		June	September	December	March
Surface	Average	32.58	35.14	31.47	33.18
	Std Dev.	3.10	0.13	2.52	2.43
	Maximum	34.98	35.24	35.00	34.73
	Minimum	25.95	34.73	26.00	25.45
5m	Average	35.27	35.20	32.00	34.86
	Std Dev.	0.06	0.08	1.94	0.12
	Maximum	35.33	35.27	34	34.96
	Minimum	35.13	34.99	28	34.67
t-test	Deg. Of Freedom	13	15	18	17
	t Stat	-3.27	-4.10	-1.69	-2.98
	P value	0.007*	0.001*	0.109	0.008*

Fairly uniform salinities were recorded across all of the nearshore stations adjacent to the Kariega Estuary during all seasons and no significant differences were identified between surface waters and 5m depth ($p>0.05$ in all cases) (Table 3.6; Appendix 2, Figures A2.1 to A2.4). During December, a refractometer was used, resulting in rounding of all salinity measurements to the nearest unit, and all stations registered exactly 35 (Appendix 2, Figure A2.3). During March an anomaly was recorded when relatively low salinities were measured upstream of the estuary mouth in both the surface waters and at 5m. The maximum salinity recorded in the nearshore adjacent to the Kariega Estuary was 35.35 during June 2004 and the minimum was 34 recorded during March 2005 (Table 3.6).

The surface salinities in the marine environment adjacent to the Great Fish and Kariega Estuaries were significantly different ($p<0.02$; $t=-2.35$), while no significant differences were observed in the bottom salinities ($p>0.05$). The significantly higher salinities adjacent to the Kariega Estuary relative to those recorded adjacent to the Great Fish are due to the low salinity estuarine plume occurring offshore of the Great Fish.

Table 3.6: The average, maximum and minimum surface and 5m salinities (practical salinity units) recorded during each sampling trip in the nearshore environment adjacent to the Kariega Estuary.

		June	September	December	March
Surface	Average	35.33	35.29	35	34.57
	Std Dev.	0.02	0.02	0	0.42
	Maximum	35.35	35.32	35	34.95
	Minimum	35.28	35.23	35	34
5m	Average	35.34	35.29	35	34.61
	Std Dev.	0.01	0.07	0	0.45
	Maximum	35.36	35.33	35	34.95
	Minimum	35.32	35	35	34

Temperature

The temperatures in the Great Fish Estuary reflected marine water incursion in a wedge during all seasons. This was evidenced through warmer water in June (Figure 3.3a Great Fish) and colder water during all other seasons (Figure 3.3b – d Great Fish). The surface waters in the estuary ranged between a December maximum of 26.20ºC to a June minimum of 13.57ºC (Table 3.7). The bottom waters similarly had a December maximum of 25.2ºC and a June minimum of 14.37ºC (Table 3.7). During all seasons except June, the average temperatures of the estuarine surface waters were warmer than the bottom waters due to warm fresh water entering the estuary, while during June this trend was reversed, with the marine waters entering along the estuary bottom being warmer than the riverine inflow.

The temperatures within the Kariega Estuary demonstrated a marine dominance in the lower reaches, with warmer marine water evident during the winter months (June) and cooler marine water evident during all other seasons (Figure 3.3). Seasonal trends in temperature were evident with the minimum temperatures being recorded in June (16.03ºC – 17ºC) and a steady increase to a summer maximum in December (23.5ºC – 28ºC) (Table 3.8). The water column was well-mixed during all seasons with the average surface and bottom waters being within 1.5ºC during all seasons (Table 3.8).

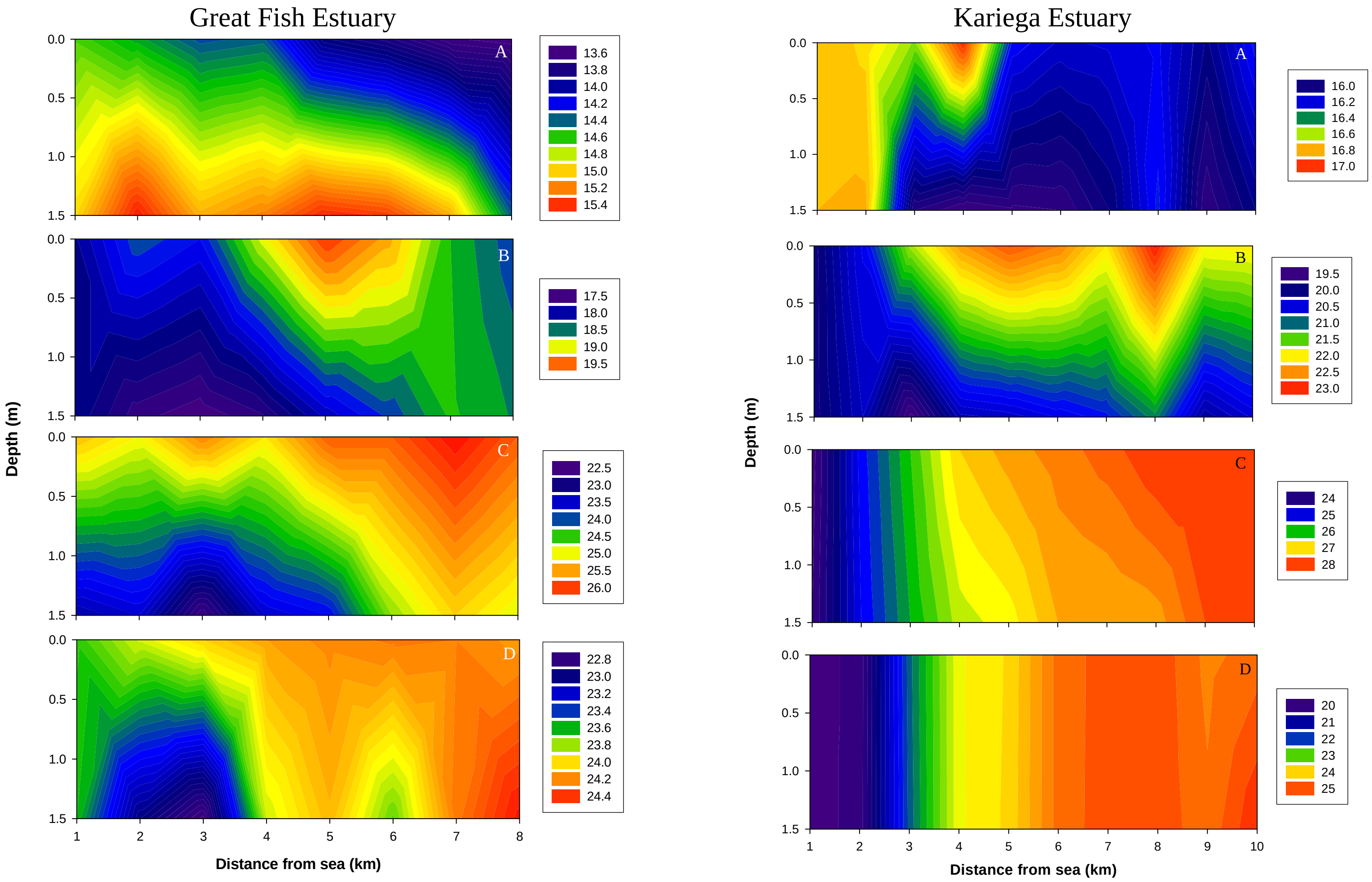


Figure 3.3: Temperature profiles (ºC) for the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). Note the different scales on the contour plots.

Table 3.7: Temperature measurements (ºC) for the surface and bottom waters within the Great Fish Estuary.

		June	September	December	March
Surface	Average	14.09	18.65	25.58	24.04
	Std Dev.	0.42	0.58	0.41	0.20
	Maximum	14.63	19.61	26.20	24.21
	Minimum	13.57	17.88	25.00	23.65
Bottom	Average	15.10	17.99	23.91	23.70
	Std Dev.	0.35	0.46	0.93	0.60
	Maximum	15.44	18.62	25.2	24.46
	Minimum	14.37	17.42	22.5	22.7

No significantly different trends were evident between the temperatures in the Kariega Estuary and the Great Fish Estuary due to the seasonal variation evident in both systems. Similarly, no significant differences in temperatures were evident in the adjacent marine environments, largely due to the observed seasonality masking any differences.

Table 3.8: The average seasonal temperatures (ºC) within the Kariega Estuary. Maximum and minimum temperatures for each season as well as standard deviations are presented.

		June	September	December	March
Surface	Average	16.41	21.86	26.81	23.29
	Std Dev.	0.32	0.99	1.5	2.03
	Maximum	17	23.04	28	24.94
	Minimum	16.03	19.85	23.5	19.74
Bottom	Average	16.12	20.29	26.5	23.35
	Std Dev.	0.36	0.46	1.35	2.09
	Maximum	16.77	21.06	27.9	25.2
	Minimum	15.84	19.35	23.6	19.72

In the nearshore environment adjacent to the Great Fish Estuary no statistically different spatial trends in temperature were evident during each season ($p>0.05$) (Appendix 2, Figure A2.5 – A2.7). The largest variation across all sites was recorded in March 2005, where differences between the lowest and highest temperatures were approximately 2ºC. However, a t-test indicated that the observed differences were not significant ($p>0.05$) (Appendix 2, Figure A2.8).

The temperatures in the nearshore environment adjacent to the Great Fish Estuary indicated strong seasonal trends, with maximum temperatures at the surface and in 5m waters being recorded in December (21.7ºC and 21.6ºC, respectively) and the minimum temperatures being recorded in June (15.54ºC and 15.79ºC, respectively) (Table 3.9). Intermediate temperatures were recorded in September and March.

Stratification of the water column adjacent to the Great Fish was evident during three seasons, with cooler 5m water recorded during September, December and March (Table 3.9). During June, the difference in temperature between the surface and 5m layers was minimal with the average surface temperature (15.86ºC) being only 0.04ºC cooler than the 5m temperature (15.9ºC).

Table 3.9: Temperature measurements (ºC) for the surface and 5m waters in the nearshore environment adjacent to the Great Fish Estuary. Delta temperature (ºC) values are provided for surface differences between surface and bottom waters (+ = 5m water is warmer, - = 5m water is cooler)

		June	September	December	March
Surface	Average	15.86	17.25	21.48	18.77
	Std Dev.	0.19	0.15	0.10	0.38
	Maximum	16.11	17.62	21.70	19.78
	Minimum	15.54	17.09	21.30	18.24
5m	Average	15.90	17.21	21.30	18.51
	Std Dev.	0.07	0.14	0.24	0.24
	Maximum	16.06	17.50	21.60	18.79
	Minimum	15.79	17.00	20.70	17.83
Δ Temperature	Average	-0.01±0.22SD	-0.05±0.05SD	-0.11±0.1SD	-0.26±0.40SD
	Maximum	0.52	0.12	0.3	0.94
	Minimum	0.	0	0	0.03

The seasonal variations in temperatures recorded for the sites in the nearshore environment adjacent to the Kariega Estuary demonstrated a June minimum of 16.06ºC and a December maximum of 22.5ºC (Table 3.10). The water column was well-mixed with a variation in the average temperatures between surface waters and 5m depth being less than 0.1ºC during all seasons (Table 3.10). No spatial trends in water temperature were evident during the four surveys conducted in the marine environment (Appendix 2, Figures A2.5 – A2.8).

Table 3.10: The average, minimum and maximum temperatures (ºC) recorded during each season in the nearshore marine environment adjacent to the Kariega Estuary. Standard deviations of the mean are provided.

		June	September	December	March
Surface	Average	16.34	18.03	22.08	20.19
	Std Dev.	0.19	0.05	0.23	0.16
	Maximum	16.68	18.1	22.5	20.43
	Minimum	16.09	17.88	21.7	19.93
5m	Average	16.26	18.02	22.05	20.1
	Std Dev.	0.13	0.06	0.25	0.07
	Maximum	16.48	18.1	22.5	20.22
	Minimum	16.06	17.83	21.6	19.96

Marine water densities (σ_t)

The marine water densities offshore of the Great Fish Estuary ranged from a March minimum of 17.55 on the surface to a June maximum of 26.05 on the bottom. The surface densities were consistently lower than the bottom densities during all surveys, with the average delt σ_t ranging from 0.06 to 2.19 (Table 3.11). The average delta σ_t demonstrated weak water column stratification (delta σ_t between 0.00 – 0.05) during the September survey, while during the December and March surveys moderate (delta σ_t between 0.05 – 2.00) water stratification was evident. The surface estuarine plume across most of the stations during June resulted in high stratification (delta σ_t>2.00) between the surface and 5m depth. The spatial patterns of water densities, closely matched that of salinity throughout the offshore survey grids, with delta σ_t showing a density plume in the surface waters during June, December and March (Figure 3.4).

Table 3.11: The water density (σ_t) and delta σ_t values calculated in the marine environment adjacent to the Great Fish Estuary. The average, standard deviation, maximum and minimum values are presented.

		June	**September**	**December**	**March**
Surface	Average	23.80	25.57	21.68	23.66
	Std Dev.	2.29	0.13	1.98	2.03
	Maximum	25.71	25.66	24.36	24.88
	Minimum	18.86	25.16	17.56	17.55
5m	Average	25.99	25.63	22.26	25.04
	Std Dev.	0.04	0.08	1.41	0.06
	Maximum	26.05	25.69	23.68	25.1
	Minimum	25.92	25.39	19.07	24.87
Delta σ_t	Average	2.19	0.06	1.04	1.37
	Std Dev.	2.28	0.05	1.00	2.00
	Maximum	7.13	0.23	3.74	7.32
	Minimum	0.32	0.00	0.00	0.17

Adjacent to the Kariega Estuary the water column was very stable, with the average surface σ_t only slightly lower (<0.07) than the bottom water densities (Table 3.12). Similarly, delta σ_t was always <0.11 demonstrating very weak stratification between surface and 5m depth (Table 3.12). The seasonal variation in σ_t was similarly very low, with the minimum recorded σ_t of 23.97 recorded during March and the maximum recorded σ_t of 25.99 occurring during June (Table 3.12). No spatial patterns in the surface or 5m water densities were apparent (Figure 3.4).

The water density at 5m depth was similar adjacent to both systems, while the recorded surface water density opposite the Kariega Estuary was significantly higher than that recorded adjacent to the Great Fish Estuary ($p<0.05$; $t=-2.25$). In addition, a correlation analysis comparing the surface water densities adjacent to both estuaries to the recorded salinities produced a significant result ($rs=0.92$; $p<0.05$).

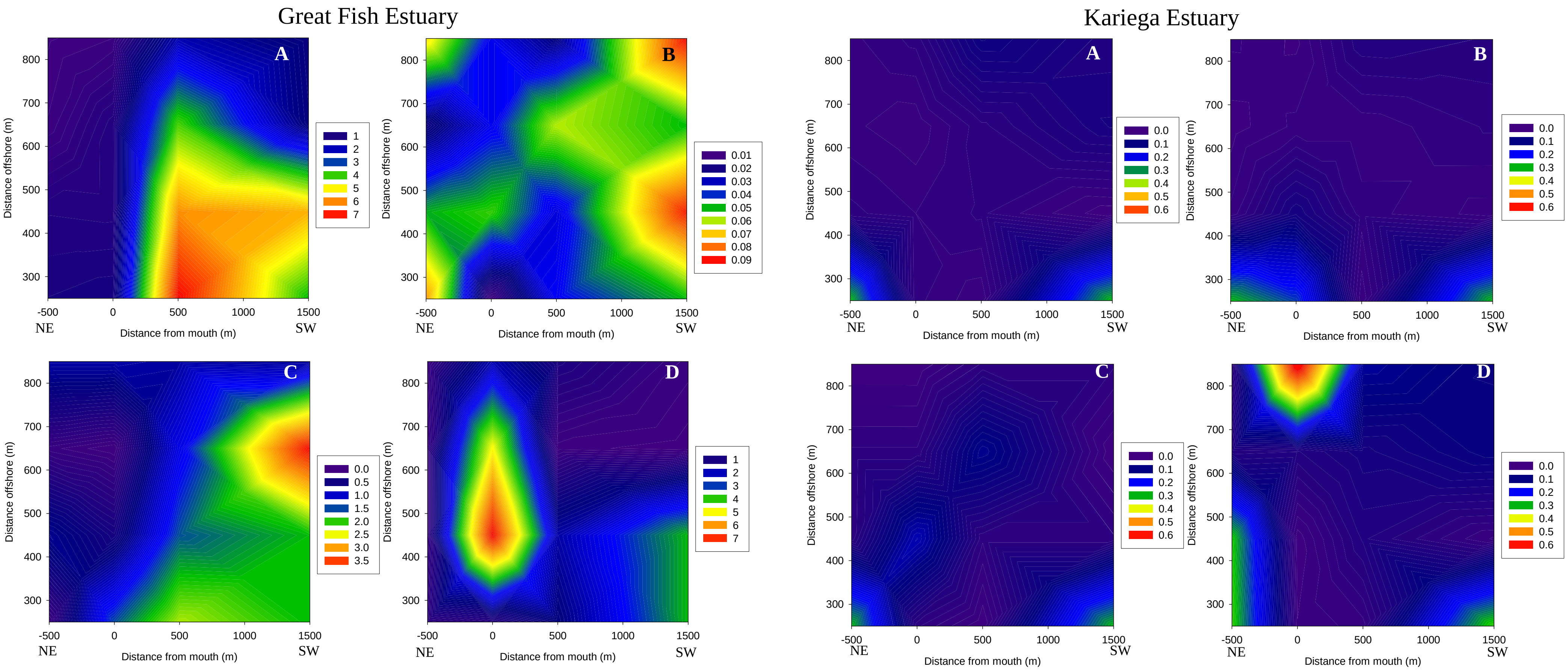


Figure 3.4: Delta σ_t plots for the marine environment adjacent to the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). NE (north-east) and SW (south-west) have been inserted along the x-axis to indicate compass direction.

Table 3.12: The water density (σ_t) and delta σ_t calculated in the marine environment adjacent to the Kariega Estuary. The average, standard deviation, maximum and minimum values are presented.

		June	**September**	**December**	**March**
Surface	Average	25.92	25.49	24.20	24.38
	Std Dev.	0.04	0.02	0.06	0.29
	Maximum	25.98	25.55	24.30	24.64
	Minimum	25.85	25.45	24.08	23.97
5m	Average	25.95	25.49	24.21	24.44
	Std Dev.	0.03	0.05	0.07	0.33
	Maximum	25.99	25.52	24.33	24.70
	Minimum	25.91	25.32	24.08	23.98
Delta σ_t	Average	0.03	0.03	0.03	0.1
	Std Dev.	0.02	0.05	0.04	0.16
	Maximum	0.09	0.23	0.14	0.65
	Minimum	0.01	0.01	0.01	0.01

Particulate organic matter (POM) concentration

The particulate organic matter (POM) concentrations measured within the Great Fish Estuary demonstrated no spatial pattern during any season (Figure 3.5). The POM concentrations measured during September were significantly lower (p=0.012; df=62; T-statistic=-2.58) than those determined for all other seasons, with a surface and bottom minimum of 0.67mg.L^{-1} and maximum of 6.67mg.L^{-1} and 8.00mg.L^{-1}, respectively (Table 3.13). The maximum surface and bottom POM concentrations were measured during March (97.67 and 59.00mg.L^{-1}), while the minimum surface value of 0.67mg.L^{-1} was measured during September and March. The minimum bottom value (0.67mg.L^{-1}) was measured during September (Table 3.13).

The particulate organic matter concentrations recorded within the Kariega Estuary, although variable, demonstrated no longitudinal patterns along the estuary (Figure 3.5). The seasonal trends in POM within the estuary indicated a March minimum of 0.33mg.L^{-1} and a December maximum of 26.00mg.L^{-1} (Table 3.14). During March, the average POM concentration for both the surface and bottom waters was relatively low (3.87 and 2.60mg.L^{-1}, respectively) when compared to the other seasons. The POM concentrations recorded during June and September were intermediate, with average surface values of 8.00mg.L^{-1} (±6.30SD) and 8.90mg.L^{-1} (±1.43SD), respectively, and POM concentrations of 6.40mg.L^{-1} (±3.03SD) and 9.63mg.L^{-1} (±1.97SD), respectively, for bottom waters (Table 3.14). The water column was well-mixed during all seasons (Figure 3.5).

Table 3.13: Particulate organic matter concentrations (mg.L^{-1}) in the surface and bottom waters of the Great Fish Estuary.

		June	September	December	March
Surface	Average	4.58	3.29	8.21	38.54
	Std Dev.	2.20	2.07	2.57	33.23
	Maximum	7.33	6.67	12.33	97.67
	Minimum	1.67	0.67	4.33	0.67
Bottom	Average	8.38	5.04	11.88	28.33
	Std Dev.	5.2	2.27	5.23	15.37
	Maximum	21.00	8.00	21.00	59.00
	Minimum	5.67	0.67	6.33	14.00

Table 3.14: The average, minimum and maximum particulate organic matter concentrations (mg.L^{-1}) recorded within the Kariega Estuary during each season.

		June	September	December	March
Surface	Average	8.00	8.90	16.13	3.87
	Std Dev.	6.30	1.43	2.03	1.63
	Maximum	18.67	11.33	19.33	8.00
	Minimum	2.67	6.67	12.67	2.33
Bottom	Average	6.40	9.63	16.47	2.60
	Std Dev.	3.03	1.97	4.10	1.27
	Maximum	11.00	11.67	26.00	4.33
	Minimum	2.67	5.67	12.00	0.33

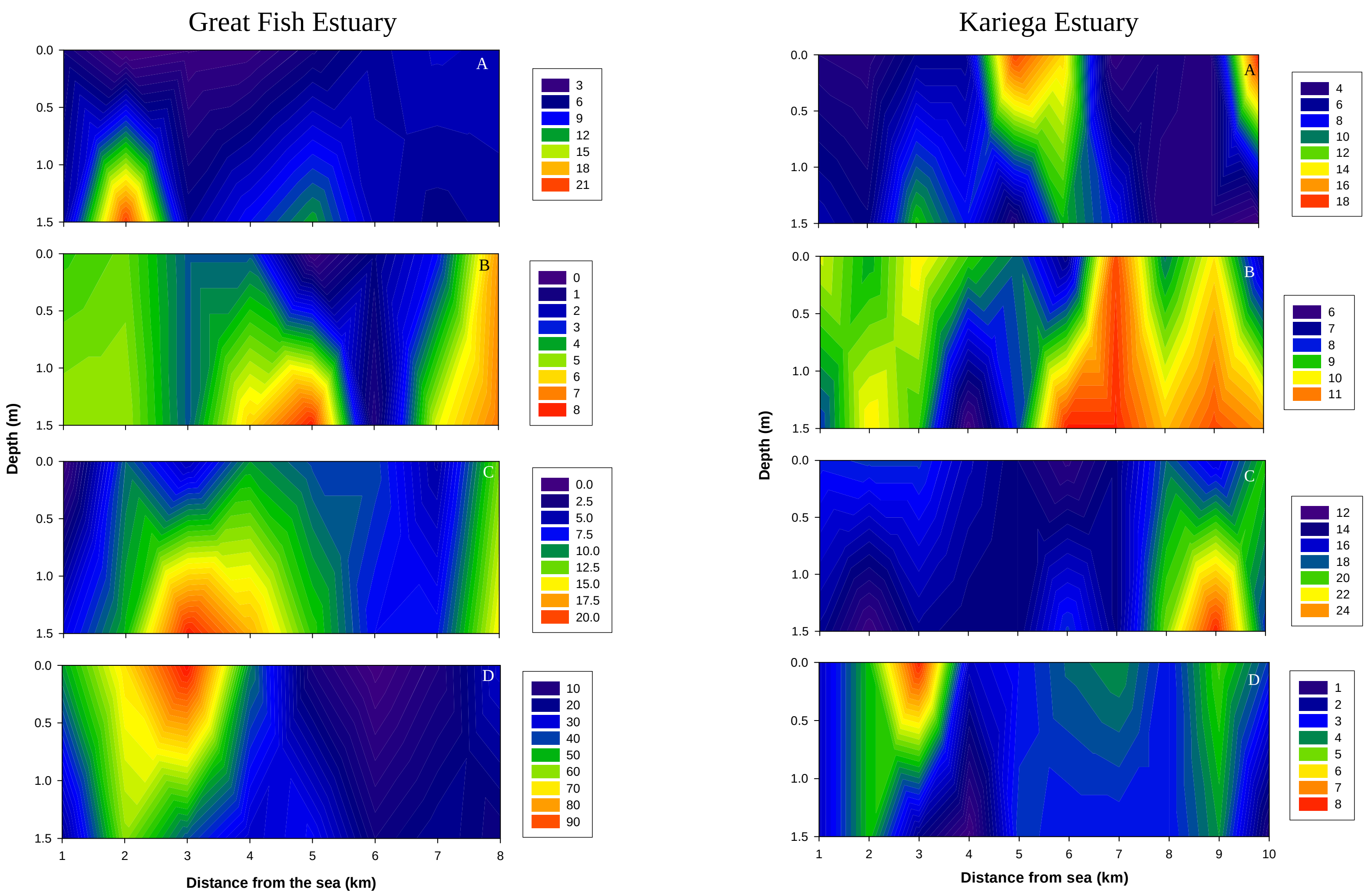


Figure 3.5: Particulate organic matter concentration profiles (mg.L^{-1}) for the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). Note the different scales on the contour plots.

Seasonal patterns in the POM concentrations were evident within the nearshore environment adjacent to the Great Fish Estuary, with the June values being significantly lower than all other seasons ($p<0.0001$; df=132) and March being significantly higher than all other seasons ($p<0.0001$; df=132). The minimum surface POM concentration of 1.33mg.L^{-1} was recorded during June, while the maximum (42.67mg.L^{-1}) recorded during March (Table 3.15). Similarly, the maximum 5m POM concentration of 34.67mg.L^{-1} was recorded during March, but the minimum of 0.67mg.L^{-1} was recorded during September (Table 3.15). There were no significant differences in POM concentration between surface and 5m waters during all four seasons (Table 3.15; Appendix 2, Figure A2.9 – A2.12).

No spatial trends in POM concentration were evident in the nearshore environment adjacent to the Great Fish Estuary during December 2005 and March 2006 (Appendix 2, Figure A2.11 – A2.12). During June, however, significantly lower POM concentrations ($p=0.036$) were recorded for transect three relative to the remaining transects. Similarly, the transects near the mouth of the estuary (one and two) contained significantly higher POM concentrations ($p=0.014$) during September.

Table 3.15: Particulate organic matter concentrations (mg.L^{-1}) in the surface and 5m waters in the nearshore environment opposite the Great Fish Estuary (* denotes significant difference from a t-test between surface and 5m waters).

		June	September	December	March
Surface	Average	2.5	7.97	8.57	13.27
	Std Dev.	0.93	1.93	6.13	8.43
	Maximum	4	11.67	18.67	42.67
	Minimum	1.33	4.67	3	1.67
5m	Average	2.77	8.6	6.43	14.63
	Std Dev.	1.23	1.27	5.73	6.53
	Maximum	6.67	11	20.33	34.67
	Minimum	1.67	6	0.67	1.33
t-test	Deg. Of Freedom	14	15	17	17
	t Stat	-0.78	-1.1	1.83	-0.44
	P value	0.45	0.29	0.08	0.66

The POM concentrations in the nearshore environment adjacent to the Kariega Estuary indicated no differentiation between the surface waters and those at 5m during all seasons except December (Appendix 2, Figures A2.9 – A2.12; Table 3.16). During December the average 5m POM concentration (4.30mg.L^{-1}) was significantly greater than the surface POM concentration (2.23mg.L^{-1}) ($p>0.05$).

In the nearshore environment adjacent to the Kariega Estuary no spatial trends in the POM concentration were evident (Appendix 2, Figure A2.9 – A2.12). The POM concentrations recorded during the March survey were significantly higher ($p<0.0001$; df=137) than those recorded for all other seasons, with a surface average of 11.37mg.L^{-1} and a 5m average of 14.07mg.L^{-1} (Table 3.16). During the remaining surveys POM concentrations in surface and 5m waters were generally less than 5mg.L^{-1} (Table 3.16).

Table 3.16: The average, minimum and maximum POM concentration (mg.L^{-1}) recorded for each season in the surface waters and those at 5m in the nearshore environment adjacent to the Kariega Estuary.

		June	September	December	March
Surface	Average	3.10	2.17	2.23	11.37
	Std Dev.	0.73	0.63	1.20	4.10
	Maximum	4.33	3.67	4.67	17.33
	Minimum	1.33	1.33	0.33	0.67
5m	Average	3.23	2.43	4.30	14.07
	Std Dev.	0.90	0.87	1.80	8.40
	Maximum	4.67	4.33	7.33	42.33
	Minimum	1.67	1.00	0.67	6.67
t-test	Deg. Of Freedom	18	18	18	18
	t Stat	-0.56	-1.29	-3.78	-1.29
	P value	0.58	0.21	0.001	0.21

No significant differences in the POM concentrations recorded in the Kariega Estuary relative to the Great Fish Estuary was noted. Similarly, offshore of these systems the high variability recorded for POM concentrations prevented any significant differences occurring between these two systems.

Chlorophyll-a concentration

The mean total chlorophyll-*a* (chl-*a*) concentration recorded within the Great Fish Estuary ranged from 2.27µg.L^{-1} to 9.61µg.L^{-1} and demonstrated distinct spatial trends during all seasons (Figure 3.6). During June, September and December the maximum total chl-*a* concentration was recorded in the upper reaches and the minimum near the estuary mouth. During March, an inverse pattern was evident, with the highest chl-*a* concentrations at the mouth of the estuary, associated with marine water incursions (Figure 3.6).

The total chl-*a* concentration recorded in the Great Fish Estuary indicated seasonal trends that appeared to be related to the magnitude of fresh water input. June and December demonstrated the highest chl-*a* concentrations, and were associated with medium flow rates of approximately 5 – 10m^{3}.s^{-1}, while during September a significantly ($p<0.001$; df=62) lower chl-*a* concentration was recorded (Table 3.17), associated with the lowest flow rates. The chl-*a* concentrations recorded during March were also low (Table 3.17), but associated with substantially higher flow rates of 32m^{3}.s^{-1} (Table 3.2).

Within the Great Fish Estuary all seasons except June demonstrated a well-mixed water column in terms of total chl-*a* concentration, with very little differentiation between the surface and bottom waters (Table 3.17; Figure 3.6). During June, total chl-*a* concentration in the bottom waters (average 4.52µg.L^{-1} ±3.62SD) was significantly lower ($p<0.001$; df=7) than the surface waters, which averaged 9.61µg.L^{-1} (Table 3.17).

The total chlorophyll-*a* concentration in the Kariega Estuary ranged from a June minimum of 0.04µg.L^{-1} to a March maximum of 5.36µg.L^{-1} (Table 3.18). Although variable, no longitudinal trends were evident during September and December (Figure 3.6). During June there was an increase in the total chl-*a* concentration from the mouth towards the head of the estuary, while in December the inverse relationship existed, with a decrease from the mouth up the system (Figure 3.6).

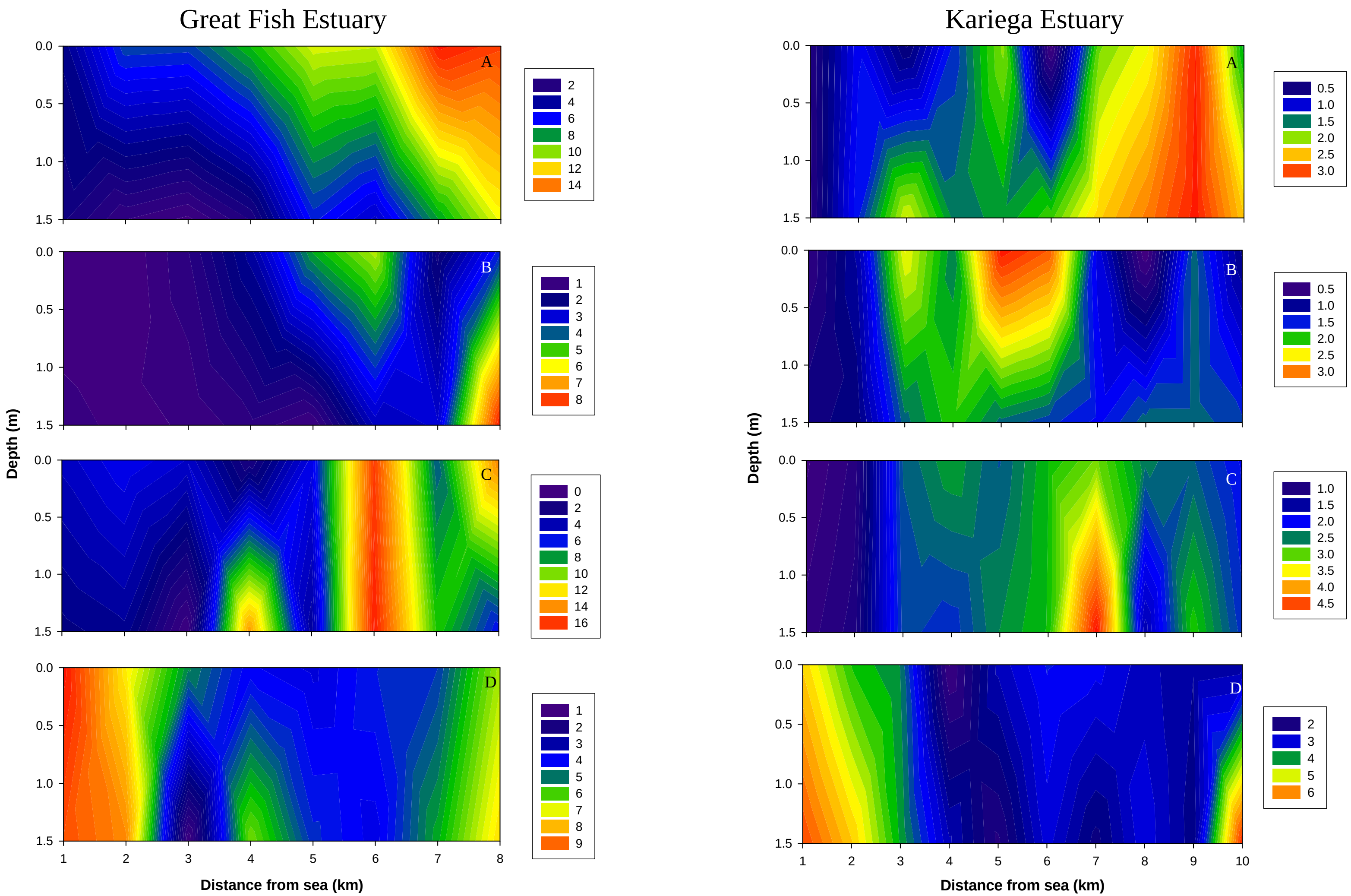


Figure 3.6: Total chlorophyll-*a* concentration profiles (µg.L^{-1}) for the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). Note the different scales on the contour plots.

Table 3.17: Total chlorophyll-*a* concentration (µg.L^{-1}) for the surface and bottom waters within the Great Fish Estuary.

		June	September	December	March
Surface	Average	9.61	2.49	7.11	5.58
	Std Dev.	4.25	1.82	5.04	2.18
	Maximum	15.76	5.51	15.69	9.91
	Minimum	3.32	0.62	1.55	3.54
Bottom	Average	4.52	2.27	7.64	5.69
	Std Dev.	3.62	2.58	5.53	2.71
	Maximum	10.95	8.28	16.49	9.18
	Minimum	0.69	0.75	2.63	0.98

The average surface and bottom total chlorophyll-*a* concentrations in the Kariega Estuary during the June, September and December surveys were less than 2.5µg.L^{-1} (Table 3.18). The chlorophyll-*a* concentrations recorded during March were significantly higher ($p<0.001$; df=78) than all other seasons, with a surface maximum value of 5.36µg.L^{-1} and a bottom maximum value of 6.63µg.L^{-1} (Table 3.18).

Table 3.18: The average, maximum and minimum total chlorophyll-*a* concentrations (µg.L^{-1}) recorded within the Kariega Estuary for surface and bottom waters during all seasons surveyed.

		June	September	December	March
Surface	Average	1.38	1.62	2.1	3.13
	Std Dev.	0.95	1.05	0.79	1.1
	Maximum	3.1	3.37	3.02	5.36
	Minimum	0.04	0.31	0.58	1.39
Bottom	Average	1.9	1.46	2.25	3.71
	Std Dev.	0.84	0.38	1.13	1.82
	Maximum	3.16	1.97	4.78	6.63
	Minimum	0.27	0.78	0.74	1.75

The Kariega Estuary surface chlorophyll concentration was significantly higher than that recorded within the Great Fish Estuary ($p<0.05$; $t=2.16$). The surface chlorophyll concentration recorded within both estuaries was shown to correlate significantly with the river flow rate of the two systems ($r_s=0.822$; $p<0.05$) and negatively with the particulate organic content of the estuarine waters ($r_s=-0.791$; $p<0.05$) (Table 3.19).

Table 3.19: The Spearman Rank Correlation Coefficient (r_s) demonstrating the degree of relationship between the various estuarine parameters and river flow rates adjacent to both estuaries studied. Significance ($p<0.05$) is indicated with an * (n=8).

	Zooplankton Density	**Estuarine POM**	**Surface Chlorophyll-*a***	**Salinity**	**River Flow**
Zooplankton Density	1.000				
Estuarine POM	-0.414	1.000			
Chlorophyll-*a*	-0.116	0.079	1.000		
Salinity	-0.206	-0.413	-0.791*	1.000	
River Flow	-0.034	0.494	0.822*	-0.945	1.000

In the nearshore environment adjacent to the Great Fish Estuary total chlorophyll-*a* concentration in September and December demonstrated no distinct vertical or horizontal patterns. Alternatively, during the June and March surveys, total chlorophyll-*a* concentrations in surface waters were significantly higher than those recorded at 5m depth ($p=0.03$ and $p<0.01$ respectively) (Table 3.20). The maximum surface and 5m chl-*a* concentrations were measured during March (11.83 and 8.26μg.L^{-1}, respectively), while the minimum concentrations for surface and 5m waters were measured during June (0.09 and 0.02μg.L^{-1} respectively) (Table 3.20). Seasonal differences in chlorophyll-*a* concentrations were identified adjacent to the Great Fish, with the June total chl-*a* concentration being significantly lower ($p<0.001$; df=128) than those determined for all other seasons. Similarly, the total chl-*a* concentration in March was significantly higher than during all other seasons ($p<0.001$; df=128).

Spatial trends in the total chl-*a* concentration in the nearshore environment adjacent to the Great Fish Estuary were only evident during June and September (Appendix 2, Figure A2.13 – A2.16). During June, the surface water total chl-*a* concentration in transect three and four was significantly higher than the remaining sites (Appendix 2, Figure A2.13). Similarly, during September, the total chl-*a* concentrations at all transects downstream of the mouth (transects 3, 4 and 5) were significantly higher than those recorded upstream and adjacent to the estuary mouth (Appendix 2, Figure A2.14).

Table 3.20: Total chlorophyll-*a* concentration (µg.L^{-1}) for the surface waters and those at 5m depth in the nearshore environment opposite the Great Fish Estuary, including t-test results for comparisons between the values recorded for the surface and 5m waters (* indicates significant p-values).

		June	September	December	March
Surface	Average	0.48	1.51	1.74	8.37
	Std Dev.	0.42	0.58	0.19	2.54
	Maximum	1.39	3.31	2.2	11.83
	Minimum	0.09	0.77	1.49	3.74
5m	Average	0.21	1.48	1.84	6.52
	Std Dev.	0.09	0.59	0.31	1.58
	Maximum	0.35	2.54	2.63	8.26
	Minimum	0.02	0.48	1.42	2.87
t-test	Deg. Of Freedom	14	15	18	17
	t Stat	2.35	0.1	-1.4	2.9
	P value	0.03*	0.92	0.18	0.009*

The total chl-*a* concentration in the marine environment adjacent to the Kariega Estuary was lower than that recorded in the estuary during all seasons, with the exception of March, with a surface average during June, September and December of 0.18, 0.62 and 0.79µg.L^{-1} respectively (Table 3.21). The March surface and 5m concentrations of 9.02µg.L^{-1} and 8.86µg.L^{-1} were significantly higher than any other season ($p<0.0001$; df=182) and higher than those recorded within the estuary during the same period.

The total chlorophyll-*a* concentration recorded in the nearshore environment adjacent to the Kariega Estuary indicates a well-mixed water column with the difference between surface and 5m waters always being less than 0.2µg.L^{-1} (Table 3.21). The seasonal chl-*a* values demonstrated a steady increase from June to December, with a large increase observed in March in both surface and 5m waters. The June and September surveys recorded a spatial trend of significantly lower chl-*a* concentrations in the transects near the mouth ($p<0.002$; df=36 and $p<0.001$; df=36 respectively) (Appendix 2, Figure A2.13 and A2.14). In December a similar, but not significant trend was observed ($p>0.05$), with lower concentrations only at sites five and six (Appendix 2, Figure A2.15).

Table 3.21: The average, maximum and minimum chlorophyll-*a* concentrations ($\mu g.L^{-1}$) recorded in the nearshore environment adjacent to the Kariega Estuary during all four surveys.

		June	September	December	March
Surface	Average	0.18	0.62	0.79	9.02
	Std Dev.	0.09	0.24	0.18	1.82
	Maximum	0.47	1.04	1.13	12.04
	Minimum	0.08	0.33	0.33	4.03
5m	Average	0.16	0.62	0.84	8.86
	Std Dev.	0.09	0.18	0.25	1.46
	Maximum	0.42	0.94	1.25	11.31
	Minimum	0.05	0.38	0.33	6.23

The surface chlorophyll-*a* concentration in the marine environment adjacent to the Kariega Estuary was significantly lower than that recorded adjacent to the Great Fish during June, September and December ($p<0.03$; $t=2.2$). The marine surface chlorophyll-*a* concentration was found to significantly correlate to the flow rate in the adjacent marine environment ($r_s=-0.762$; $p<0.05$) (Table 3.22). Chlorophyll concentrations were also shown to significantly correlate with the zooplankton densities and biomasses recorded in the marine environment (Table 3.22).

Table 3.22: The Spearman Rank Correlation Coefficient (r_s) demonstrating the degree of relationship between the various offshore parameters and river flow rates adjacent to both estuaries studied. Significance ($p<0.05$) is indicated with an * (n=8).

	Zooplankton Density	**Zooplankton Biomass**	**Surface Chlorophyll-*a***	**Particulate Organic Matter**	**River Flow**
Zooplankton Density	1.000				
Zooplankton Biomass	0.738*	1.000			
Chlorophyll-*a*	0.714*	0.738*	1.000		
Particulate Organic Matter	0.881*	0.738*	0.762*	1.000	
River Flow	0.708*	0.439	0.415	0.634	1.000

3.3.3 Zooplankton density and biomass

Zooplankton density

The average total zooplankton densities within the Great Fish Estuary ranged from 72 to 10 244ind.m^{-3} during the study period (Table 3.23). During the June, September and December surveys the maximum zooplankton densities were recorded in the upper reaches of the estuary, while during the March survey the maximum zooplankton densities were recorded in the middle and lower reaches of the system (Figure 3.7). Although seasonal trends were evident, the high degree of variability in the total zooplankton densities resulted in differences not being significant ($p>0.05$). March demonstrated the lowest densities of zooplankton, with a minimum of 16.04ind.m^{-3} and a maximum of 112.35ind.m^{-3} (Table 3.23). Densities of zooplankton during the remaining months were, on average, an order of magnitude higher, although the minimum values were in the same range as the March values (Table 3.23). The highest densities within the Great Fish Estuary were recorded in September, with an average of 10 244.52ind.m^{-3} (±15 111.13SD) (Table 3.23). During the June and December surveys the total zooplankton densities ranged between 22.01 and 4 860.25ind.m^{-3} and 22.79 and 13 603.26ind.m^{-3}, respectively (Table 3.23).

Table 3.23: The total zooplankton densities (ind.m^{-3}) recorded within the Great Fish and Kariega Estuaries during the study. Standard deviations, maximum and minimum densities are shown for each month.

		June	September	December	March
Great Fish	Average	1 389.30	10 244.52	3 449.34	72.31
	Std Dev.	1 815.76	15 111.13	5 160.47	36.93
	Maximum	4 860.25	42 896.56	13 603.26	112.35
	Minimum	22.01	63.81	22.79	16.04
Kariega	Average	1 727.31	581.36	1 031.89	966.29
	Std Dev.	1 148.62	474.32	740.28	630.91
	Maximum	3 785.73	1 550.20	2 748.28	2 464.23
	Minimum	121.60	53.51	157.42	380.00

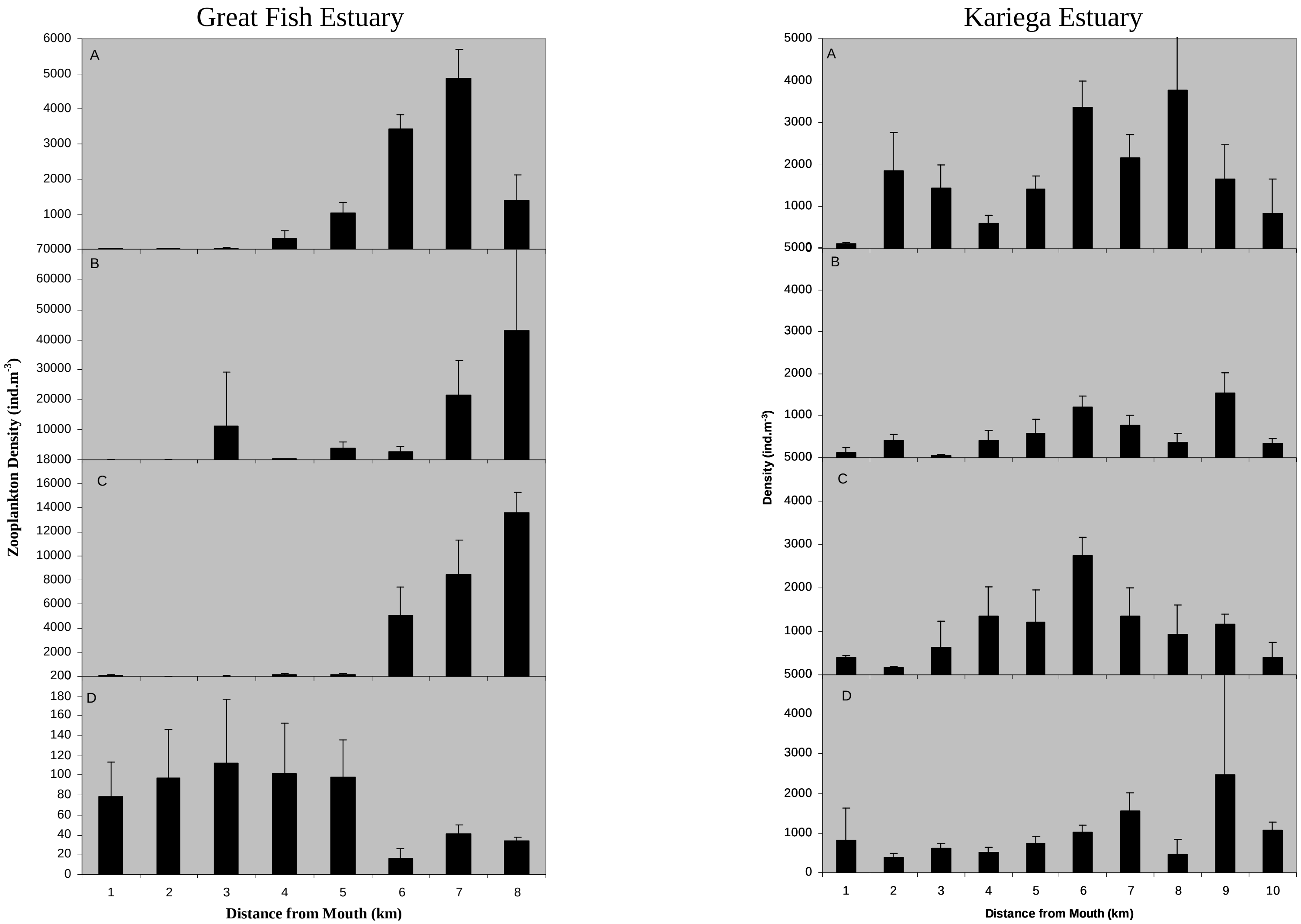


Figure 3.7: The total zooplankton densities (ind.m^{-3}) recorded in the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D) surveys. Error bars represent standard deviation.

The total zooplankton density recorded within the Kariega Estuary generally demonstrated a similar longitudinal pattern during all seasons, with peaks recorded in the middle to upper reaches of the system (Figure 3.7). The average zooplankton densities in the mouth region during the June, September and December surveys were 121ind.m^{-3}, 127.73ind.m^{-}3 and 405.06ind.m^{-3} respectively. The maximum zooplankton densities recorded during June, September and December were 3 785.73ind.m^{-3}, 1 550.20ind.m^{-3} and 2 748.28ind.m^{-3} (Figure 3.7). During the March survey the average zooplankton density in the mouth region was higher at approximately 823.44ind.m^{-3}, with a maximum density of 2 464.23ind.m^{-3} (Figure 3.7). No seasonal trend in the average zooplankton densities recorded within the Kariega Estuary was evident, with minimum densities occurring in September (581.36ind.m^{-3}) and maximum densities occurring in June (1 727.31ind.m^{-3}) (Table 3.23). The average densities recorded in December and March were approximately 1 000ind.m^{-3}.

The mean total zooplankton densities within the grid survey occupied adjacent to the Great Fish Estuary ranged from 72 to 37 055ind.m^{-3} (Table 3.24). Peaks in total zooplankton abundance during the June, September and March surveys were associated with the plume of low salinity water leaving the estuary. Alternatively, during December, the highest zooplankton densities were recorded along Transect 1, located upstream of the estuary mouth (Figure 3.8).

Table 3.24: Average total zooplankton densities (ind.m^{-3}) recorded in the nearshore marine environment adjacent to the Great Fish and Kariega Estuaries, including standard deviation, maximum and minimum values.

		June	September	December	March
Great Fish	Average	694.11	276.53	2 091.36	15 713.15
	Std Dev.	404.14	179.70	2 104.51	8 694.71
	Maximum	1 229.36	730.08	9 242.91	37 055.95
	Minimum	213.04	62.25	693.97	5 663.31
Kariega	Average	110.41	96.56	90.29	30 513.20
	Std Dev.	92.57	74.38	66.51	22 609.15
	Maximum	412.69	307.33	264.06	91 589.50
	Minimum	35.56	14.93	28.88	6 729.70

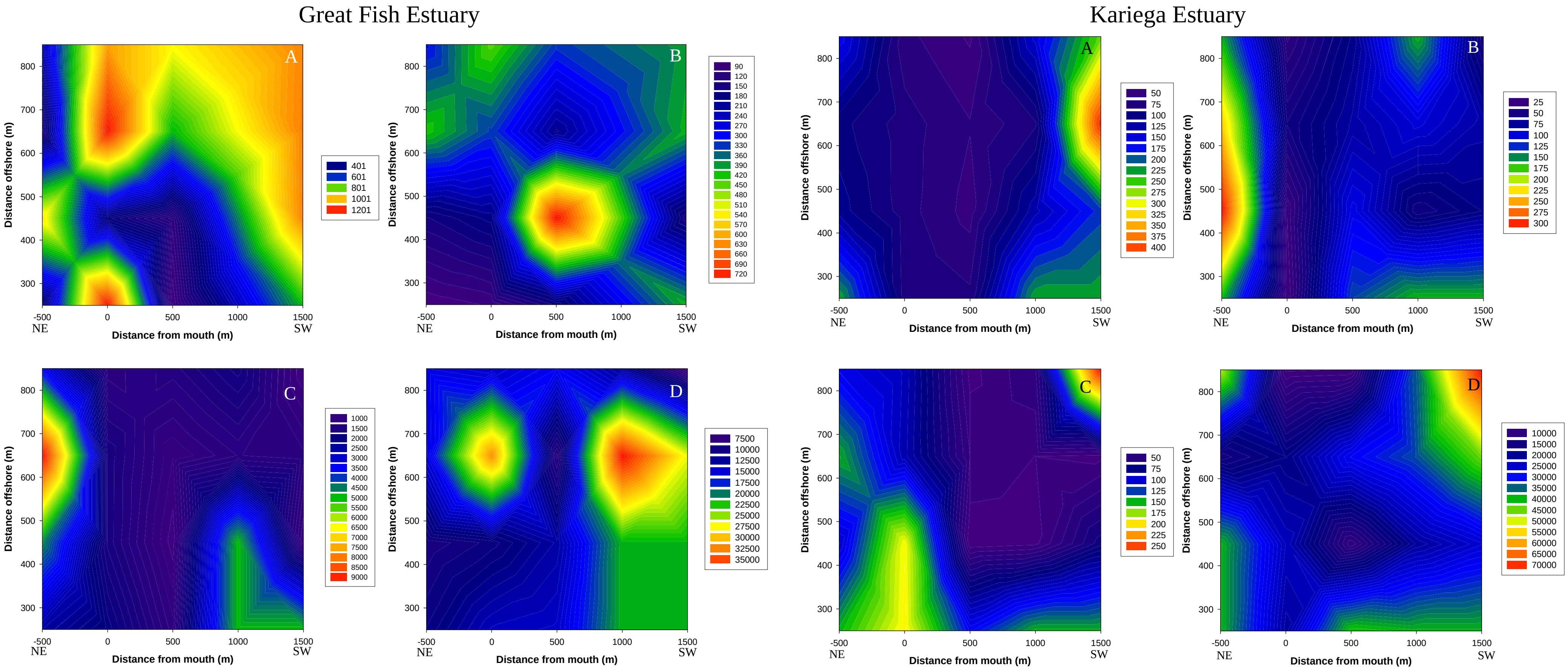


Figure 3.8: The total zooplankton densities (ind.m^{-3}) recorded offshore of the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). Note the different scales on each contour plot. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Variations in the total zooplankton densities in the marine environment adjacent to the Great Fish Estuary were strongly correlated to the outflow of estuarine water (r_s=0.708; $p<0.05$) (Table 3.22). Significantly higher ($p<0.0001$; df=57) zooplankton density observed during March coincided with the highest flow rates recorded. Similarly, the significantly lower ($p<0.01$; df=57) densities observed during September coincided with the lowest flow rates recorded during the study (Table 3.2). Total densities of zooplankton in the marine environment ranged from 62.25ind.m^{-3} to 1 229ind.m^{-3}. The minimum zooplankton density recorded in the nearshore environment during the study was 62.25ind.m^{-3} during September, while the minimum for March of 5 663.31ind.m^{-3} was higher than the maximum value for both June (1 229.36ind.m^{-3}) and September (730.08ind.m^{-3}) (Table 3.24).

The total zooplankton densities in the nearshore environment adjacent to the Kariega Estuary ranged from 14.93 to 91 589.50ind.m^{-3} (Table 3.24). Densities during the March survey (6729ind.m^{-3} to 91 589.5ind.m^{-3}) were significantly higher ($p<0.0001$; df=73) than all other seasons (Table 3.24). The seasonal trend demonstrated a decrease in average densities from June (110.41ind.m^{-3} ±92.57SD) to December (90.29ind.m^{-3} ±66.51SD). Although no significant spatial patterns in total zooplankton density were evident during the surveys (Figure 3.8), peaks in zooplankton densities occurred in transect one and two during the September, December and March surveys.

The spatial patterns in total zooplankton densities in the marine environments adjacent to both estuaries correlated significantly with the fresh water flow rates (r_s=0.708; $p<0.05$), total chlorophyll-a concentration (r_s=0.714; $p<0.05$) and particulate organic matter concentrations (r_s=0.881; $p<0.05$) (Table 3.22).

Zooplankton biomass

The total zooplankton biomass within the Great Fish Estuary ranged between a June minimum of 11.92mg dwt m^{-3} (±15.09SD) and a March maximum of 184.87mg dwt m^{-3} (±117.41SD) (Table 3.25). The total zooplankton biomass during the June to December surveys broadly demonstrated a similar spatial pattern with highest values generally being recorded in the upper reaches of the system and the lowest at the mouth. An exception was recorded during the March survey where maximum zooplankton biomass was recorded in the middle reaches of the estuary (Figure 3.9; Table 3.25). Seasonal variations in the total zooplankton biomass were evident within the Great Fish Estuary, with significantly lower biomass ($p=0.02$; $df=15$) being recorded in June and December relative to September and March. The highest zooplankton biomass was recorded in the upper reaches during September (1 010.58mg dwt m^{-3}), while the lowest was recorded in the mouth region in June (2.36mg dwt m^{-3}) (Table 3.25).

Table 3.25: Total zooplankton biomass (mg dwt m^{-3}) averaged across all sites within the Great Fish and Kariega Estuaries for each season. Standard deviation, maximum and minimum values are presented.

		June	September	December	March
Great Fish	Average	11.92	157.41	24.20	184.87
	Std Dev.	15.08	350.55	25.72	117.41
	Maximum	46.53	1010.58	83.71	408.42
	Minimum	2.36	5.89	5.26	63.44
Kariega	Average	21.59	12.57	33.29	145.89
	Std Dev.	5.62	3.36	20.17	275.26
	Maximum	34.23	16.11	80.31	887.08
	Minimum	13.98	7.39	15.24	24.56

The total zooplankton biomass recorded within the Kariega Estuary ranged between a September minimum of 7.39mg dwt m^{-3} to a March maximum of 887.08mg dwt m^{-3} (Table 3.25). During June and December a longitudinal trend of increasing zooplankton biomass towards the middle reaches of the Kariega Estuary from both the head and mouth region was observed (Figure 3.9). No obvious longitudinal trend was evident in September and March (Figure 3.9). The high biomasses recorded in June and December occurred at sites adjacent to the salt marshes, while there was also a high biomass at sites located at the mouth of the estuary during March. The lowest zooplankton biomass was recorded in September, where the average zooplankton biomass was estimated at 12.57mg dwt m^{-3} (Table 3.25). The highest zooplankton biomass was recorded in March, with an average biomass of 145.89mg dwt m^{-3} (Table 3.25).

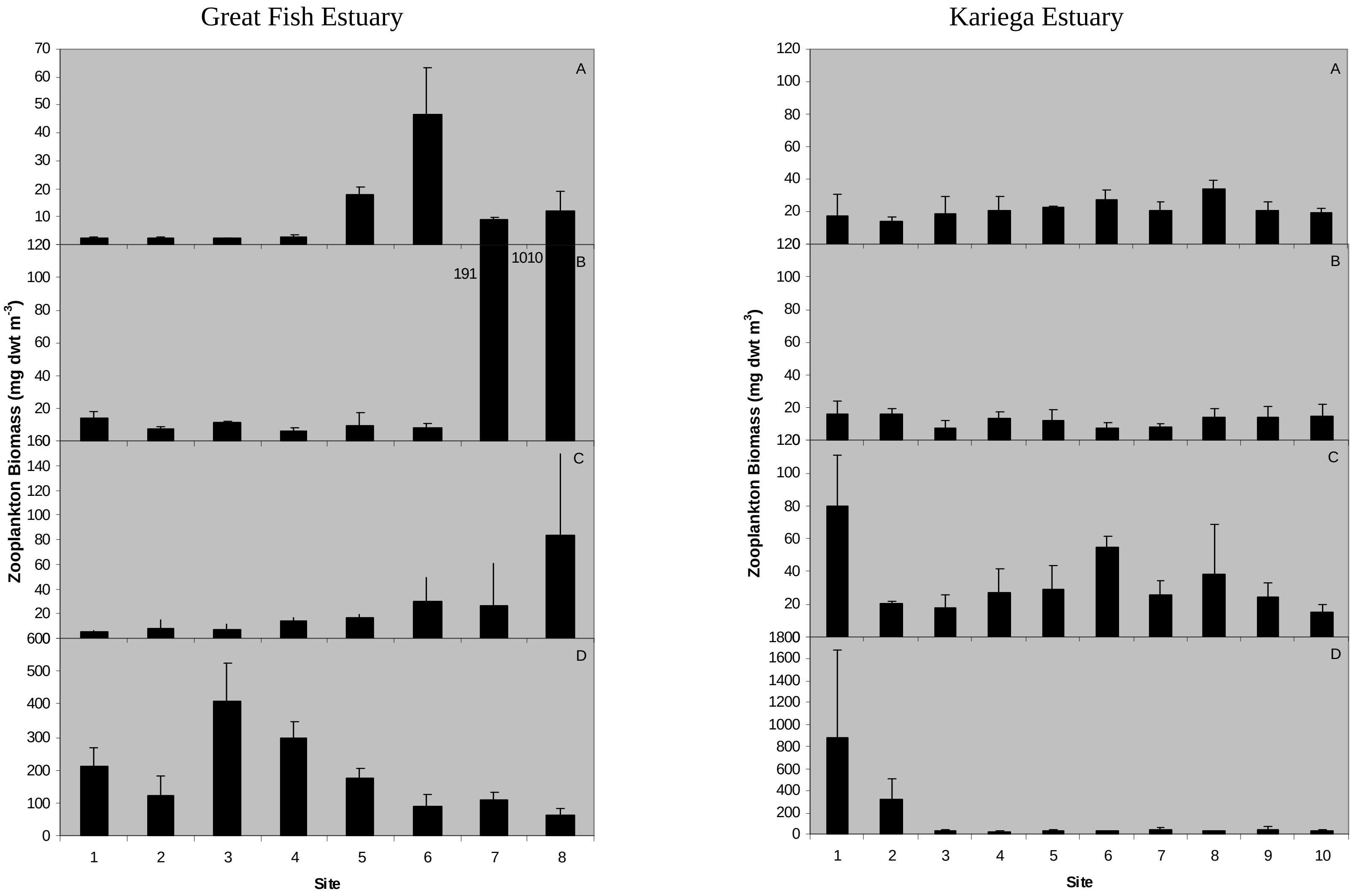


Figure 3.9: Total zooplankton biomass recorded in the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). Error bars are standard deviation.

The mean total zooplankton biomass within the nearshore environment adjacent to the Great Fish Estuary was highly patchy and ranged from 9.60 to 45.12mg dwt m^{-3}. Similar spatial trends were evident during September and December with peak biomass occurring close inshore in transects downstream of the estuary mouth (Figure 3.10). During June and March the peak zooplankton biomass was recorded offshore, but adjacent to the estuary mouth (transect 2). The highest biomass was recorded in transect one during March (163.14mg dwt m^{-3}), while the lowest was recorded in transect one during September (4.57mg dwt m^{-3}) (Table 3.26; Figure 3.10).

The total zooplankton biomass in the nearshore environment adjacent to the Great Fish Estuary indicated the highest values close inshore and slightly downstream of the mouth of the estuary during the September and December surveys (Figure 3.10). This corresponded to the inshore edge of the plume of estuarine water entering the marine environment (as evident from density and salinity values) (Appendix 2, Figures A2.2, A2.3 and A2.82). Similarly, peaks in total zooplankton biomass identified during June (156.60mg dwt m^{-3}) and March (163.14mg dwt m^{-3}) were closely related to the fresher estuarine water entering the nearshore environment (Appendix 2, Figures A2.1 and A2.4).

The total zooplankton biomass in the nearshore marine environment adjacent to the Kariega Estuary demonstrated a similar pattern to that recorded within the estuary, with the lowest average zooplankton biomass recorded in September (7.82mg dwt m^{-3}) and the highest during the March survey (210.9mg dwt m^{-3}) (Table 3.26). Intermediate values were recorded in June (20.27mg dwt m^{-3} ±24.55SD) and December (27.04mg dwt m^{-3} ±32.79SD). The zooplankton biomass recorded near the mouth of the estuary (transect 1 and 2) was significantly higher ($p<0.05$) than that at the remaining stations during all seasons (Figure 3.10).

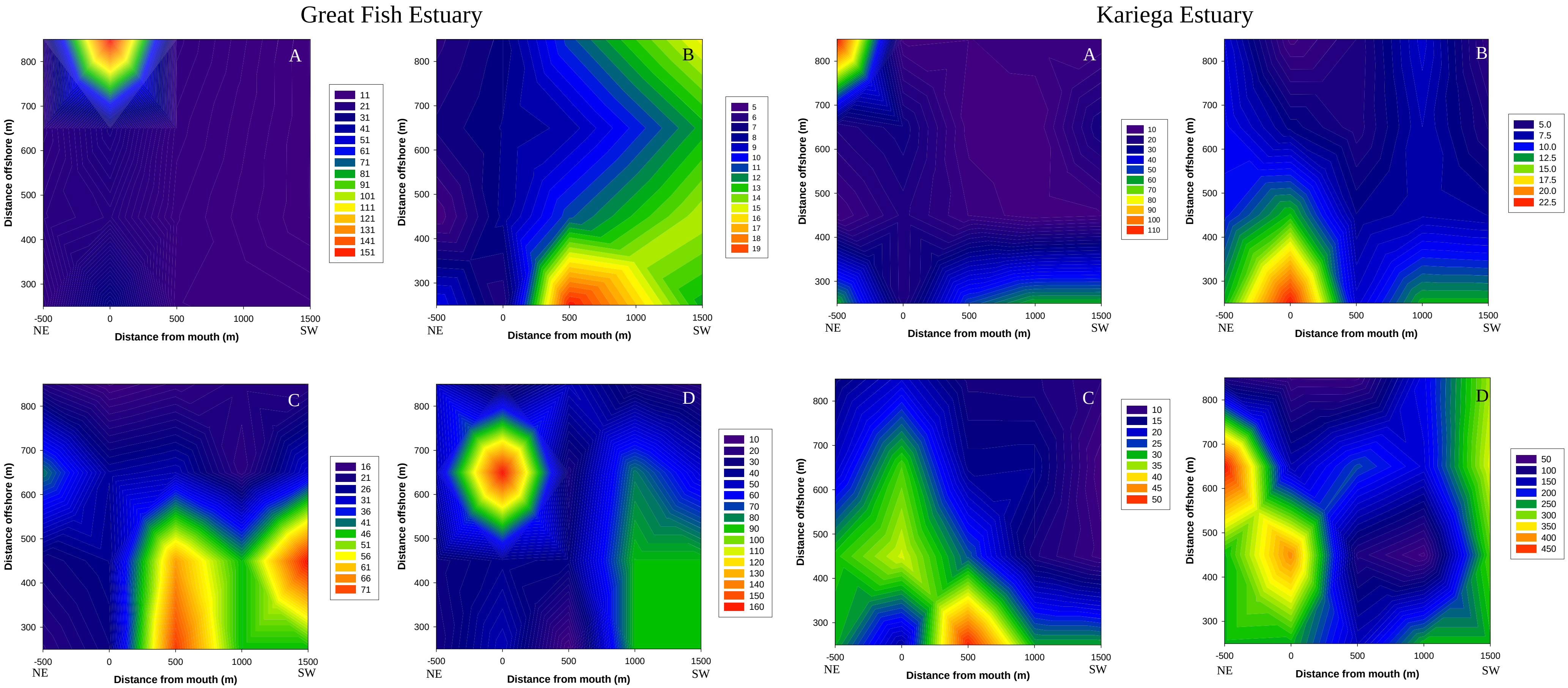


Figure 3.10: The total zooplankton biomass (mg dwt m^{-3}) recorded offshore of the Great Fish (left) and Kariega (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). Note the different scales on each contour plot. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Table 3.26: Total zooplankton biomass (mg dwt m^{-3}) averaged across all sites in the sampling grid in the nearshore environment adjacent to the Great Fish and Kariega Estuaries. Standard deviation, maximum and minimum values for each season are presented.

		June	September	December	March
Great Fish	Average	25.44	9.60	31.06	45.12
	Std Dev.	35.53	4.29	20.01	35.24
	Maximum	156.60	19.87	75.79	163.14
	Minimum	10.31	4.57	13.81	9.36
Kariega	Average	20.27	7.82	27.04	210.95
	Std Dev.	24.55	4.36	32.79	123.80
	Maximum	113.25	22.82	154.66	467.58
	Minimum	8.14	2.80	7.20	46.93

3.3.4 Zooplankton community structure and numerical analysis

Great Fish Estuary and adjacent marine environment

A total of 58 species of zooplankton were recorded in the Great Fish Estuary and adjacent marine environment. Fifty-seven species were recorded in the marine environment, while 35 species occurred in the estuary (see Appendix 3 for the recorded species lists). Margalef's species richness index values for the estuarine zooplankton ranged between 2.06 and 3.39, while in the marine environment the values ranged between 2.48 and 7.16 (Table 3.27). The Shannon-Weiner diversity values calculated for the marine environment ranged from 1.17 to 1.84, while in the estuary, the diversity values varied between 0.24 and 1.53 (Table 3.27). During all seasons, except for March, highest species richness and diversity were recorded in the marine environment, with maximum values recorded in June 2004 (Table 3.27).

Results of numerical analyses conducted on June zooplankton abundance data (Figure 3.11) indicated the presence of two significantly different (ANOSIM; $p<0.05$) groupings of stations, designated Groups 1 and 2. Group 1 comprised stations occupied in the marine environment, while Group 2 consisted of the stations located within the estuary. Group 2 was further separated into the upper (1 – 4) and lower reach (5 – 8) stations. The observed pattern was generally similar for the three remaining surveys (Figure 3.12 to 3.14), with September indicating the only variation with the lower reach sites being more closely related to the marine stations, possibly due to the low flow conditions that predominated in September.

Table 3.27: The combined total number of species, species richness and species diversity for all estuarine and marine sites during each season.

		Number of Species	Margalef's Species Richness	Shannon-Weiner Diversity
June	Estuarine	22	2.90	0.42
	Marine	48	7.16	1.89
September	Estuarine	20	2.06	0.54
	Marine	36	6.29	1.25
December	Estuarine	24	2.82	0.24
	Marine	35	4.45	1.84
March	Estuarine	15	3.39	1.53
	Marine	25	2.48	1.17

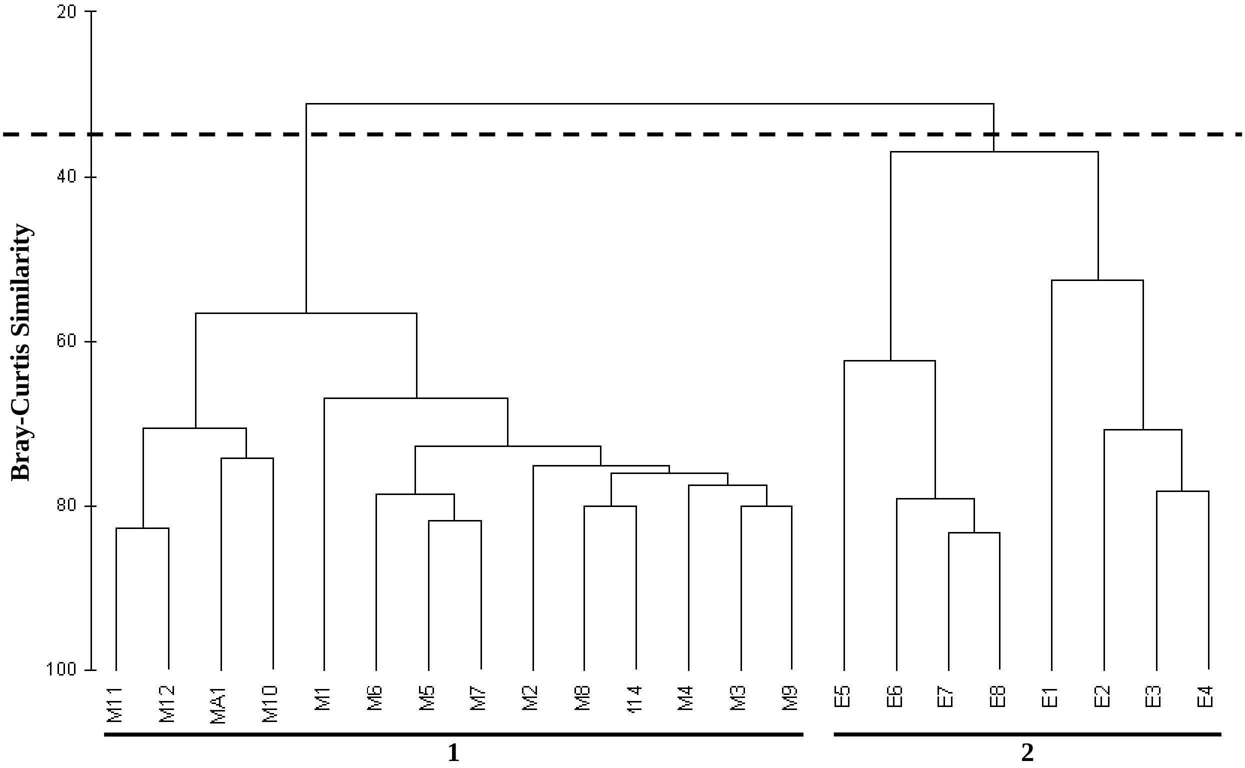


Figure 3.11: Cluster diagram showing the grouping of sites based on the zooplankton community structure sampled in the nearshore environment adjacent to the Great Fish Estuary during June 2004. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents a 35% similarity.

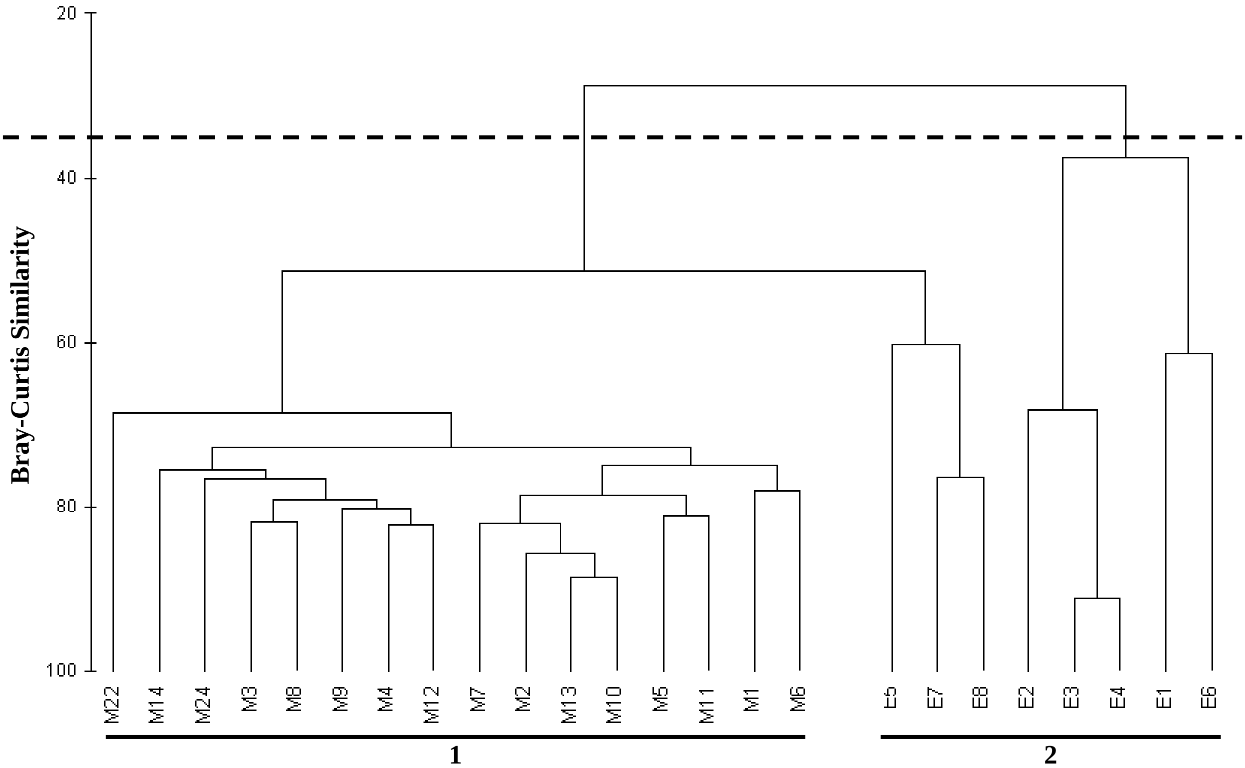


Figure 3.12: Cluster diagram showing the grouping of sites based on the zooplankton community structure sampled in the nearshore environment adjacent to the Great Fish Estuary during September 2004. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents a 35% similarity.

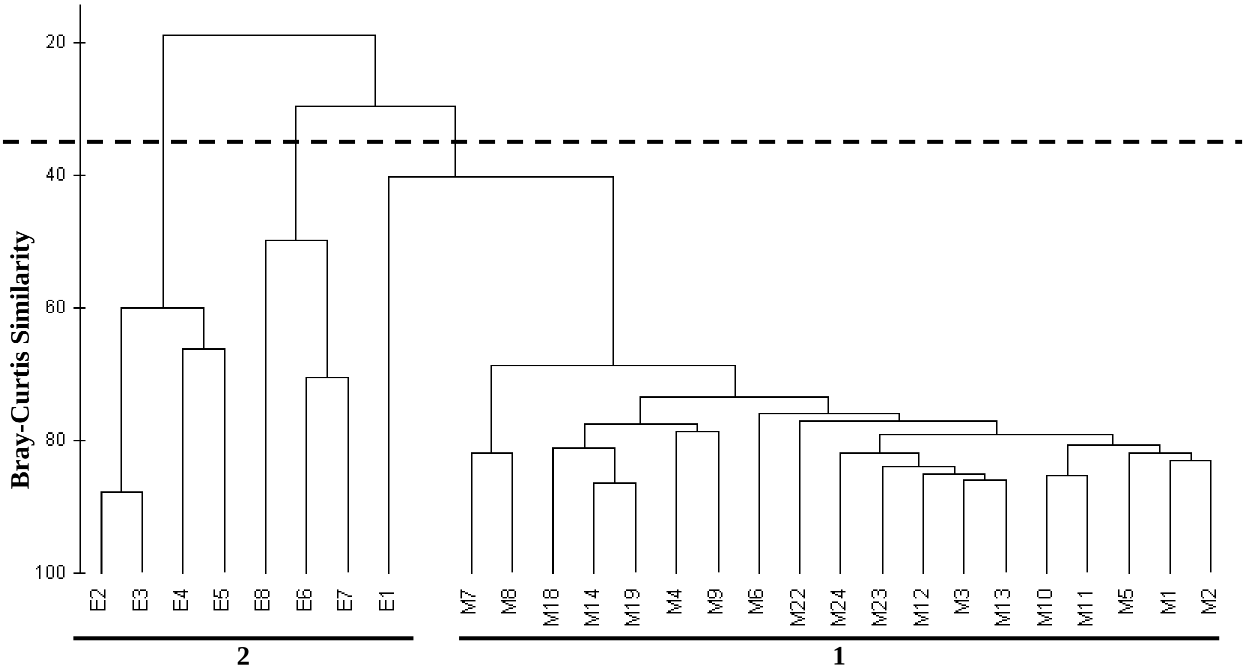


Figure 3.13: Cluster diagram showing the grouping of sites based on the zooplankton community structure sampled in the nearshore environment adjacent to the Great Fish Estuary during December 2004. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents a 35% similarity.

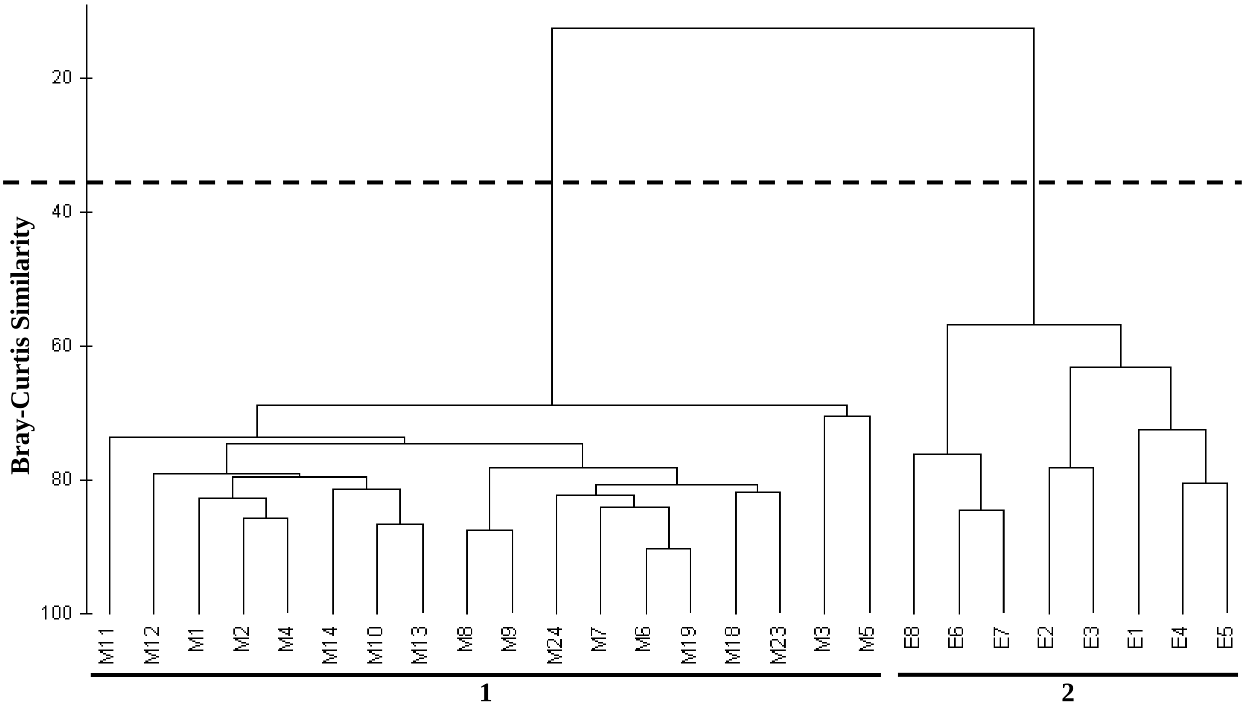


Figure 3.14: Cluster diagram showing the grouping of sites based on the zooplankton community structure sampled in the nearshore environment adjacent to the Great Fish Estuary during March 2005. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents a 35% similarity.

The dominant species causing the separation between the estuarine and marine sites during all seasons are presented in Table 3.28. In June the differences in densities of copepod nauplii (6.5%), *Calanus agulhensis* (De Decker, Kaczmaruk & Marska, 1991) (8.6%) and *Calanus simillimus* (Giesbrecht, 1902) (7.77%) were responsible for 22.9% of the difference between estuarine and marine sites. During September similar species, nauplii (17.2%), *C. agulhensis* (14.0%) and *Oithona* spp. (13.2%), accounted for 44.3% of the difference between the two groups (Table 3.28). The dominant contributors to the community separation during December were Noctiluca (11.7%), *C. agulhensis* (8.2%) and *Oithona* spp. (9.5%). Finally, during March three species, *Oithona* spp. (15.9%), *C. agulhensis* (14.9%) and unidentified zoeae (11.6%), accounted for 42.3% of the separation between marine and estuarine sites (Table 3.28).

Table 3.28: The contribution of the 15 most important species towards community separation into estuarine and marine groups during each season. Included is the average abundance of the species within the estuary and the marine environment in each season. The analysis was conducted in the SIMPER routine of the PRIMER statistical package (Clarke and Warwick, 1994).

	Taxonomic Group/Species	Copepod nauplii	*Calanus agulhensis*	*Calanus simillimus*	Harpacticoida	*Oithona* spp	*Rhopalopthalmus terranatalis*	*Pseudodiaptomus hessei*	*Pontella gaboonensis*	*Noctiluca* spp	Zoeae	*Clausocalanus* spp	*Acartia longipatella*	*Microsetella norvegica*	Corycaeidae spp	Appendicularian spp
June	Average Estuarine Abundance	1280	5	0	4	19	21	4	0	0	4	0	4	12	0	0
	Average Marine Abundance	270	197	41	45	60	0	0	6	0	3	20	1	0	14	2
	Percentage Contribution to Dissimilarity	6.5	8.6	7.8	6.1	5.5	3.8	2.9	3.5	0	2.5	6.1	1.8	4.5	5.1	2.2
September	Average Estuarine Abundance	8990	15	0.1	5	36	65	201	0	0	1	0	0	0	0	0
	Average Marine Abundance	22	64	0.2	2	142	0	0	2	0	3	2	0.3	0.1	1	0.3
	Percentage Contribution to Dissimilarity	17.2	14.0	0.8	4.1	13.2	6.6	5.4	3.2	0	3.8	2.9	0.9	0.2	2.9	1
December	Average Estuarine Abundance	3302	3	0	0	6	50	59	0	0	3	5	0	7	0	0
	Average Marine Abundance	287	137	3	25	527	0	2	0.1	638	227	87	3	0	7	20
	Percentage Contribution to Dissimilarity	7.4	8.2	2.3	5.8	9.5	4.7	3.6	0.1	11.66	7.9	5.7	2.0	3.3	3.5	4.8
March	Average Estuarine Abundance	1	0	0	4	0	17	30	0	0	1	0	0	0	0	0
	Average Marine Abundance	232	5356	4	28	8061	2	7	2	107	2141	107	16	0	5	17
	Percentage Contribution to Dissimilarity	8.7	14.9	0.9	2.4	15.9	2.7	4.8	0.5	5.37	11.6	8.2	3.2	0	1.1	3.4

Kariega Estuary and adjacent marine environment

A total of 34 zooplankton species were collected within the Kariega Estuary, while in the adjacent marine environment 51 species were identified (see Appendix 3 for the recorded species lists). All species recorded within the estuary were recorded in the adjacent marine environment. Similarly to the Great Fish results, the highest species diversity and richness was recorded within the marine environment during all seasons with the exception being March (Table 3.29). The Shannon-Weiner diversity values for the estuarine samples for June, September and December was very low (0.28 – 0.55) indicating a dominance of these samples by a few taxonomic groups, *viz.* copepod nauplii and *Acartia longipatella* (Connell and Grindley, 1974). The relatively low diversity indices recorded for the marine environment in March could largely be attributed to the numerical dominance of *Oithona* species within the total zooplankton counts. The higher Margalef's richness values calculated in the marine environment could be attributed to the higher number of species recorded in this environment during all seasons.

Table 3.29: The total number of species, species richness and diversity for the estuarine and marine environments during each season sampled.

		Number of Species	Margalef's Species Richness	Shannon-Weiner Diversity
June	Estuarine	24	3.08	0.28
	Marine	47	9.69	2.45
September	Estuarine	20	2.98	0.40
	Marine	39	8.30	1.99
December	Estuarine	27	3.75	0.55
	Marine	33	7.03	2.50
March	Estuarine	25	3.49	1.78
	Marine	28	2.61	1.26

An analysis of the zooplankton data collected within the estuary and the adjacent marine environment indicated that two significantly different groupings (ANOSIM; $p<0.05$) were recorded during all seasons (Figures 3.15 to 3.18). Group 1 comprised predominantly the marine stations, while Group 2 was generally comprised of the estuarine stations. During the June, December and March surveys the estuarine site situated near the mouth of the estuary was included in the marine grouping (Group 1).

This influence extended further up the estuary during December and March, with the lower two and three estuarine stations (respectively) grouping with the marine samples during these two seasons (Figures 3.17 and 3.18).

The separation between the estuarine and marine groups during June, September and December could largely be ascribed to differences in densities of copepod nauplii (>14% during all three seasons) relative to total zooplankton counts (Table 3.30). Further species that contributed to the dissimilarity of estuarine and marine groupings during June and December surveys were *Acartia longipatella* (13.3% and 13.1% respectively) and *C. agulhensis* (9.5% and 7.8%, respectively). During September, *C. agulhensis* (11.3%) was similarly important, while *Oithona* sp. (10.6%) also contributed to the estuarine/marine site separation (Table 3.30). During the March survey the separation of estuarine and marine sites was largely attributed to differences at these stations of the total abundances of *C. agulhensis* (12.7%), *Noctiluca* sp (8.7%) and *Clausocalanus* sp (7.7%).

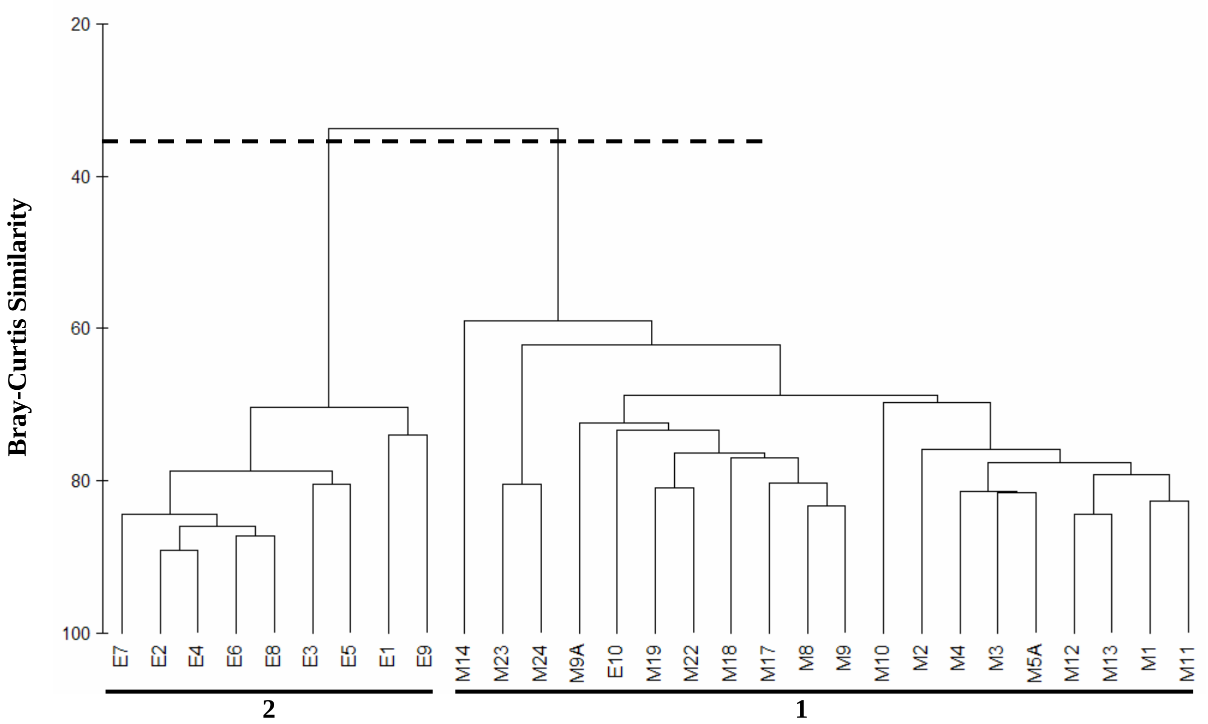


Figure 3.15: Cluster diagram showing the grouping of sites based on the zooplankton abundance data for June 2004. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents 35% similarity.

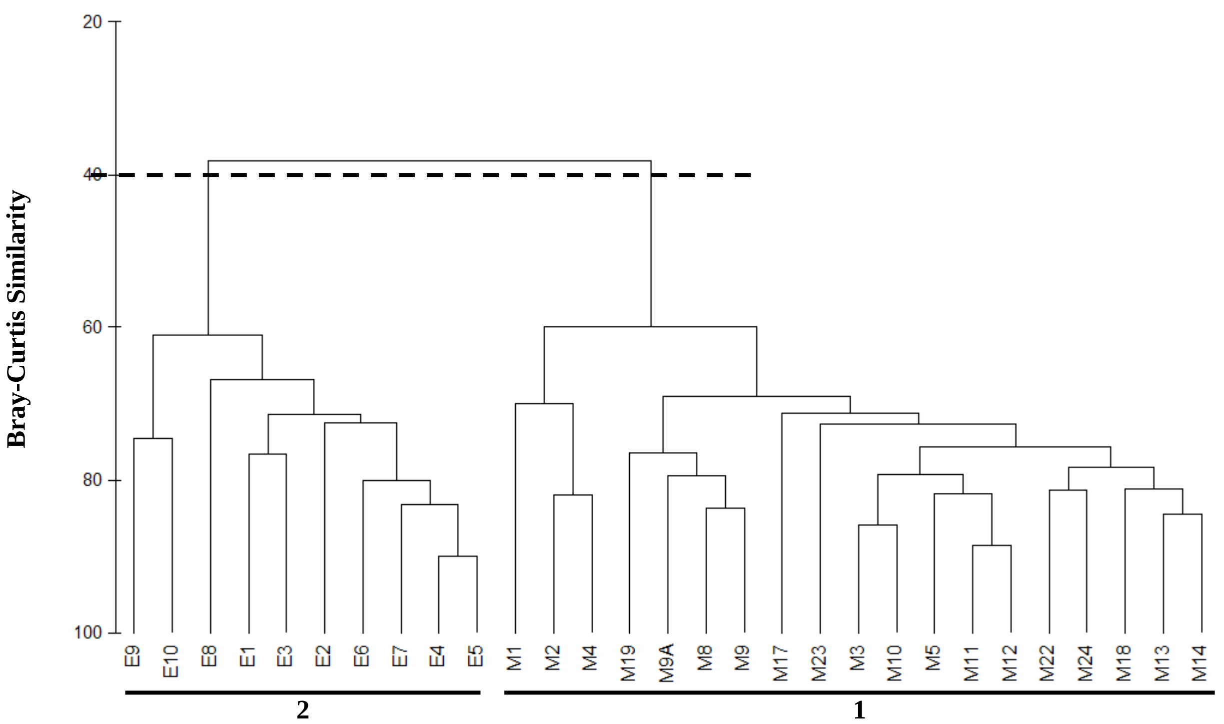


Figure 3.16: Cluster diagram showing the grouping of sites based on the zooplankton abundance data for September 2004. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents 40% similarity.

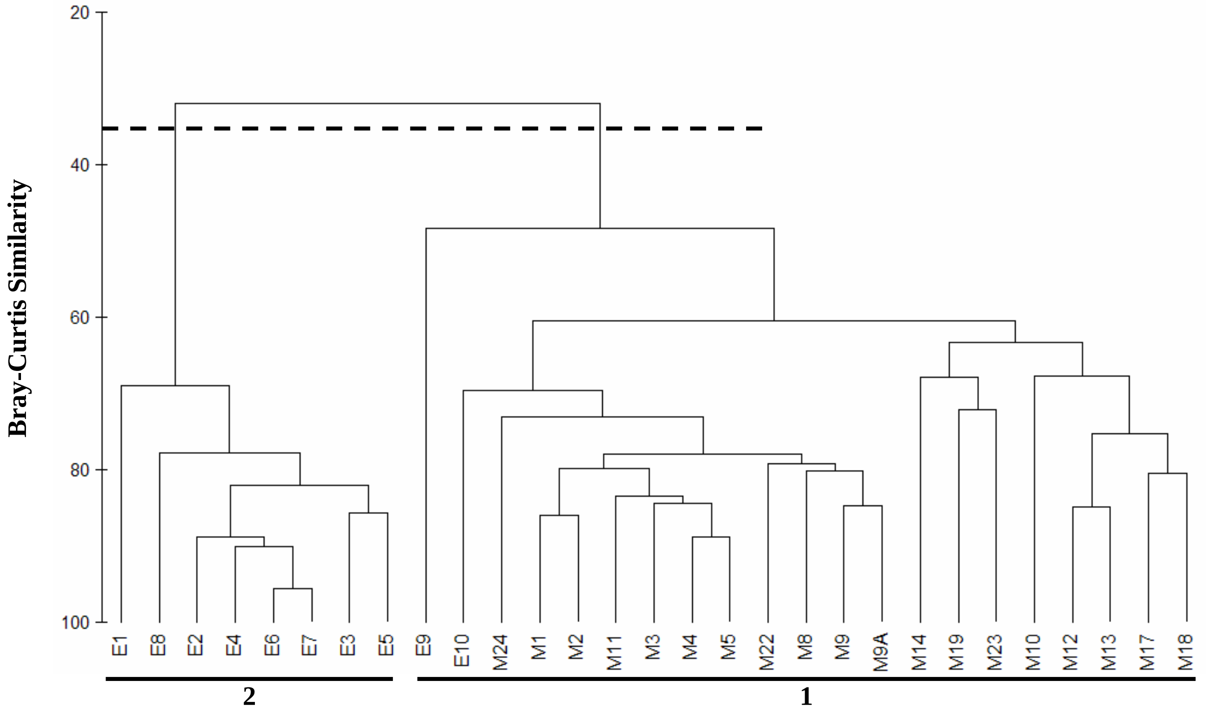


Figure 3.17: Cluster diagram showing the grouping of sites based on the zooplankton abundance data for December 2004. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents 35% similarity.

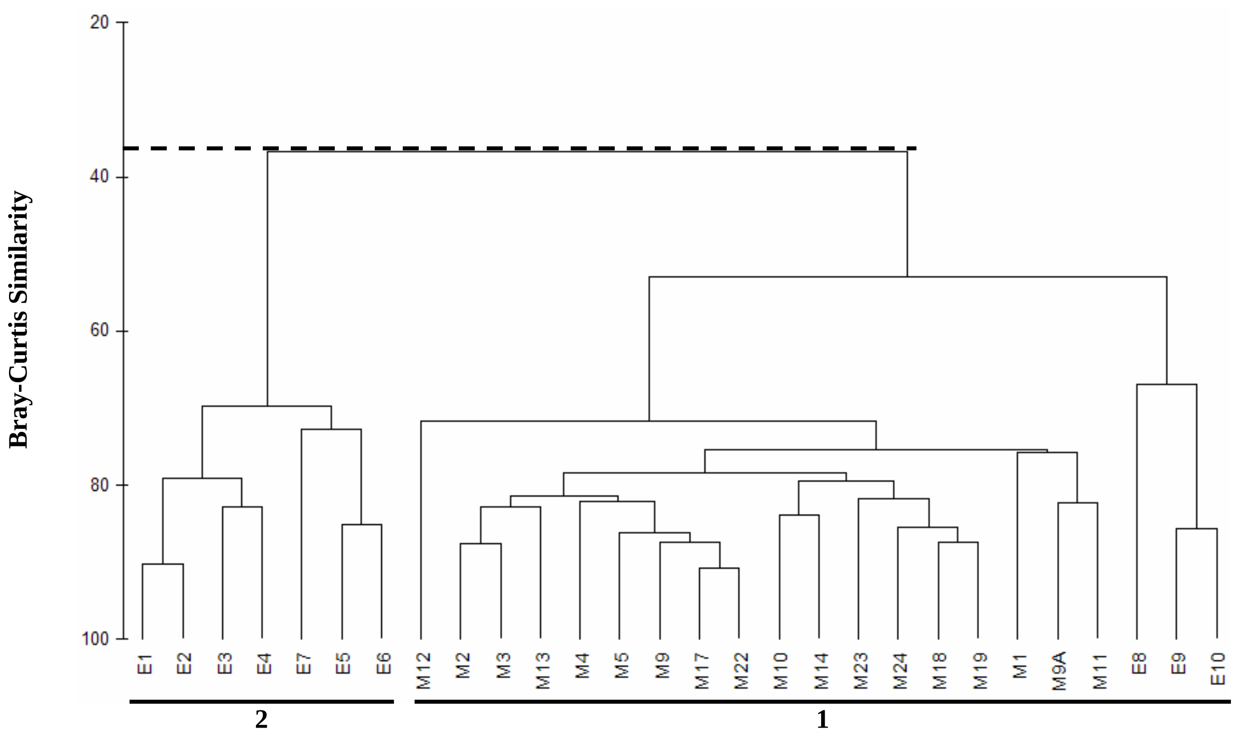


Figure 3.18: Cluster diagram showing the grouping of sites based on the zooplankton abundance data for March 2005. The coding of sites is a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line represents 35% similarity.

3.3.5 Combined zooplankton numerical analysis

The results of the numerical analyses conducted with the combined data sets for both estuaries is shown in Figure 3.19. A similar pattern emerges in that the estuarine sites form a distinct grouping from the marine sites adjacent to the two estuaries (Figure 3.19). Most of the estuarine stations separated from the marine stations at approximately a 38% similarity level and formed a Kariega Estuary group, a March Great Fish Estuary group and a upper reach group for the Great Fish during June, September and December (Figure 3.19). The remaining estuarine stations were lower reach stations within the Great Fish that separated from the marine stations at approximately a 45% similarity. As presented in the individual systems analyses above, some of the lower reach estuarine stations were within the grouping of marine sites.

Table 3.30: The contribution of the 15 most important species towards community separation into estuarine and marine groups during each season. Included is the average abundance of the species within the estuary and the marine environment in each season.

	Taxonomic Group/Species	*Calanus agulhensis*	Nauplii	*Acartia longipatella*	*Oncaea* spp	*Oithona* spp	*Limacina* spp	*Calanus simillimus*	Corycaeidae	*Noctiluca* spp	Harpacticoida	Zoaea	*Clausocalanus* spp	*Pseudodiaptomus hessei*	Appendicularian spp	Barnacle larvae
	Ave Estuarine Abundance	0	1820	60	0	12	4	0	0	0	3	0	0	3	0	0
June	Ave Marine Abundance	18	32	0	8	13	1	4	2	0	7	5	2	0	2	0
	Percentage Contribution to Dissimilarity	9.5	17.1	13.3	6.3	3.2	3.6	4.2	3.8	0	3.6	4.7	3.5	2.2	1.4	0
	Ave Estuarine Abundance	0	535	15	0	0	25	0	0	0	2	0	0	1	0	0
September	Ave Marine Abundance	15	40	0	2	14	2	7	3	0	4	1	1	0	0.1	3
	Percentage Contribution to Dissimilarity	11.3	14.4	8.2	4.9	10.6	8.8	7.9	5.6	0	3.1	2.5	3.4	1.3	0.2	5.1
	Ave Estuarine Abundance	0	1144	40	0	0	2	0	0	0	9	3	0	3	0	0
December	Ave Marine Abundance	15	13	0	0.2	7	5	0.1	3	34	11	4	1	2	0.1	7
	Percentage Contribution to Dissimilarity	7.8	17.9	13.1	0.4	5.1	2.8	0.2	4.1	7.1	3.4	2.4	2	3	0.2	7.1
	Ave Estuarine Abundance	5	315	57	0	150	6	0	0	0	6	6	1	1	0	0
March	Ave Marine Abundance	7884	282	3	4.5	13936	35	0	24	2241	113	1186	239	40	66	0
	Percentage Contribution to Dissimilarity	12.7	3.3	4.2	0.8	7.2	2.5	0	3.2	8.7	4.9	7.3	7.7	3.9	4.3	0

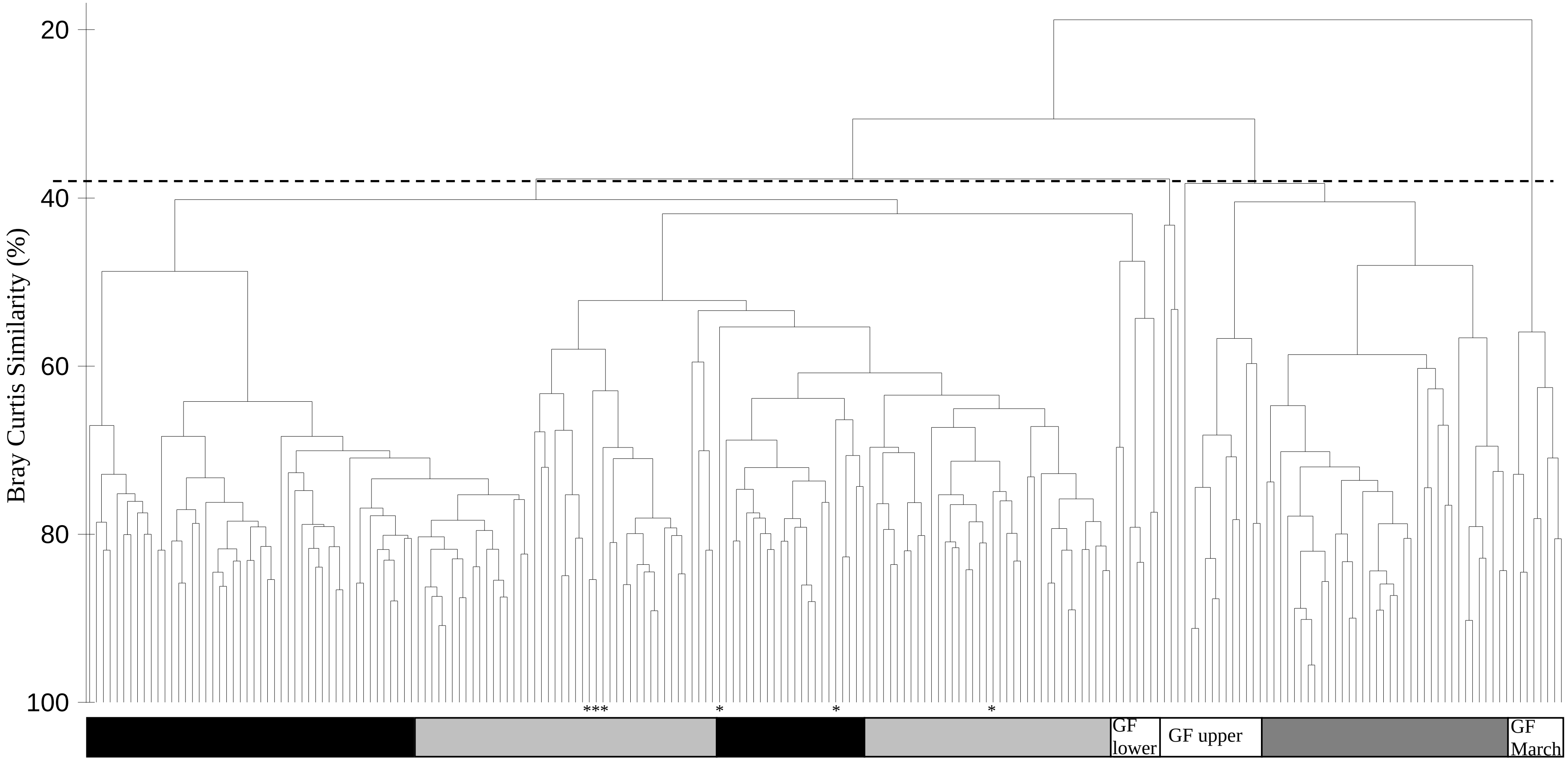


Figure 3.19: The cluster diagram representing the numerical analysis for all sites during all seasons. The black zones represent Great Fish Marine sites, the white zones the Great Fish Estuarine sites. The light grey zones represent Kariega Marine sites and the dark grey zones represent Kariega Estuarine sites. The sites marked with an asterisk represent those estuarine sites within the marine zone. The dotted line represents a 38% similarity.

Several species were identified as important in causing the observed separation of sites when all the stations for both systems were examined, but three species contributed a combined dissimilarity of 29.5%. These include *C. agulhensis* (10.7%), *Oithona* sp (9.5%) and various copepod nauplii (9.3%) (Table 3.31). Their contribution to the separation is a result of marine sites having approximately two orders of magnitude higher abundances of *C. agulhensis* and *Oithona* sp. relative to the estuarine sites (Table 3.31).

Table 3.31: The three most important species in causing the community separation displayed in Figure 3.19, including their average abundances in both environments and their contribution to the cluster formation.

Species	Ave Estuarine Abundance	Ave Marine Abundance	Contribution to dissimilarity
Calanus agulhensis	13	1837	10.7
Oithona sp	32	3136	9.5
Nauplii	1969	150	9.3

3.4 DISCUSSION

Although the two estuaries examined during this study are both classified as large permanently open systems, they have very different hydrodynamic characteristics. The flow rates within the Great Fish were at least three orders of magnitude greater than those recorded in the Kariega Estuary (Tables 3.2). As a result of the high base flows due to the interbasin transfer scheme, a distinct salt wedge was evident within the Great Fish Estuary throughout the study (Figure 3.2). Alternatively, the persistence of a reverse salinity gradient in the Kariega Estuary (Figure 3.2) reflected the low fresh water flow rates into the system. According to Whitfield and Bruton (1989) the presence of a reverse salinity gradient within southern African estuaries can be related to a combination of low fresh water inflow and high evaporation rates.

The establishment of sampling grids upstream or downstream of the estuary mouth (relative to the Agulhas Current) was determined on the specific survey dates. On all occasions the prevailing winds, and therefore surface currents, were northerly or easterly (blowing in a southerly or westerly direction). In addition, the observed longshore drift in the swash and surf zones adjacent to both systems was predominantly south-westerly in nature. The contour plots of salinity and delta σ_t adjacent to the Great Fish Estuary confirm these personal observations, as the plume of low salinity water leaving the estuary was recorded to the south-west of, or directly adjacent to (September sample), the estuary mouth (Appendix 2, Figures A2.1 to A2.4). It should be noted that the direction of the plume relative to the mouth of the estuary may demonstrate a high degree of temporal variability reflecting hydrodynamic processes (current and wind patterns). Thus under conditions when westerly winds prevail within the region, the plume of estuarine water will most likely be in an easterly orientation.

In the marine environment adjacent to the Great Fish Estuary, the outflow of fresh water from the estuary was clearly evident as a plume of low salinity water (26 practical salinity units) adjacent to or immediately downstream of the mouth of the estuary (Appendix 2, Figures A2.1, A2.3 and A2.4). The occurrence of a small surface plug of low salinity water adjacent to the estuary during the March survey can likely be related to the survey being undertaken during high tide due to logistical constraints. The inflow of a tidal plug of marine water into the estuary would have masked the effect of a fresh water plume. The lack of low salinity water recorded during September is most likely a combination of sampling close to the high tide (including time lag) and relatively low flow rates for this period (Table 3.2). Adjacent to the fresh water deprived Kariega Estuary, there was no evidence of any fresh water outflow to the marine environment. A body of reduced salinity water was observed adjacent to the Kariega Estuary during the March survey, but it is unlikely that this water was derived from the estuary. Rather it appears that it can be ascribed to oceanographic processes upstream of the estuary. Lutjeharms *et al.* (2000) have identified reduced salinity conditions associated with upwelling centres along the inshore edge of the Agulhas Current. In a study conducted in parallel to the current study, Jennings (2005) identified an extraneous nutrient source that was not normally evident in the nearshore environment adjacent to the Kariega Estuary. It was suggested that the nutrients were derived from an upwelling event centred around the Port Alfred region, some 20km upstream from the Kariega Estuary.

The delta σ_t values observed adjacent to the Great Fish Estuary supports the salinity findings with stratification observed during all seasons except September (Figure 3.4). Lower density water is typically reported within estuarine plumes. For example, Kingsford and Suthers (1994) identified a longitudinal density gradient between Botany Bay and the plume front in the adjacent marine environment. The observed stratification evident in the delta σ_t slightly offshore adjacent to the mouth of the Great Fish Estuary in March is most likely the result of flood tide dissipation of the estuarine plume (Figure 3.4). Similarly, during September the very slight stratification demonstrated by delta σ_t to the west of the study area, most likely a result of the dissipating estuarine plume on the flooding tide. This effect has been reported adjacent to estuaries in Australia such as Botany Bay, with incoming tidal currents resulting in mixing between the estuarine water plume and marine waters (Kingsford and Suthers, 1996). Botany Bay is, however, a substantially larger estuary and with the plume extending further offshore than was recorded in this study and therefore being more easily dissipated on flood tides. The lack of any stratification in the water column adjacent to the Kariega Estuary confirms the lack of fresh water outflow from this system. The consistently higher stratification occurring adjacent to the Great Fish Estuary reinforces the greater impact that this system has on the adjacent marine hydrology relative to the Kariega Estuary. During June and December 2004 the westward direction of the stratification indicates stronger inshore currents than were observed during March 2005. The March survey showed evidence of very little surface current due to the density stratification between surface and bottom water occurring directly adjacent to the estuary mouth. This is supported by the reported low wind speeds on the sampling date ($1.4 m.s^{-1}$; Appendix 1, Table A1.1).

The temperatures within the Kariega Estuary demonstrate the moderating influence of the marine environment on the lower reaches, with large seasonal fluctuations only being recorded in the upper reaches of the estuary (Figure 3.3). The water temperatures in the Great Fish Estuary indicated a dominance by fresh water derived from the inter-basin transfer scheme, with marine temperatures penetrating into the lower estuarine sites within the bottom waters (Figure 3.3). The entry of fresh water into the marine environment is similarly indicated on the contour plots during each season, with plumes of higher temperature water during December and March, and lower temperature water during June and September (Appendix 2, Figures A2.5 to A2.7). Relatively low temperatures were recorded during March in the nearshore environment adjacent to the Great Fish Estuary, which could be related to the abovementioned upwelling event (Jennings, 2005).

Although several studies have demonstrated that particulate organic matter (POM) concentrations within estuaries are largely dependent on fresh water inflow (Baird and Ulanowicz, 1993; Grange and Allanson, 1995; Baird and Heymans, 1996; Grange *et al.*, 2000), during the present study POM concentrations within the two estuaries were with few exceptions, not significantly different. The observed pattern is surprising given the marked differences in the hydrodynamics of the two systems and can likely be attributed to the different origins of the POM in the two estuaries. In the Great Fish Estuary, the POM is most likely derived from the interbasin water transfer, while in the Kariega Estuary, the extensive salt marshes and submerged macrophytes in the middle and lower reaches of the estuary form the main source of the POM (Chapter 5). The POM values recorded within the Kariega Estuary during June, September and December were comparable to those recorded by other authors (Lucas, 1986; Allanson and Read, 1987; Grange and Allanson, 1995; Taylor and Allanson, 1995) ($11 – 23mg.L^{-1}$), while the POM concentrations documented in the Great Fish Estuary during the same period were lower, although the flow rates during this study were also slightly depressed relative to the literature. The absence of any significant difference in the POM concentrations within the two estuaries contributed to the marine environment adjacent to the two systems having similar POM concentrations (Table 3.15 and 3.16). The occurrence of high POM concentrations in the marine environment adjacent to both estuaries during the March survey is likely the result of the abovementioned upwelling event (Jennings, 2005).

The total chlorophyll-*a* concentration in the Kariega Estuary was consistently less than $2.5\mu g.L^{-1}$ in both surface and bottom waters. In the Great Fish Estuary, total chlorophyll-*a* concentration was higher, ranging from 0.69 to $16.9\mu g.L^{-1}$). A Spearman Correlation indicated that total chlorophyll-*a* concentration in the estuary was significantly correlated to flow rates ($r_s = 0.87$; $p < 0.05$) (Table 3.22). Lucas (1986) identified allochthonous import and hydrodynamic trapping of riverine phytoplankton as the main sources of the high chlorophyll-*a* concentrations recorded in the Great Fish Estuary, while Grange and Allanson (1995) commented that the tidally-mediated resuspension of phytoplankton allowed for the high chlorophyll-*a* concentrations despite high turbidity reducing the light penetration in this system. The observed discrepancies in total chlorophyll-*a* concentration between these two estuaries is well documented and can be related to the different flow rates and nutrient sources in these two systems (Lucas, 1986; Allanson and Read, 1987; Grange and Allanson, 1995; Taylor and Allanson, 1995).

Not surprisingly, the marine environment adjacent to the Great Fish Estuary was characterised by significantly higher total chlorophyll-*a* concentrations than that recorded adjacent to the Kariega Estuary. The total chlorophyll-*a* concentrations adjacent to both estuaries were significantly correlated to the POM concentrations ($r_s = 0.762$; $p < 0.05$) (Table 3.22). This relationship has been identified by several authors (Baird *et al.*, 1987; Baird and Winter, 1989; Lutjeharms *et al.*, 1989a; Winter and Baird, 1991; Winter *et al.*, 1996; Lutjeharms *et al.*, 2000; Meyer *et al.*, 2002) who have related peaks in nutrients and particulate organics to chlorophyll-*a* concentrations. The observed pattern is likely the result of a combination of chlorophyll-*a* export from the Great Fish Estuary, as well as the recognised relationship between fresh water flow rates and consequently higher nutrient concentrations causing stimulated growth of phytoplankton (Froneman, 2002a; Perissinotto *et al.*, 2002; Jennings, 2005; Gama *et al.*, 2005). It is likely that the POM concentrations at the stations closest inshore were biased by wave action in the surfzone, however, as demonstrated in the contour plots this was not apparent along the entire length of the shore during any individual survey.

Jennings (2005) completed a land ocean interface in the coastal zone (LOICZ) model for both these estuaries based on sampling carried out on the same days as the biological data collected during this study. The results from the LOICZ model indicated consistently higher nitrate, nitrite and silicate levels at stations adjacent to the Great Fish Estuary relative to those adjacent to the Kariega Estuary during all seasons except March. The March sample indicated similar ranges adjacent to both estuaries for these nutrients and this was attributed to an upwelling event (Jennings 2005). These results support the concept that the chlorophyll concentrations recorded during this study were related to the nutrient conditions prevailing adjacent to these rivers. Alternatively, it is possible that the increased chlorophyll-*a* concentrations recorded in the marine environment adjacent the Great Fish Estuary are the result of increased phytoplankton production rates due to the increased water column stability.

The zooplankton sampling carried out during this study is not strictly comparable to previous research due to the fact that the sampling was only conducted during the daytime and thus does not consider the marked diel vertical migrations patterns of the zooplankton in the estuaries. This absence of night-time zooplankton data is as a result of the logistical constraints surrounding sampling in the marine inshore zone after dark and the need for comparability between the marine samples and the estuarine samples. Previous research has indicated diel trends in surface zooplankton densities and abundances within estuaries due to the vertical migration habits of various zooplankters (Wooldridge and Erasmus, 1980; Wooldridge, 1986; Wooldridge and Webb, 1988; Schlacher and Wooldridge, 1994; Wooldridge, 1999; Perissinotto *et al.*, 2000; Perissinotto *et al.*, 2003).

The total estuarine zooplankton biomass and density in the Great Fish Estuary demonstrated little or no seasonal pattern (Figures 3.7 and 3.9). The observed temporal pattern in total zooplankton density and biomass in the Great Fish Estuary could be related to changes in hydrodynamic conditions and surface water retention times. The lowest zooplankton biomass was recorded during the periods of highest fresh water outflow and lowest surface retention times (<1 day; Jennings, 2005) within the estuary. Seasonal trends in zooplankton biomass and density were evident within the Kariega Estuary, which could likely be related to seasonal changes in physico-chemical conditions. The zooplankton biomass recorded in both systems, but particularly the Great Fish Estuary, during this study was relatively low compared to that recorded by Grange *et al.* (2000). The lower biomass values can be related to a change in community structure, as Grange *et al.* (2000) recorded a mysid dominated community, whereas during this study the community was dominated by calanoid copepods. The seasonal trends in average zooplankton density did not mirror those of average biomass, mainly due to the different body sizes of species caught in the various seasons. For example, in March within the Great Fish Estuary the highest biomass was recorded, but the lowest zooplankton density. This was due to the predominance of nauplii in the samples during June, September and December, but the lack of these small bodied zooplankton in the March sample. The zooplankton recorded in March demonstrated a dominance of the larger-bodied mysid, *Rhopalophthalmus terranatalis* (Wooldridge, 1986), and the copepod, *Acartia longipatella*.

The offshore zooplankton densities adjacent to the Kariega Estuary demonstrated little or no seasonal trends (Figure 3.8). The large increase in zooplankton density recorded adjacent to the estuary during March was mirrored in the nearshore environment adjacent to the Great Fish Estuary and is likely due to an upwelling event that occurred immediately prior to the March survey (Jennings, 2005). This rapid response in zooplankton density and biomass has been reported by other authors in terms of tidal fronts adjacent to estuaries (e.g. Largier, 1993). Largier (1993) suggests that certain species of phytoplankton and zooplankton are concentrated in the area of tidal fronts that last for no longer than an hour or two. It is also possible that advection of fauna from surrounding waters could account for the increased densities in the plume during this study. Kingsford and Suthers (1996) reported advection of adjacent marine water into the Botany Bay plume front, despite moving against the prevailing winds on occasion. The advection of animals into the plume front at high rates was used by Rissik and Suthers (1996) to explain the variability in gut fullness index of larvae captured in the estuarine water plume. Evidence of an upwelling event during the period of the March survey is provided from satellite imagery of the region (www.rsmarinesa.org.za) that shows water 3 – 4˚C lower than the average temperatures three days prior to the March survey (10 March 2005). Similarly, maximum zooplankton biomass was observed in March adjacent to both these systems, with identical seasonal trends of minimum recorded biomasses in September, followed by June and December, offshore of both these estuaries. The average biomasses and densities were higher adjacent to the Great Fish, but the seasonal and spatial trends observed were similar off both estuaries.

The total chlorophyll-*a* and POM concentrations in the nearshore environment were found to correlate significantly ($r_s = 0.762$; $p < 0.05$) with one another (Table 3.22). Chlorophyll-*a* and POM peaks did not overlay the reduced temperature and salinity values that would indicate a fresh water plume into the marine environment. However, the trends in these two parameters were found to closely track the salinity and temperature trends observed. Several authors have identified higher primary productivity along the edges of tidally induced (i.e. short term) estuarine fronts (Tyler and Seliger, 1978; Garcon *et al.*, 1986; Martin and White, 1988). This productivity has been explained by phytoplankton species with short enough time scales as well as physical entrainment and concentration of individuals in these zones.

The highest total zooplankton biomass and density in the nearshore environment adjacent to the Great Fish Estuary were shown to be associated with plumes of estuarine water in the marine environment. Alternatively, maximum biomass and density values were recorded directly adjacent to the mouth of the Kariega Estuary during all seasons except March (Figure 3.8 and 3.10). In addition, the zooplankton density results were shown to significantly correlate with the chlorophyll-*a* and POM concentrations in the nearshore environment (Table 3.22). Both the zooplankton densities and chlorophyll-*a* concentrations were shown to correlate significantly with the river flow rates entering the adjacent estuaries (Table 3.22). This demonstrates that the zooplankton communities in the nearshore environment adjacent to these estuaries are reliant to some degree on the water exchanged (in the case of the Kariega) or leaving (in the case of the Great Fish) these systems as well as the productivity of the mixing fronts associated with this water. The fact that the Kariega Estuary demonstrates a localised effect on the adjacent zooplankton communities (increase in biomass and densities), indicates that fresh water is not imperative to the influence an estuary may have on the nearshore zooplankton community. However, the significantly larger values observed offshore of the Great Fish Estuary do indicate that increased fresh water flow rates can significantly affect zooplankton biomass and density.

Numerical analyses indicated the existence of two distinct zooplankton groupings corresponding to estuarine and marine stations during all seasons for both systems (Figures 3.11 – 3.14 and 3.15 – 3.18). The presence of the two groupings suggests limited exchange of plankton between estuaries and the marine environment. The low densities of estuarine fauna occurring within the marine habitat indicates that the zooplankton within the estuaries generally appear to have evolved retention strategies to reduce flushing into the marine environment. This is supported by a study by Wooldridge and Erasmus (1980), who identified various copepods and mysids in the

Sundays River Estuary that changed their position in the water column and river channel depending on the tidal state to prevent flushing from the estuary. Of interest is the fact that the majority of the zooplankton species recorded in the estuarine samples were also identified in the marine environment adjacent to both estuaries although in very low densities. This is not common due to the retention strategies described for zooplankton species, which allow them to retain position within an estuary (Wooldridge, 1999). The occurrence of most estuarine zooplankton species from within the Kariega Estuary in the adjacent marine environment is explained by the marine nature of the Kariega, therefore allowing marine species to enter the estuarine area. Alternatively, the occurrence of the estuarine species in the marine environment adjacent to the Great Fish is most likely due to these species being flushed from the estuary into the adjacent marine environment.

The clear separation between the estuarine and marine communities identified with numerical analyses was due to differences in abundant species within the two groupings. Within the estuaries, *Acartia longipatella* and *Pseudodiaptomus hessei* (Jerling, 1988) were numerically dominant, and although these species did occur in the marine environment it was generally in very small numbers (Table 3.28 and 3.131). These copepod species are recognised as pioneer species within estuaries (Wooldridge, 1999; Froneman, 2004a). In the marine environment adjacent to both systems, the dominant zooplankton species was *C. agulhensis*, which was virtually absent within the estuarine samples. *C. agulhensis* is the dominant copepod in Agulhas Bank waters, accounting for between 50 and 83% of total copepod biomass (Verheye *et al.*, 1994; Huggett and Richardson, 2000). During cross shelf surveys in the Port Alfred region in 1989, the recorded densities of *C. agulhensis* ranged between 1 and 1 000ind.m^{-3}, with biomasses in the region of ≈700mg dwt m^{-3} (Verheye *et al.*, 1994; Huggett and Richardson, 2000). The densities of *C. agulhensis* during this study thus compared favourably with the abovementioned published results, ranging between an average of 27ind.m^{-3} during September and a March average of 4 850ind.m^{-3}.

While the numerical analyses identified a clear separation of estuarine and marine stations, it was evident that marine waters were able to penetrate into the estuary, resulting in lower estuarine stations in the Kariega Estuary, grouping with marine sites. The observed pattern was particularly evident when sampling was undertaken during the upwelling event in March. The grouping of the lower estuarine sites within the marine stations was largely attributed to the incursion of *C. agulhensis* into the estuarine waters. The observed pattern suggests a mobile ecotone between the estuary and the marine environment, which appears to be dependent on the flow rate and tidal state. Sanchez-Velasco *et al.* (1996) recorded a similar situation in the fish larval distribution in the inshore environment off the Terminos Lagoon (Gulf of Mexico), with a mobile estuarine community which extended or reduced its distribution depending on the rainy or dry season. Similarly, Harris *et al.* (2001) recorded three larval fish communities occurring along an estuarine – marine gradient between the estuary lower reaches and the nearshore environment adjacent to the St Lucia Estuary. One group occurred within the estuary and was comprised of predominantly estuarine species, with a surf zone grouping of some estuarine and some nearshore species, and a nearshore grouping of distinctly nearshore species. Harris *et al.* (2001) and Harris and Cyrus (1995; 1996) have recorded different fish species using all three of the identified environments as nursery areas and some species using these zones as a transit route into the estuary.

The clear separation between the estuarine and marine zooplankton communities observed in this study for both estuaries indicates that the elevated zooplankton biomass generally recorded in the nearshore environment adjacent to the estuaries is not derived from the estuarine community. The zooplankton within the region of elevated biomass appear to be accumulating adjacent to the mouth of the estuaries to feed on the high chlorophyll-*a* and POM concentrations that prevail in the region. The cues that promote these aggregations do not appear to be salinity related, as aggregations were found to occur adjacent to the fresh water deprived Kariega Estuary. Largier (1993) has commented that the accumulation of biota associated with estuarine fronts is not unusual, with higher trophic levels being attracted to these regions due to the enhanced food availability. In addition, Yanagi *et al.* (1992) and Franks (1992a) have recorded various invertebrates being passively collected in mixing zones due to convergent surface flows. This passive collection of biota in frontal mixing zones is considered important, especially in terms of short duration frontal systems, such as those induced by tidal movement (Largier and Taljaard, 1992). Species have developed means of maintaining position in areas frequented by tidally induced fronts that cycle over short periods (2 – 6hrs). For example, Franks (1992a) recorded oyster larvae using vertical migrations to maintain position in the James River front.

3.4.1 Conclusions

Due to large variations in fresh water input, these permanently open systems differed in terms of their hydrographic impact on the adjacent marine environment. The reasons for these differences related to the river flow rates entering the systems, with the fresh water deprived Kariega Estuary having a very limited impact on the hydrography in the adjacent marine environment, while the fresh water rich Great Fish Estuary influenced salinity, temperature and chlorophyll regimes in the adjacent marine environment. Despite the limited impact on the adjacent hydrography, the Kariega Estuary was still shown to impact on the zooplankton biomass and density in the adjacent marine environment. However, the effects of the estuarine water outflow adjacent to the Great Fish Estuary were demonstrated to influence a substantially greater area relative to the Kariega Estuary. This difference was most likely due to the difference in the volume of water entering the marine environment from these two systems.

The availability of estuarine water in the nearshore environment is influenced on several temporal scales, including daily tidal cycles, monthly lunar cycles and stochastic upwelling events (Figure 3.20). In addition, the impact of estuarine water on the primary and secondary productivity in this region is influenced by seasonal trends (Adams *et al.*, 1999). The shortest temporal scale is caused by the daily tidal oscillations, from high to low tide, twice a day. At high tide, marine water penetrates into the lower reaches of the estuaries in a wedge, and therefore eliminates the presence of estuarine water in the nearshore environment. At low tide estuarine water flows from these systems into the adjacent marine environment. The effect of the high and low tide oscillations is heightened when viewed in the context of the monthly time frame of spring to neap tides. On a spring tide the intrusion of marine waters into the estuary is increased whereas during the low tide, the outflow of estuarine water into the marine environment is more prominent. During neap tides, the role of a high and low tide is reduced, with estuarine water entering the nearshore environment even on a high tide, albeit in reduced volumes, while a low neap tide does not permit as much water outflow as a spring low tide.

The influence of estuary derived water on primary and secondary productivity in the nearshore environment appears to be seasonally controlled (Figure 3.20). In this study, low chlorophyll-*a* and POM concentrations, as well as reduced zooplankton biomass and densities were recorded adjacent to the Great Fish Estuary in June despite the relatively high flow rates (Table 3.2). Reduced temperature during the winter months may have resulted in reduced levels of primary and secondary productivity. Several authors (Franks, 1992b; Adams *et al.*, 1999; Froneman, 2001a) have identified this phenomena in estuarine environments and estuarine frontal systems, with temperature as a controlling influence on phytoplankton productivity.

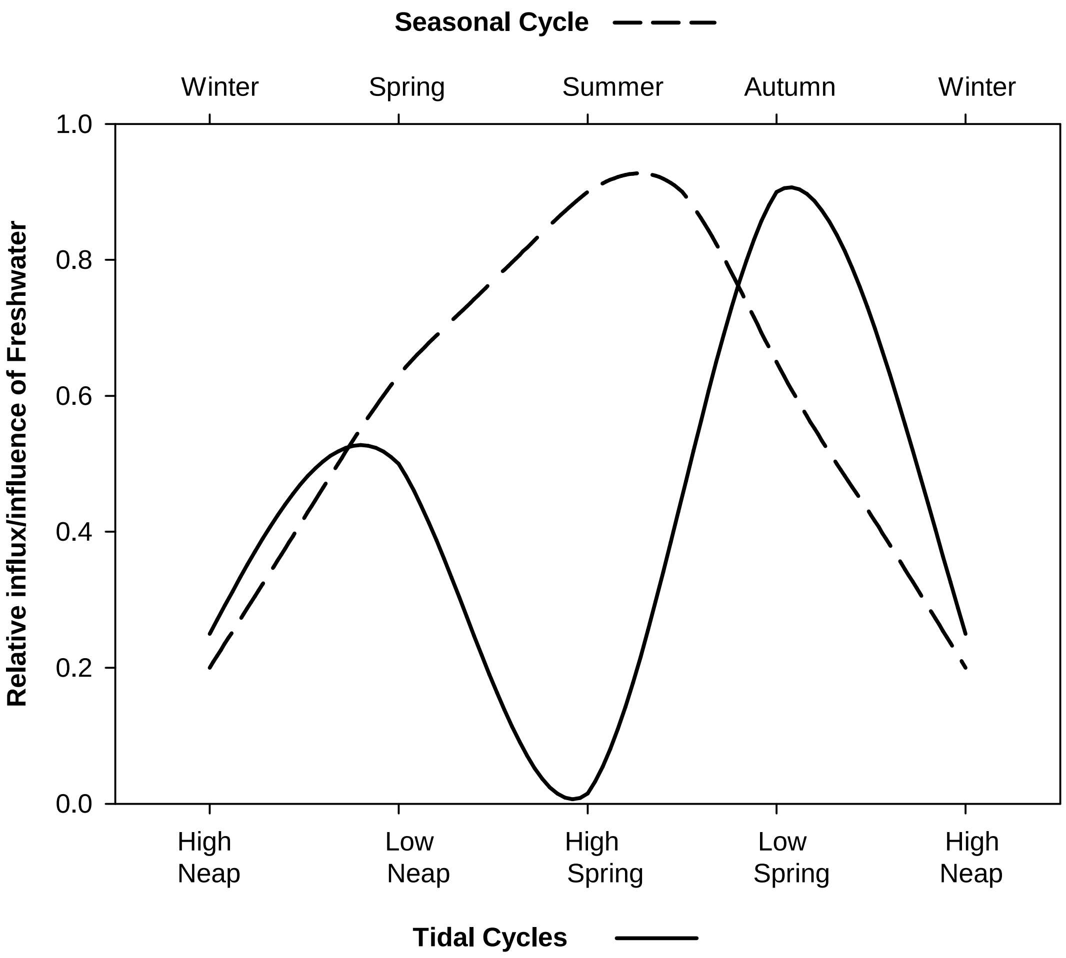


Figure 3.20: A representation of the relative influx of fresh water into the marine environment over different tidal and lunar cycles, as well as the varying ability of this water to influence the biology in this zone seasonally.

In addition to tidal and seasonal influences on estuarine water availability to the nearshore environment, productivity in this region appears to be significantly influenced by stochastic upwelling events. The results presented above in terms of temperatures, chlorophyll-*a* and POM concentrations all indicate an external water source during the March sampling trip. However, that external source is not related to estuarine outflow and appears to be a wide reaching event (affects both the Kariega and Great Fish estuaries). In addition, Jennings (2005) indicated the presence of upwelling when investigating the nutrient characteristics in the nearshore environment adjacent to these estuaries over the same period. Lutjeharms *et al.* (2000) has recorded the presence of an upwelling cell in the Port Alfred region and has indicated that it occurs randomly, but upwelled water was observed 45% of the time between 1988 and 1994. Both the chlorophyll-*a* and particulate organic matter concentrations as well as zooplankton biomass and densities sampled during this period were significantly higher than those sampled during other months off both the Kariega and Great Fish estuaries. This indicates the overwhelming influence of an upwelling event on the nearshore primary and secondary productivity.

CHAPTER 4

THE EFFECT OF TEMPORARILY OPEN/CLOSED ESTUARIES ON ZOOPLANKTON COMMUNITIES IN THE ADJACENT NEARSHORE ENVIRONMENT

4.1 INTRODUCTION

South African estuaries have been separated into five main categories, permanently open estuaries, temporarily open/closed estuaries (TOCEs), estuarine bays, estuarine lakes and river mouths (Whitfield, 1992a). Permanently open estuaries and TOCEs comprise over 98% of the 258 recognised estuaries along the South African coastline (Whitfield, 2000). Temporarily open/closed estuaries (TOCEs) are the dominant estuary type in the country, comprising approximately 70% of all estuaries (Perissinotto *et al.*, 2000). The importance of these smaller estuaries to the marine environment is uncertain as it has not been investigated previously.

Dame and Allen (1996) discussed how the net flux of biological matter between estuaries and the marine environment varies depending on the estuary type due to the different hydrological processes occurring. Permanently open estuaries have a permanent link to the marine environment and therefore, even if riverine flows are extremely low, they interact significantly with the sea on a daily basis due to tidal flows (Postma, 1981; Kjerfve, 1989). This differs from TOCEs as these systems are separated from the marine environment for varying periods of time (Cowley *et al.*, 2001; Bell *et al.*, 2001; Froneman, 2002a). TOCEs, however, may still interact with the nearshore environment due to import or export of biological material during overtopping or breaching events or nutrient exchange through water seepage via the sandbar during closed mouth conditions (Whitfield, 1992b; Whitfield, 1998; Kemp and Froneman, 2004). Overtopping refers to occasions when, due to extremely high spring tides or large coastal swells, marine water washes over the sandbar at the mouth of a TOCE (Cowley *et al.*, 2001; Bell *et al.*, 2001).

A mouth opening event occurs in response to precipitation in the catchment and an increase in volume of water in the lower estuary, resulting in the system breaking through the sandbar and establishing a link with the sea (Cowley and Whitfield, 2001; Froneman, 2002c). Fish and invertebrate larvae have been recorded recruiting into TOCEs during both mouth opening events and overtopping events (Cowley *et al.*, 2001; Bell *et al.*, 2001; Froneman, 2004a; Kemp and Froneman, 2004). In addition, sub-adult fish and on occasion invertebrates leave these systems during both of these types of marine interactions (Cowley, 1998).

Very few studies have investigated the importance of TOCEs to the nearshore marine environment. A major consideration of the importance of these systems is the high usage by large populations of estuarine-dependent marine fish species (Cowley and Whitfield, 2002; Lukey *et al.*, 2006). Cowley and Whitfield (2002) conducted a population estimate on the East Kleinemonde Estuary on two occasions and identified a total population of *Rhabdosargus holubi* (Steindachner, 1881), a marine fish species that uses estuaries as a nursery area, of 133 000 and 18 000 individuals. Similarly, in the smaller Grants Valley Estuary (3ha), Lukey *et al.* (2006) identified a total population of estuarine-dependent marine fish species of 18 200. This indicates a significant contribution from these smaller systems to the marine environment in terms of ichthyofauna.

In a study by Harris *et al.* (2001) on the St Lucia estuarine lake (which is a very large temporarily open/closed system), a continuum of different fish larval communities was identified during an open mouth phase between the estuary and the marine environment. Three communities were identified, namely the estuarine community, surf zone community and nearshore community. Species were identified that overlapped between these communities, but generally separate congregations of species were identified that were using the different zones for different purposes and not just as a transit route to the estuary. These studies identify biological contributions by the marine environment to the estuaries concerned as well as *vice versa*.

This study addressed the interaction between the marine environment and two TOCEs on the Eastern Cape coastline. The specific aims of the study were to:

1. Determine if TOCEs influence the specific variables (temperature, salinity, particulate organic matter and chlorophyll) in the marine environment adjacent to their mouths;
2. Identify any changes in the zooplankton community structure, density or biomass in relation to the estuary mouth; and
3. Identify the geographic extent of any impact on the adjacent marine environment during different seasons and mouth phases.

The study estuaries were the Kasouga (see 2.2.3 in Chapter Two for details) and East Kleinemonde (see 2.2.4 in Chapter Two for details). Two estuaries were sampled to include a greater range of mouth variability in TOCEs. The two study systems differ substantially in terms of mouth phase and breaching characteristics allowing for a comparison of the effect of this important estuarine characteristic on their interacton with the marine environment.

4.2 MATERIALS AND METHODS

4.2.1 Sampling protocol

The estuarine samples were collected from six stations, approximately 0.5km apart, within the Kasouga and East Kleinemonde estuaries (see Figures 2.9 and 2.10 for a diagrammatic representation of station positions). In the nearshore environment adjacent to the estuary mouth 12 stations were occupied in a sampling grid of four transects perpendicular to the coast. The transects started 250m offshore and were 250m apart, with each of the three stations in a transect positioned 200m apart (Figure 4.1). One transect was established north-east of the estuary mouth (upstream relative to the flow of the Agulhas Current), one opposite the mouth and three transects at 250m intervals south-west of the estuary (downstream relative to the Agulhas Current). The sampling grid as described above was considered mobile and could have been moved to sample three transects north-east of the estuary mouth and only one south-west depending on prevailing current conditions. The surveys were conducted on a seasonal basis covering two mouth phases (see Table 4.1 for the sampling dates, tides and mouth status).

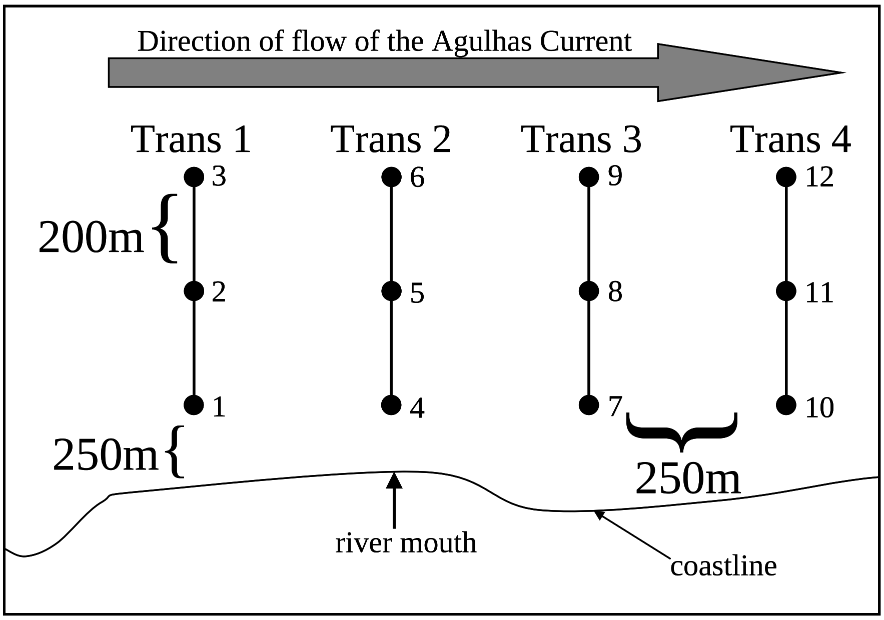


Figure 4.1: A stylised layout of the sampling grid used in the nearshore marine environment adjacent to the Kasouga and East Kleinemonde estuaries.

Table 4.1: Listing of the dates on which sampling took place as well as the mouth status and high tide times and tide types on those dates (Tide types and times given for the marine sampling day). Tide type is represented by a spring tide or a tide that is between spring and neap tide (mid). Mouth status describes an open condition (O), closed condition with no overtopping (C) and closed condition with overtopping occurring (C/OT).

Month	Estuary Name	Estuary		Marine		Tide Type	Tide Time	Mouth Status
		Date	Start Time	Date	Start Time			
June	East Kleinemonde	08/06/2005	12H35	07/06/2005	07H27	Mid	03H40	C
	Kasouga	21/06/2005	12H50	21/06/2005	07H00	Mid	15H05	C
September	East Kleinemonde	09/09/2005	10H00	08/09/2005	06H53	Mid	05H45	C
	Kasouga	09/09/2005	07H35	08/09/2005	09H35			C
November	East Kleinemonde	18/11/2006	09H40	17/11/2005	06H25	Spring	16H00	O
	Kasouga	18/11/2006	09H10	17/11/2005	09H15			C/OT
March	East Kleinemonde	01/03/2006	10H20	28/02/2006	09H10	Spring	04h00	C/OT
	Kasouga	01/03/2006	09H35	28/02/2006	06H35			C/OT

4.2.2 Physico-chemical parameters

Temperature and salinity measurements were taken at the surface and bottom (≈1.5m depth) for the estuarine stations and at the surface and 5m for the marine stations. The 5m depth sample for the marine stations was used to target any possible buoyant salinity plume and the potential zone of interaction between the plume and marine waters. Temperatures and salinities were measured using a YSI 600XL probe during June, September and November 2005. Due to technical problems this was changed to a YSI 610 probe during the March 2006 sample. Salinity was measured using an optical refractometer during this period.

4.2.3 Chlorophyll-*a* and particulate organic matter (POM) determination

See section 3.2.3 in Chapter Three as the methods used were identical.

4.2.4 Zooplankton sampling

See section 3.2.4 in Chapter Three as the methods used were identical. Within the East Kleinemonde the number of sampling stations for zooplankton were reduced in November 2005 to those closest to the mouth due to breaching causing shallow water conditions which prevented the towing of the zooplankton net.

4.2.5 Statistical analysis

See section 3.2.5 in Chapter Three as the methods used were identical.

4.3 RESULTS

4.3.1 Sea state, current and wind direction at the time of sampling

The predominant longshore swash zone and surfzone current direction on the sampling dates was consistently in a south-westerly direction due to rip currents adjacent to rocky promontories on the south-west of the sampling grids. On the survey dates and evenings prior to the surveys the wind direction, and therefore surface current direction, was similarly consistently blowing towards the north or west (see Appendix 1, Table A1.3 and A1.4 for specific data) (South African Weather Service, Port Alfred Station). The sea state during all surveys was light to moderate with swells of 2.5m or less (South African Weather Service, unpublished data). The depth below the study sites ranged from approximately 4m at the stations 200m from shore to 11m at the stations 800m from shore.

4.3.2 Physico-chemical and hydrological variables

4.3.3 Kasouga Estuary

Mouth status

The Kasouga Estuary never breached during any of the seasons studied; however, just prior to the November 2005 and March 2006 surveys, overtopping was noted. During June and September 2005 the estuary was closed with no evidence of overtopping.

The East Kleinemonde Estuary was closed with no indications of overtopping during the June and September surveys. The estuary had breached just prior to the November survey and was still open with a link to the sea at the time of the survey. Prior to the March survey overtopping of the sand berm was noted.

Salinity

The Kasouga Estuary demonstrated a mean salinity that varied seasonally in conjunction with rainfall patterns and evaporation rates. The lowest average salinities were recorded in June 2005 (16.73 practical salinity units ±0.27) (Table 4.2), with November 2005 being intermediate (22.83 ±1.17) and September 2005 (25.17 ±0.41) and March 2006 (26.00 ±0.63) being significantly higher ($p<0.005$; df=46). The lower salinities in June and November 2005 were a result of large amounts of rainfall (≈150mm and ≈180mm respectively) in the region in the two months preceding the samples. The elevated salinity values recorded in November 2005 can be ascribed to greater evaporation during the summer months.

Table 4.2: The average, maximum and minimum surface and bottom salinity (practical salinity units) recorded in the Kasouga Estuary during all seasons sampled.

		June	September	November	March
Surface	Average	16.73	25.17	22.83	26.00
	Std Dev.	0.27	0.41	1.17	0.63
	Maximum	16.92	26.00	24.00	27.00
	Minimum	16.22	25.00	21.00	25.00
Bottom	Average	15.25	25.00	22.50	26.58
	Std Dev.	2.23	0.00	1.87	1.80
	Maximum	16.93	25.00	24.00	30.00
	Minimum	12.30	25.00	19.00	25.00

There was very little evidence of longitudinal trends in salinity along the Kasouga Estuary, with the salinity being relatively uniform during June, September and November 2005 (Figure 4.2). During March 2006 there was a weak longitudinal gradient in salinity, with salinities in the mouth region being ≈4 units higher than in the upper reaches. There was no evidence of water column stratification during the four seasons sampled (Figure 4.2).

Significantly lower salinities were recorded in both the surface ($p<0.02$; $t=2.11$) and bottom ($p<0.03$; $t=2.1$) waters in the East Kleinemonde Estuary relative to the Kasouga Estuary. Salinity values (practical salinity units) within the East Kleinemonde Estuary were low in November (3.25 ±0.06) and moderate in June (18.77 ±0.62) and March (14.17 ±1.17), with a peak in September (24.83 ±0.41) (Table 4.3). No horizontal patterns in salinity were evident during the June and September surveys (Figure 4.2). However, in November the system demonstrated low salinity water throughout the estuary, with a slight increase near the mouth. During March a typical horizontal gradient in salinity was evident with high values recorded at the mouth and lower values at the head of the system. The patch of low salinity water at Station 2 represents a stormwater entry point into the system (Figure 4.2). There was no apparent water column stratification at any stage during the sampling trips conducted.

Table 4.3: The average, maximum and minimum salinity values (practical salinity units) recorded on the surface and bottom within the East Kleinemonde Estuary during the sampling period.

		June	September	November	March
Surface	Average	18.77	24.83	3.25	14.17
	Std Dev.	0.62	0.41	0.96	1.17
	Maximum	19.81	25.00	4.00	15.00
	Minimum	18.03	24.00	2.00	12.00
Bottom	Average	19.26	24.83	3.50	14.17
	Std Dev.	1.29	0.41	2.12	1.17
	Maximum	21.68	25.00	5.00	15.00
	Minimum	18.14	24.00	2.00	12.00

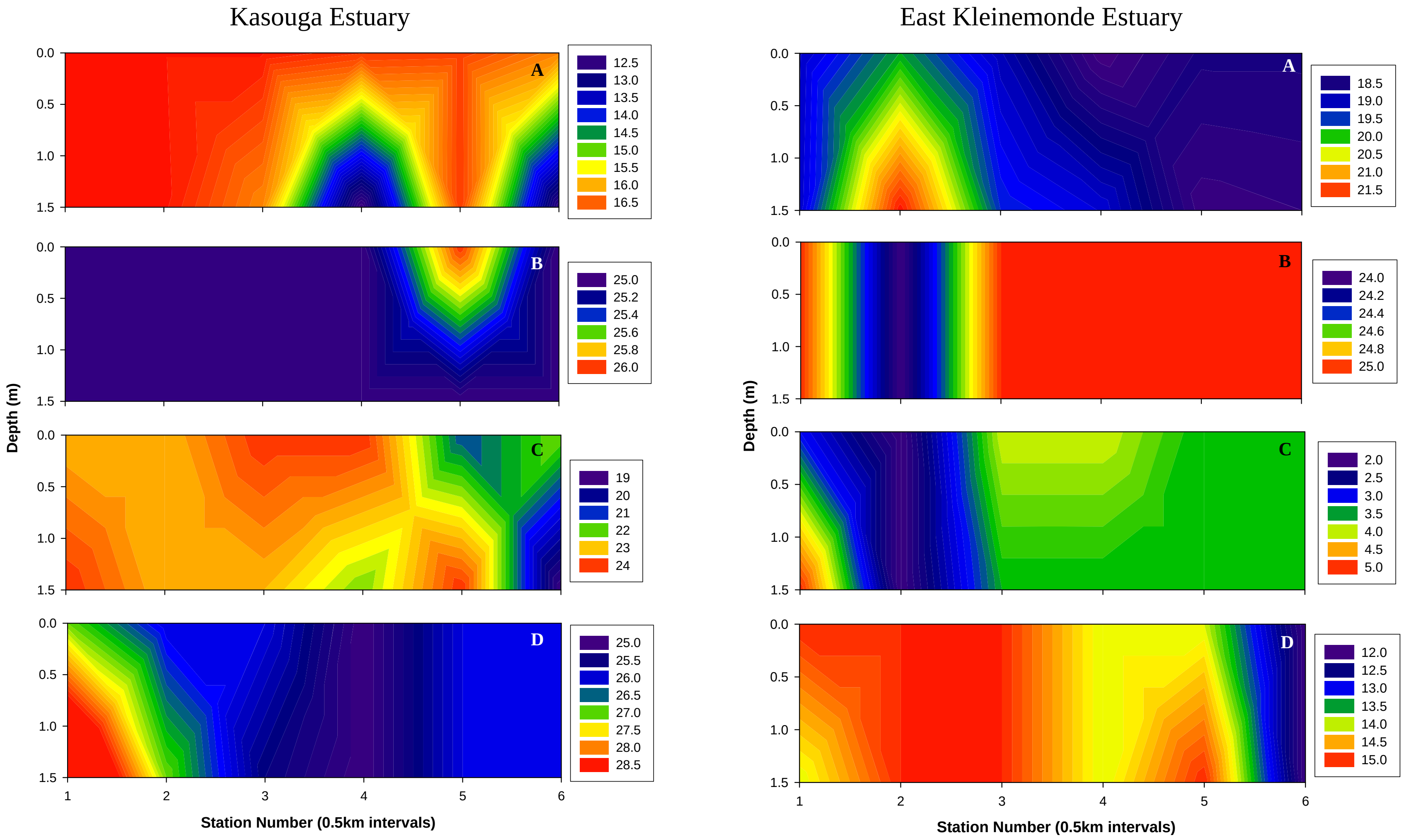


Figure 4.2: Vertical profiles of the salinity (practical salinity units) recorded within the Kasouga (left) and East Kleinemonde Estuaries during June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D). Note the different scales on the contour plots.

The average salinities recorded in the nearshore environment adjacent to the Kasouga Estuary varied between a March 2006 minimum value of 35 (±0.00SD) at the surface and 5m to a September 2005 maximum value of 36.92 (±0.19SD) at the surface and 5m (Table 4.4). No significant seasonal trends were apparent. No spatial trends were observed in the nearshore environment, with the variation across the sites during all seasons being less than one practical salinity unit (Appendix 4, Figure A4.1 to A4.4).

Table 4.4: The average, minimum and maximum surface and 5m salinity values (practical salinity units) recorded in the nearshore environment adjacent to the Kasouga Estuary.

		June	September	November	March
Surface	Average	35.38	36.92	35.83	35.00
	Std Dev.	0.03	0.19	0.83	0.00
	Maximum	35.43	37.00	37.00	35.00
	Minimum	35.34	36.50	35.00	35.00
5m	Average	35.40	36.92	36.18	35.00
	Std Dev.	0.02	0.19	0.87	0.00
	Maximum	35.43	37.00	38.00	35.00
	Minimum	35.36	36.50	35.00	35.00

In the nearshore marine environment adjacent to the East Kleinemonde no significant ($p>0.05$) spatial trends in salinity values were evident during the study (Appendix 4, Figure A4.1 to A4.4). A zone of low salinity water was, however, observed at Station 1 or upstream of the estuary mouth during the June, September and November surveys. The water column was well-mixed during all seasons, with the average variation between surface and 5m waters being less than 0.2 (Table 4.5; Appendix 4, Figure A4.1 to A4.4). No seasonal trends were evident in the nearshore marine environment, with the average salinities during June, September and March being ≈35 (Table 4.5). The only sample that had an average salinity of less than 35 was November, due to surface and bottom minima of 34. Due to the uniform salinity adjacent to both systems no significant differences were noted at the surface or at 5m.

Table 4.5: The average, minimum and maximum surface and 5m salinity (practical salinity units) values recorded in the nearshore marine environment adjacent to the East Kleinemonde Estuary.

		June	September	November	March
Surface	Average	35.26	36.75	34.88	35.00
	Std Dev.	0.05	0.40	0.31	0.00
	Maximum	35.30	37.00	35.00	35.00
	Minimum	35.12	36.00	34.00	35.00
5m	Average	35.28	36.96	34.83	35.00
	Std Dev.	0.02	0.14	0.39	0.00
	Maximum	35.31	37.00	35.00	35.00
	Minimum	35.22	36.50	34.00	35.00

Temperature

The water temperatures recorded within the Kasouga Estuary show a non-significant ($p>0.05$) seasonal trend with the lowest average temperature being recorded in June (15.19ºC ±0.27) and the maximum being recorded in March (26.18ºC ±0.15). Intermediate temperatures were evident in September and November (Table 4.6). The estuary was well-mixed, with variations between surface and bottom waters being within 1ºC during all seasons (Figure 4.3; Table 4.6). The spatial temperature trends in the estuary indicated well-mixed conditions, with slightly lower temperatures during all seasons in the mouth region and an increase towards the head of the estuary (Figure 4.3).

Table 4.6: The average, maximum and minimum temperatures (ºC) recorded in the Kasouga Estuary during the sampling period.

		June	September	November	March
Surface	Average	15.19	17.40	23.17	26.18
	Std Dev.	0.27	0.45	0.41	0.15
	Maximum	15.54	18.00	23.50	26.40
	Minimum	14.82	16.70	22.50	26.00
Bottom	Average	14.92	17.38	22.92	26.02
	Std Dev.	0.26	0.49	0.20	0.36
	Maximum	15.38	18.00	23.00	26.40
	Minimum	14.75	16.60	22.50	25.60

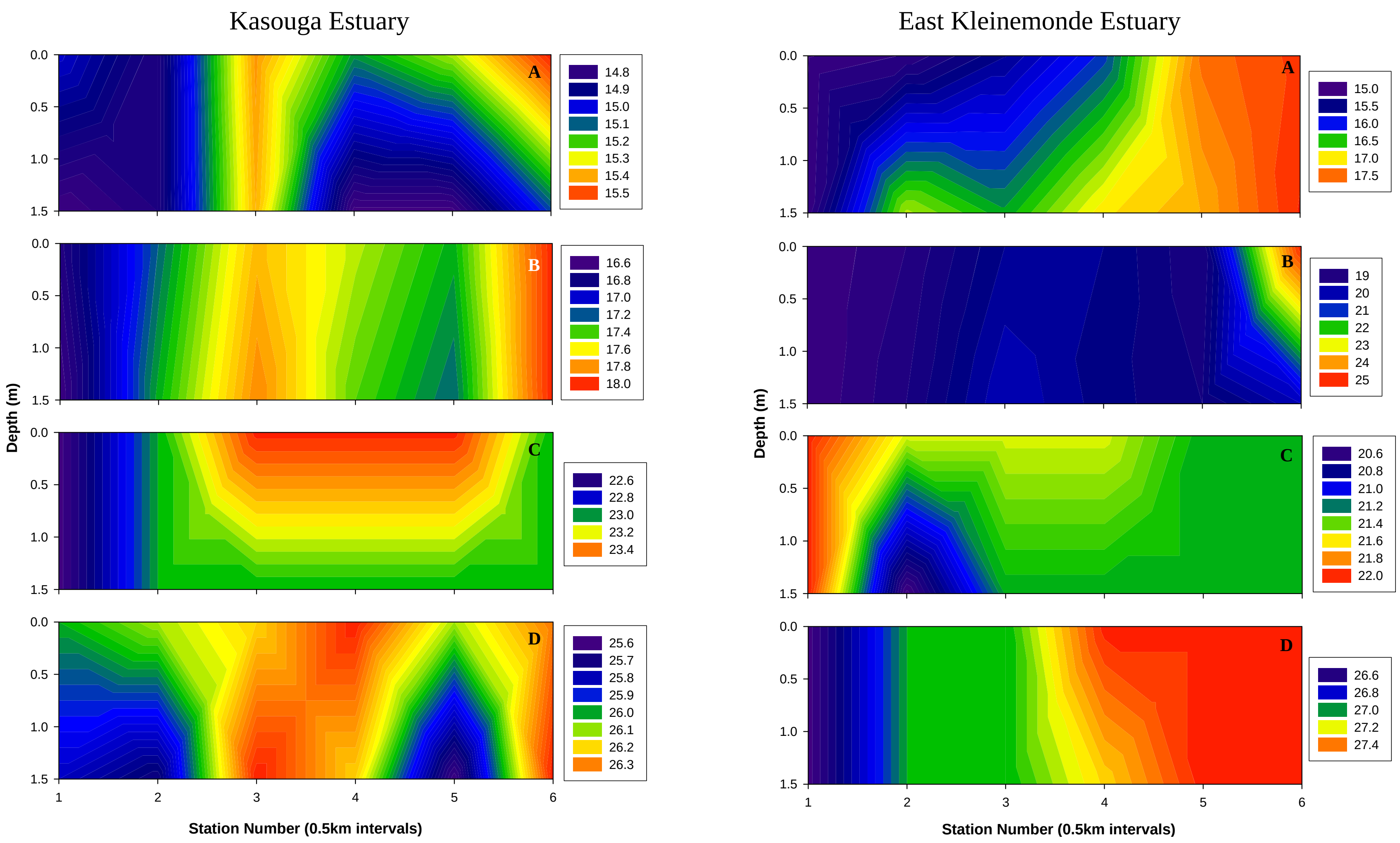


Figure 4.3: Vertical profiles of the temperatures (ºC) recorded within the Kasouga (left) and East Kleinemonde (right) Estuaries during the June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D) surveys. Note the different scales on the contour plots.

Water temperatures within the East Kleinemonde Estuary demonstrated a non-significant (p>0.05) seasonal trend. Water temperatures increased from a surface and bottom minimum in June (surface=16.12ºC ±1.16; bottom=16.67ºC ±0.92) to a maximum in March (surface=27.17ºC ±0.41; bottom=27.13ºC ±0.38) (Table 4.7). A distinct horizontal pattern in water temperatures was observed during the June and March surveys, with the highest values recorded near the head and the lowest near the mouth. During the November survey the observed pattern was reversed (Figure 4.3).

Table 4.7: The average, maximum and minimum temperatures (ºC) at the surface and bottom within the East Kleinemonde Estuary during each season sampled.

		June	September	November	March
Surface	Average	16.12	20.07	21.63	27.17
	Std Dev.	1.16	2.46	0.25	0.41
	Maximum	17.64	25.00	22.00	27.50
	Minimum	14.99	18.40	21.50	26.50
Bottom	Average	16.67	19.35	21.25	27.13
	Std Dev.	0.92	0.62	1.06	0.38
	Maximum	17.71	20.00	22.00	27.50
	Minimum	15.04	18.40	20.50	26.50

The average temperatures in the nearshore marine environment adjacent to the Kasouga Estuary demonstrated a non-significant (p>0.05) seasonal trend, except that the minimum occurred during September rather than June (Table 4.8). The marine environment maintained higher temperatures than the estuary during the winter months (between 17.70ºC and 18.84ºC) and lower temperatures during the summer months (18.00ºC to 22.00ºC). No water column stratification in terms of temperature was evident during June and November surveys. During September and March a small degree of stratification was evident with a temperature difference of ≈0.3ºC between surface and 5m waters at most sites (Appendix 4, Figures A4.5 to A4.8).

Table 4.8: The average, maximum and minimum temperatures (ºC) recorded in the nearshore environment adjacent to the Kasouga Estuary during all seasons sampled.

		June	September	November	March
Surface	Average	18.67	17.83	19.06	21.98
	Std Dev.	0.16	0.08	0.45	0.08
	Maximum	18.84	17.90	19.50	22.10
	Minimum	18.41	17.70	18.00	21.80
5m	Average	18.67	17.78	19.24	21.79
	Std Dev.	0.15	0.08	0.94	0.08
	Maximum	18.84	17.90	22.00	21.90
	Minimum	18.44	17.70	18.00	21.70

Seawater temperatures in the nearshore marine environment adjacent to the East Kleinemonde Estuary were generally lowest adjacent to the estuary mouth during the June, September and March surveys (Appendix 4, Figure A4.5, A4.6 and A4.8). The inverse was true for November, with a plug of warm water adjacent to the mouth (Appendix 4, Figure A4.7). No vertical water column stratification in temperatures in the nearshore environment adjacent to the East Kleinemonde Estuary was evident (Appendix 4, Figure A4.5 to A4.8; Table 4.9). A seasonal trend was evident with an increase from a June minimum (17.32ºC ±0.18) to a March maximum (21.58ºC ±0.10) (Table 4.9). Due to seasonal variability in temperatures no significant differences were observed when the two estuaries and adjacent marine environments were compared.

Table 4.9: The average, minimum and maximum surface and 5m temperatures (ºC) recorded in the nearshore environment adjacent to the East Kleinemonde Estuary.

		June	September	November	March
Surface	Average	17.32	18.06	19.29	21.58
	Std Dev.	0.18	0.16	0.63	0.10
	Maximum	17.54	18.30	19.90	21.70
	Minimum	16.95	17.80	17.50	21.50
5m	Average	17.17	18.09	18.98	21.56
	Std Dev.	0.16	0.62	1.53	0.05
	Maximum	17.45	20.00	23.00	21.60
	Minimum	16.85	17.70	17.00	21.50

Marine water densities (σ_t)

Adjacent to the Kasouga Estuary no spatial patterns in marine water density were evident during any season (Figure 4.4). Very little variation in the surface (average: 25.4±0.05 to 24.22±0.02) and bottom (average: 25.41±0.04 to 24.28±0.02) σ_t values were recorded over all surveys (Table 4.10). The average delta σ_t values indicate weak water column stratification stratification during all the sampling surveys (0.02 – 0.55) (Table 4.10).

Table 4.10: The water density (σ_t) calculated in the marine environment adjacent to the Kasouga Estuary. The average, standard deviation, maximum and minimum values are presented.

		June	September	December	March
Surface	Average	25.4	25.25	24.75	24.22
	Std Dev.	0.05	0.15	0.43	0.02
	Maximum	25.47	25.35	25.27	24.28
	Minimum	25.32	24.92	24.13	24.19
5m	Average	25.41	25.26	24.57	24.28
	Std Dev.	0.04	0.14	0.45	0.02
	Maximum	25.47	25.35	25.27	24.3
	Minimum	25.34	24.96	24.13	24.25
Delta σ_t	Average	0.02	0.02	0.55	0.06
	Std Dev.	0.01	0.02	0.37	0.04
	Maximum	0.05	0.05	0.89	0.11
	Minimum	0	0	0	0

The average water density calculated adjacent to the East Kleinemonde was slightly elevated relative to that determined adjacent to the Kasouga Estuary (Table 4.11). In the marine environment adjacent to the East Kleinemonde the σ_t values ranged between a March minimum of 24.3 at the surface and a September maximum of 26.88 at 5m depth (Table 4.11). A spatial pattern was evident in water density (delta σ_t) adjacent to the East Kleinemonde estuary during the June, September and November surveys (Appendix 4, Figure A4.2). Similarly to the Kasouga Estuary, only weak stratification was noted in water column densities in the marine environment adjacent to the East Kleinemonde (<0.5) (Table 4.11).

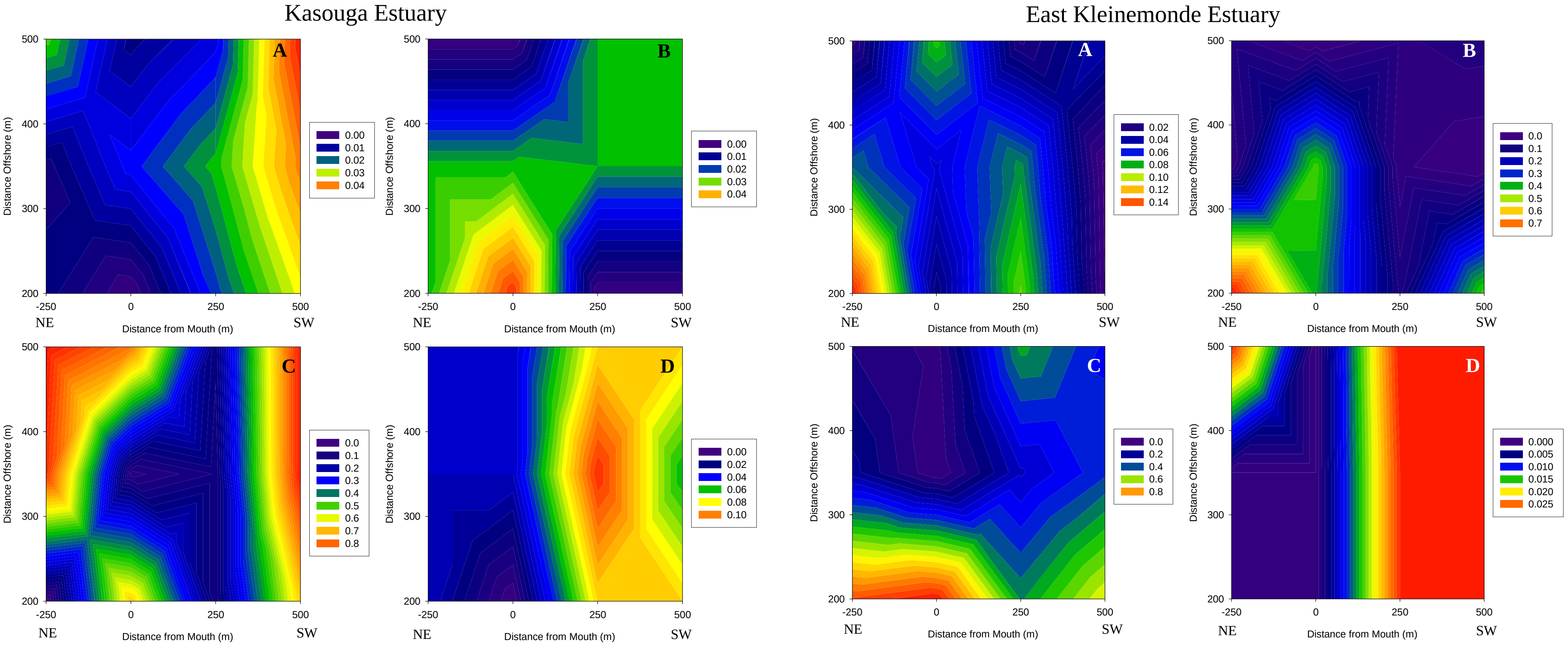


Figure 4.4: Delta σ_t plots for the marine environment adjacent to the Kasouga (left) and East Kleinemonde (right) Estuaries during June 2004 (A), September 2004 (B), December 2004 (C) and March 2005 (D). NE (north-east) and SW (south-west) have been inserted along the x-axis to indicate compass direction.

Table 4.11: The water density (σ_t) calculated in the marine environment adjacent to the East Kleinemonde Estuary. The average, standard deviation, maximum and minimum values are presented.

		June	**September**	**December**	**March**
Surface	Average	25.64	26.6	24.85	24.34
	Std Dev.	0.05	0.3	0.13	0.03
	Maximum	25.72	26.86	25.02	24.36
	Minimum	25.56	26.01	24.59	24.3
5m	Average	25.69	26.79	24.91	24.34
	Std Dev.	0.05	0.11	0.44	0.01
	Maximum	25.77	26.88	25.52	24.36
	Minimum	25.61	26.47	23.94	24.33
Delta σ_t	Average	0.05	0.19	0.38	0.02
	Std Dev.	0.04	0.26	0.32	0.01
	Maximum	0.15	0.79	0.96	0.03
	Minimum	0.01	0	0	0

Particulate organic matter

Particulate organic matter (POM) concentrations within the Kasouga Estuary demonstrated a large seasonal variation (Table 4.12). The June surface (11.11mg.L^{-1} ±13.68) and bottom (9.61mg.L^{-1} ±6.84) average POM concentrations were significantly higher (p=0.005; df=46) than all other seasons. The average November surface (1.61mg.L^{-1} ±1.04) and bottom (1.56mg.L^{-1} ±0.54) POM concentrations were significantly lower (p=0.001; df=46) than the other seasons surveyed. No longitudinal trends in POM concentration were evident within the Kasouga Estuary during the four surveys. The maximum POM concentrations during the June, September and November surveys were recorded at the surface between Stations 3 and 4 (Figure 4.5), which were adjacent to two salt marshes within the estuary. There was no evidence of any vertical stratification gradients in POM concentration during the study (Figure 4.5).

Table 4.12: The average, maximum and minimum POM (mg.L^{-1}) recorded on the surface and bottom of the Kasouga Estuary during all seasons sampled.

		June	September	November	March
Surface	Average	11.11	6.72	1.61	6.28
	Std Dev.	13.68	2.12	1.04	2.12
	Maximum	39.00	11.00	2.67	10.00
	Minimum	5.00	5.33	0.33	4.00
Bottom	Average	9.61	7.22	1.56	5.83
	Std Dev.	6.84	1.61	0.54	1.09
	Maximum	23.00	9.00	2.33	6.67
	Minimum	4.00	4.33	1.00	3.67

The average particulate organic matter (POM) concentrations in the East Kleinemonde Estuary varied seasonally (Table 4.13). The lowest POM concentrations were recorded during June (1.72mg.L^{-1} ±1.54) and November (3.50mg.L^{-1} ±1.77) and the highest POM values were recorded during the September survey, with an average surface and bottom POM concentration of 8.56mg.L^{-1} (±3.12SD) and 8.72mg.L^{-1} (±2.22SD), respectively (Table 4.13). A distinct horizontal pattern in POM concentrations was evident during the September, November and March surveys, with the highest values recorded near the mouth of the estuary and the lowest near the middle reaches (Figure 4.5).

Table 4.13: The average, maximum and minimum surface and bottom POM concentrations (mg.L^{-1}) recorded in the East Kleinemonde Estuary.

		June	September	November	March
Surface	Average	1.72	8.56	3.50	5.00
	Std Dev.	1.54	3.12	1.77	1.73
	Maximum	4.67	14.67	5.33	7.67
	Minimum	0.33	6.00	1.67	3.67
Bottom	Average	7.89	8.72	1.67	6.22
	Std Dev.	14.43	2.22	0.94	1.03
	Maximum	37.33	10.33	2.33	8.00
	Minimum	1.33	4.67	1.00	5.33

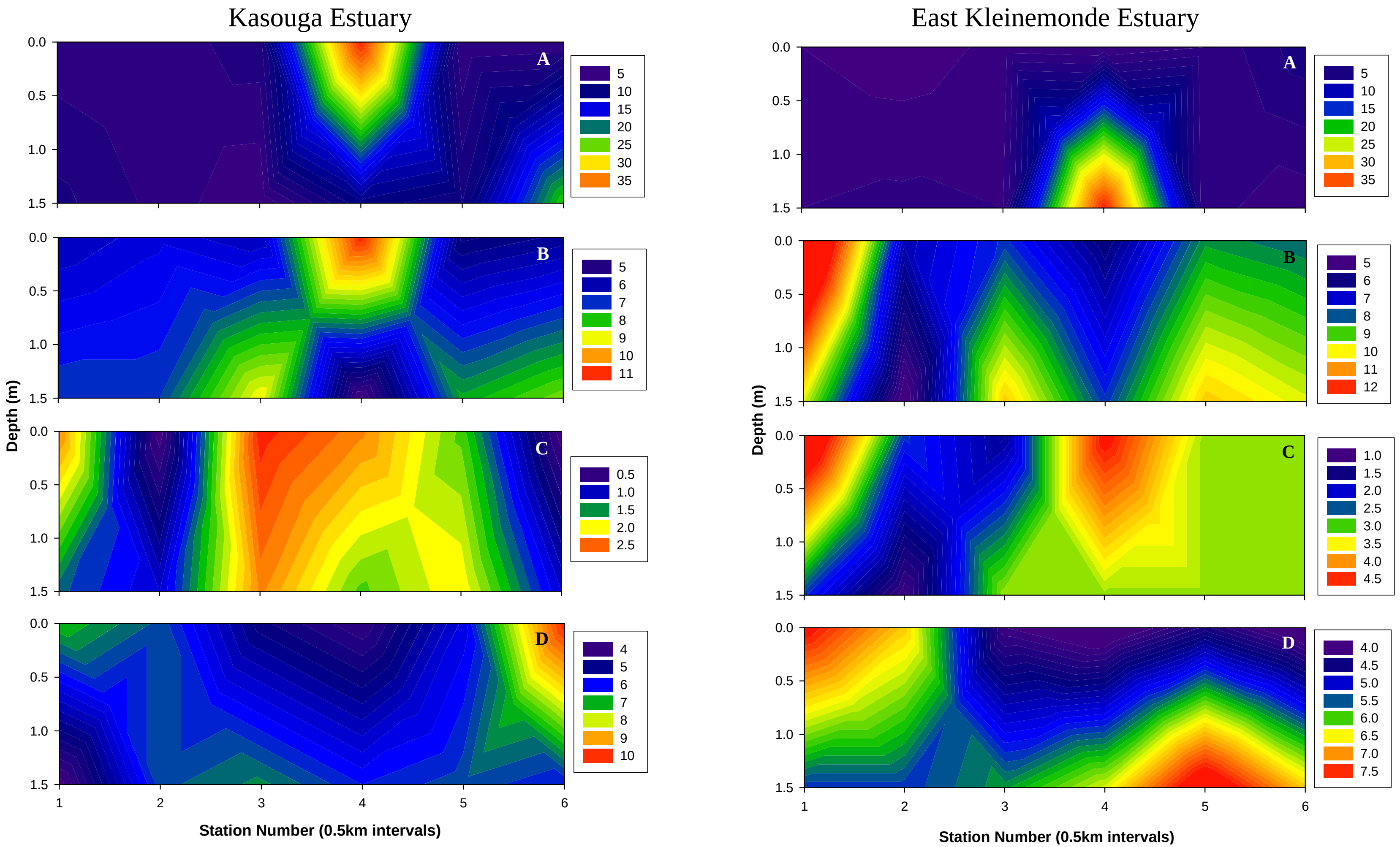


Figure 4.5: Vertical profiles of the particulate organic matter concentrations (mg.L^{-1}) recorded within the Kasouga (left) and East Kleinemonde (right) Estuaries during the June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D) surveys. Note the different scales on the contour plots.

In the nearshore environment adjacent to the Kasouga Estuary, a strong vertical gradient in POM concentrations was evident during all seasons surveyed (Table 4.14; Appendix 4, Figure A4.9 to A4.12). During the June, September and November surveys, the surface waters consistently had lower POM concentrations (10.30mg.L^{-1} [±2.14SD], 2.31mg.L^{-1} [±1.01SD] and 2.58mg.L^{-1} [±0.77SD] respectively) than waters at 5m depth (12.93mg.L^{-1} [±2.76SD], 3.31mg.L^{-1} [±1.12SD] and 2.92mg.L^{-1} [±0.97SD] respectively). During March, this trend was reversed with the highest POM concentrations recorded in the surface (10.03mg.L^{-1} ±5.59; 5m waters: 8.00mg.L^{-1} ±3.85). No spatial trends in POM concentration were evident during June and September (Appendix 4, Figure A4.9 to A4.10). Peaks in POM concentration were, however, evident opposite the estuary at a depth of 5m during November and in the surface waters during March (Appendix 4, Figure A4.11 to A4.12).

Table 4.14: The average, maximum and minimum surface and 5m POM concentrations (mg.L^{-1}) recorded in the nearshore environment adjacent to the Kasouga Estuary.

		June	September	November	March
Surface	Average	10.30	2.31	2.58	10.03
	Std Dev.	2.14	1.01	0.77	5.59
	Maximum	14.00	4.00	3.67	27.33
	Minimum	7.00	0.33	1.33	7.33
5m	Average	12.93	3.31	2.92	8.00
	Std Dev.	2.46	1.12	0.97	3.85
	Maximum	16.33	5.00	4.67	17.33
	Minimum	7.00	1.67	1.33	0.33

The POM concentrations in the marine environment adjacent to the Kasouga Estuary indicated temporal trends with significantly higher concentrations recorded in June and March ($p<0.005$; df=47) relative to the September and November surveys (Table 4.14). The maximum recorded surface (27.33mg.L^{-1}) and 5m concentrations (17.33mg.L^{-1}) occurred during the March survey, while the minimum surface and 5m POM concentrations were recorded during September (0.33mg.L^{-1}) and November (1.33mg.L^{-1}) respectively.

There were no significant spatial trends in the POM concentration in the nearshore marine environment adjacent to the East Kleinemonde during the September and

March surveys (Appendix 4, Figure A4.10 and A4.12). During June and November the highest POM concentrations (≈16mg.L^{-1} and ≈5mg.L^{-1} respectively) were recorded along the transect occupied opposite the mouth of the estuary (Appendix 4, Figure A4.9 and A4.11). During November the increased POM concentration could be attributed to estuarine water inflow through the open estuary mouth, while during June the high POM concentrations are anomalous. The POM concentrations recorded in the nearshore marine environment fluctuated between a September minimum of 0.33mg.L^{-1} and a March maximum of 27.33mg.L^{-1} (Table 4.15). The June (10.25mg.L^{-1} ±1.94) and March (10.03mg.L^{-1} ±5.59) POM concentrations were significantly higher ($p<0.001$; df=47) than those recorded during September (2.31mg.L^{-1} ±1.01) and November (2.58mg.L^{-1} ±0.77) (Table 4.15). Water column stratification was only marginally evident, indicating a well-mixed water body (Table 4.15). The high variability in the inshore and estuarine POM concentrations resulted no significant differences between the two estuaries.

Table 4.15: The average, maximum and minimum POM concentrations (mg.L^{-1}) recorded in the nearshore environment adjacent to the East Kleinemonde Estuary.

		June	September	November	March
Surface	Average	10.25	2.31	2.58	10.03
	Std Dev.	1.94	1.01	0.77	5.59
	Maximum	14.00	4.00	3.67	27.33
	Minimum	7.00	0.33	1.33	7.33
5m	Average	13.03	3.31	2.92	8.00
	Std Dev.	2.24	1.12	0.97	3.85
	Maximum	16.33	5.00	4.67	17.33
	Minimum	7.00	1.67	1.33	0.33

Chlorophyll-a concentration

Temporal trends were observed in the total chlorophyll-*a* concentration in the Kasouga Estuary. Total chlorophyll-*a* concentration during the September (1.99µg.L^{-1} ±1.53) and November (1.79µg.L^{-1} ±0.63) surveys were significantly lower ($p<0.001$; df=23) than that recorded during the June (3.07µg.L^{-1} ±1.10) and March (3.31µg.L^{-1} ±0.7) surveys (Table 4.16). With the exception of the June maximum (6.38µg.L^{-1}), which was recorded in the estuary bottom waters adjacent to the large salt marshes, total chlorophyll-*a* concentration was highest in the upper reaches of the estuary (Figure 4.6). This resulted in a trend of increasing chlorophyll-*a* concentration from the middle to the upper reaches during September, November and March (Figure 4.6). No significant differences in total chlorophyll-*a* concentration were recorded between surface and bottom waters during any season ($p>0.05$ in all cases). (Figure 4.6).

Table 4.16: The average, maximum and minimum surface and bottom total chlorophyll-*a* concentration ($\mu g.L^{-1}$) recorded within the Kasouga Estuary during all seasons sampled.

		June	September	November	March
Surface	Average	3.07	1.99	1.79	3.31
	Std Dev.	1.10	1.53	0.63	0.70
	Maximum	4.95	4.32	2.85	4.34
	Minimum	2.05	0.46	1.03	2.17
Bottom	Average	3.89	2.50	1.67	3.72
	Std Dev.	1.77	1.50	0.76	1.00
	Maximum	6.38	4.54	2.98	5.51
	Minimum	1.95	0.55	0.76	2.73

The mean total chlorophyll-*a* concentrations in the East Kleinemonde Estuary ranged from $0.39\mu g.L^{-1}$ (±0.13SD) to $5.20\mu g.L^{-1}$ (±4.80SD) in surface waters and from $0.29\mu g.L^{-1}$ (±0.03SD) to $4.94\mu g.L^{-1}$ (±5.20SD) in bottom waters (Table 4.17). Seasonal variations in the chlorophyll-*a* concentration were recorded, with June ($3.00\mu g.L^{-1}$ ±0.61) and March ($5.20\mu g.L^{-1}$ ±4.80) having significantly higher ($p<0.001$;df=40) chlorophyll-*a* concentrations than September ($0.92\mu g.L^{-1}$ ±0.34) and November ($0.39\mu g.L^{-1}$ ±0.13) (Table 4.17). The estuary water column was well-mixed in terms of chlorophyll-*a*, with bottom concentrations being less than $0.3\mu g.L^{-1}$ lower than the surface values (Table 4.17). Spatially within the system there was an increase in chlorophyll-*a* from the mouth to the head of the estuary during all seasons except November, which indicated a chlorophyll-*a* peak near the estuary mouth and at Station 4 in the middle reaches (Figure 4.6). The high variability in chlorophyll-*a* concentrations resulted in no significant differences between these two estuaries in either the surface or bottom waters.

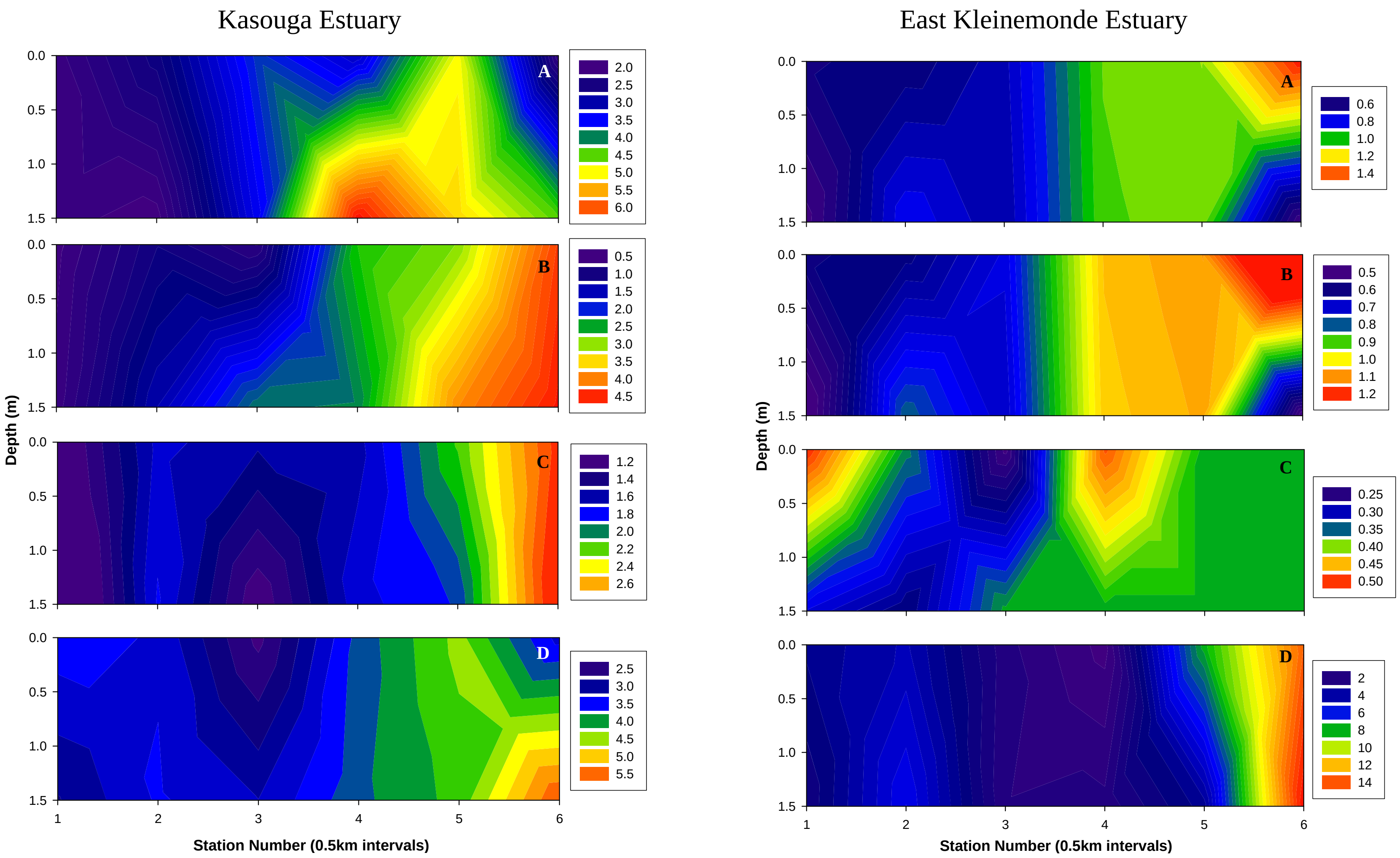


Figure 4.6: Vertical profiles of the total chlorophyll-*a* concentration (µg.L^{-1}) recorded within the Kasouga (left) and East Kleindemonde (right) Estuaries during June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D). Note the different scales on the contour plots.

Table 4.17: The average, maximum and minimum total chlorophyll-*a* concentrations (µg.L^{-1}) recorded in the surface and bottom waters in the East Kleinemonde Estuary.

		June	September	November	March
Surface	Average	3.00	0.92	0.39	5.20
	Std Dev.	0.61	0.34	0.13	4.80
	Maximum	3.77	1.47	0.50	13.60
	Minimum	2.06	0.60	0.23	0.64
Bottom	Average	2.96	0.75	0.29	4.94
	Std Dev.	0.48	0.26	0.03	5.20
	Maximum	3.71	1.06	0.31	15.20
	Minimum	2.29	0.46	0.27	1.62

The total chlorophyll-*a* concentration recorded in the nearshore environment adjacent to the Kasouga Estuary demonstrated a temporal trend, increasing from June to November and then decreasing to March (Table 4.18). Total chlorophyll-*a* concentrations in the surface and 5m waters during the November survey were significantly higher than the remaining seasons ($p<0.01$; df=91) (Table 4.18; Appendix 4, Figure A4.13 to A4.16). During September and March no apparent spatial patterns in total chlorophyll-*a* concentration were evident in the nearshore environment to the Kasouga Estuary. During June, however, a body of water containing higher total chlorophyll-*a* concentrations protruded into the nearshore environment from offshore, while in November the waters at 5m adjacent to the estuary mouth contained high chlorophyll-*a* concentrations (Appendix 4, Figure A4.13 to A4.16).

Table 4.18: The average, maximum and minimum surface and 5m total chlorophyll-*a* concentrations (µg.L^{-1}) in the nearshore environment adjacent to the Kasouga Estuary during all seasons sampled.

		June	September	November	March
Surface	Average	0.19	0.38	1.18	0.70
	Std Dev.	0.06	0.06	0.29	0.20
	Maximum	0.31	0.47	1.38	1.05
	Minimum	0.10	0.26	0.32	0.36
5m	Average	0.21	0.40	1.54	0.86
	Std Dev.	0.08	0.09	0.33	0.30
	Maximum	0.36	0.61	2.47	1.61
	Minimum	0.13	0.23	1.17	0.44

The chlorophyll-*a* concentrations in the nearshore environment adjacent to the East Kleinemonde indicated a peak in Transect 3 in the surface waters during the June, November and March surveys, while during September the chlorophyll-*a* concentration peaked in both the surface and 5m waters close inshore (Appendix 4, Figure A4.13 to A4.16). Water column stratification was evident during the June and November surveys, with significantly higher ($P<0.001$; df=11) chlorophyll-*a* concentrations in the surface water during both seasons. Temporally the chlorophyll-*a* concentrations were significantly higher ($p=0.02$; df=93) during June (1.16μg.L^{-1} ±0.46) and November (1.22μg.L^{-1} ±0.25) relative to the September (0.64μg.L^{-1} ±0.14) and March (0.94μg.L^{-1} ±0.37) surveys (Table 4.19). The maximum recorded chlorophyll-*a* was measured in June (1.96μg.L^{-1}), while the minimum value of 0.39μg.L^{-1} was recorded during September (Table 4.19).

Table 4.19: The average, maximum and minimum total chlorophyll-*a* concentrations (μg.L^{-1}) in the surface waters and at 5m depth in the nearshore environment adjacent to the East Kleinemonde Estuary.

		June	September	November	March
Surface	Average	1.16	0.64	1.22	0.94
	Std Dev.	0.46	0.14	0.25	0.37
	Maximum	1.96	1.02	1.69	1.76
	Minimum	0.56	0.47	0.92	0.40
5m	Average	0.81	0.67	0.90	1.00
	Std Dev.	0.23	0.17	0.17	0.27
	Maximum	1.25	0.99	1.13	1.46
	Minimum	0.47	0.39	0.54	0.57

4.3.4 Zooplankton density and biomass

Zooplankton density

The total zooplankton abundances within the Kasouga Estuary ranged between a November minimum of 6 472.16ind.m^{-3} (±8 652.39SD) and a March maximum of 10 701.71ind.m^{-3} (±9 020.63SD) (Table 4.20). No consistent spatial trends were observed during the different seasons (Figure 4.7). However, during June and September the highest densities were recorded near the estuary mouth. No temporal trends were evident, with similar zooplankton densities recorded during June, September and November, and slightly higher densities recorded during March (Table 4.20).

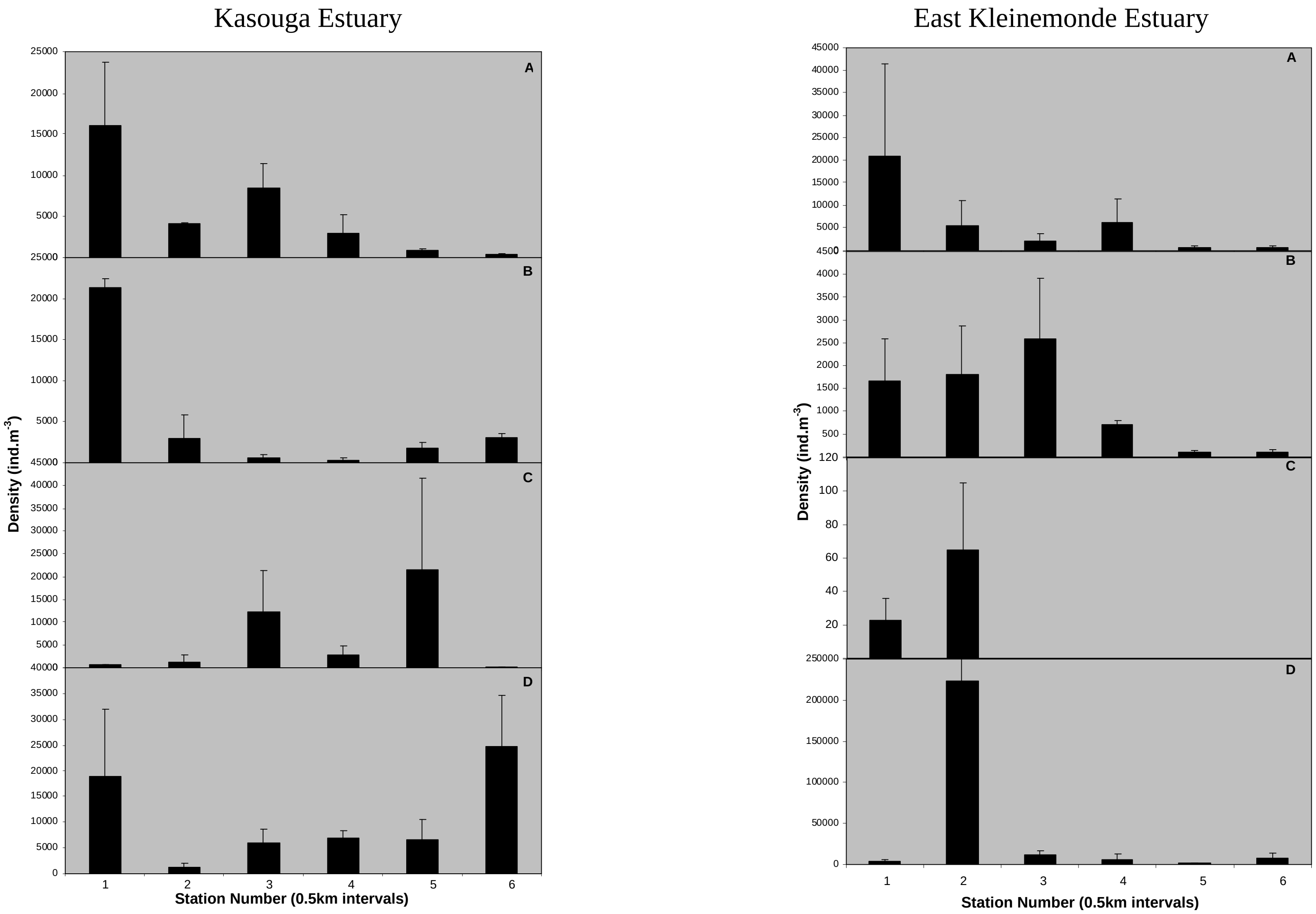


Figure 4.7: The mean total zooplankton density (ind.m^{-3}) at each site in the Kasouga (left) and East Kleinemonde (right) Estuaries during the June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D) surveys. Note the different y-axis scales.

Table 4.20: The average, maximum and minimum zooplankton densities (ind.m^{-3}) in the Kasouga Estuary during all seasons sampled.

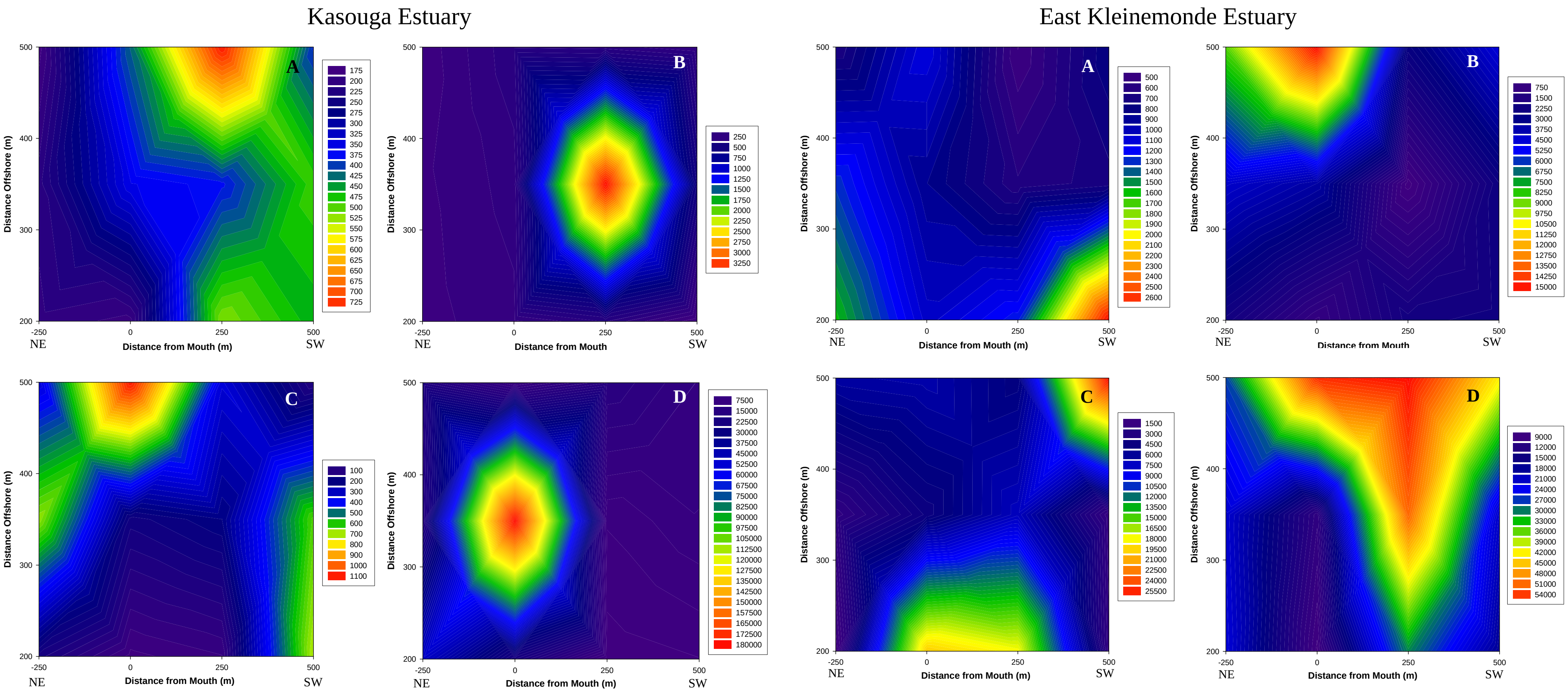
	June	September	November	March
Average	5 463.98	4 999.10	6 472.16	10 701.71
Std Dev.	5 918.87	8 041.30	8 652.39	9 020.63
Maximum	16 019.19	21 246.94	21 517.93	24 777.48
Minimum	337.65	330.73	164.60	1 299.19

The total zooplankton abundance within the East Kleinemonde Estuary demonstrated a trend of decreasing abundance from June (5 917.99ind.m^{-3} ±7 679.55) to November (43.82ind.m^{-3} ±29.79), followed by a subsequent increase to a March maximum of 42 805ind.m^{-3} (±88 367SD) (Table 4.21). The spatial trends in September and March indicate a peak in the lower to middle reaches of the estuary, with a decrease towards the head and mouth of the system (Figure 4.7). During June a trend of decreasing abundance from the mouth of the estuary to the head of the system was observed.

Table 4.21: The average, maximum and minimum zooplankton densities (ind.m^{-3}) in the East Kleinemonde Estuary during the seasons surveyed.

	June	September	November	March
Average	5 917.99	1 165.60	43.82	42 805.77
Std Dev.	7 697.55	1 015.15	29.79	88 367.94
Maximum	20 876.76	2 589.69	64.88	223 053.01
Minimum	568.19	103.35	22.76	2 444.74

In the nearshore marine environment adjacent to the Kasouga Estuary a general trend of increasing mean zooplankton density was observed from June (364.37ind.m^{-3} ±174.58) to March (27 228.65ind.m^{-3} ±49 760.58) (Table 4.22). The densities recorded in March were significantly higher than all other seasons surveyed ($p<0.001$; df=45). Minor peaks in zooplankton density were observed during all seasons adjacent to the estuary mouth in Transect 2 or 3. However, during June and November the peak occurred offshore, while during September and March the peak occurred closer inshore (Figure 4.8).


Kasouga Estuary

East Kleinemonde Estuary

Figure 4.8: The mean total zooplankton density (ind.m^{-3}) recorded in the nearshore environment adjacent to the Kasouga (left) and the East Kleinemonde (right) Estuaries during the June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D) surveys. Note the different scales on each contour plot. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Table 4.22: The average, maximum and minimum zooplankton densities (ind.m^{-3}) recorded in the nearshore environment adjacent to the Kasouga Estuary during all seasons sampled.

	June	September	November	March
Average	364.37	485.85	365.42	27 228.65
Std Dev.	174.58	930.63	338.49	49 760.58
Maximum	739.92	3 418.30	1 102.93	180 059.60
Minimum	169.18	57.36	12.82	2 162.99

The mean zooplankton densities in the nearshore environment adjacent to the East Kleinemonde Estuary demonstrated a similar seasonal trend to the biomass with a steady increase in density from a June minimum of 1 033.75ind.m^{-3} (±613.58SD) to a March maximum of 30 132ind.m^{-3} (±16 873SD) (Table 4.23). Intermediate zooplankton densities were recorded during the September (3 990.71ind.m^{-3} ±4 132.08SD) and November (8 232.11ind.m^{-3} ±8 336.54SD) surveys. Peaks in the total zooplankton density were recorded offshore and downstream of the estuary mouth during the June, September and March surveys, although the position of these peaks varied. During the November survey there was a peak in zooplankton density that occurred close inshore, extending from adjacent to the estuary mouth to stations slightly downstream (Figure 4.8).

Table 4.23: The average, maximum and minimum zooplankton densities (ind.m^{-3}) in the nearshore environment adjacent to the East Kleinemonde Estuary.

	June	September	November	March
Average	1 033.75	3 990.71	8 232.11	30 132.84
Std Dev.	613.58	4 132.08	8 336.54	16 873.48
Maximum	2 697.00	15 155.55	26 216.01	56 745.85
Minimum	447.27	218.37	712.59	8 212.64

Zooplankton biomass

The total zooplankton biomass within the Kasouga Estuary demonstrated a non-significant ($p>0.05$) temporal trend, with a steady increase in the average zooplankton biomass from June (23.48mg dwt m^{-3} ±11.85) to November (83.96mg dwt m^{-3} ±67.23), followed by a slight decrease in March (49.90mg dwt m^{-3} ±43.21) (Table 4.24). Within the estuary there was a general trend of decreasing biomass from the estuary mouth to the head of the system during all seasons (Figure 4.9).

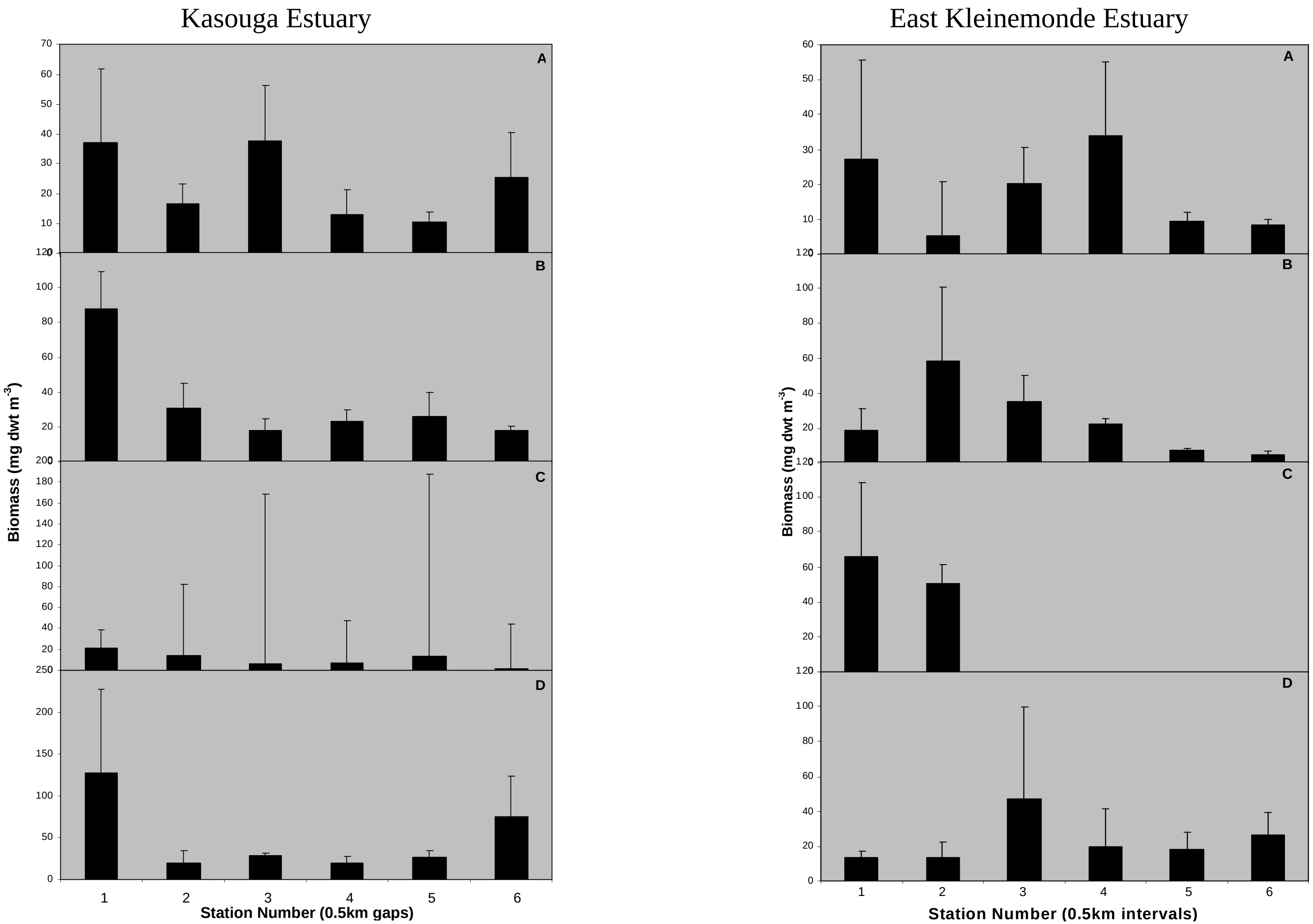


Figure 4.9: The mean total zooplankton biomass (mg dwt m^{-3}) at each site in the Kasouga Estuary during the June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D) surveys. Note the different scales on the y-axis.

Table 4.24: The average, maximum and minimum zooplankton biomass (mg dwt m^{-3}) recorded within the Kasouga Estuary during all seasons sampled.

	June	September	November	March
Average	23.48	34.12	83.96	49.90
Std Dev.	11.85	26.62	67.23	43.21
Maximum	37.79	87.59	174.07	127.59
Minimum	10.79	18.35	17.48	20.27

The mean zooplankton biomass in the East Kleinemonde Estuary ranged from a June minimum of 17.42mg dwt m^{-3} (±11.58SD) to a November maximum of 58.31mg dwt m^{-3} (±10.64SD) (Table 4.25). The observed seasonal trend in zooplankton biomass was the reverse of that recorded for the total zooplankton densities (Table 4.25). The zooplankton biomass increased between June and November and subsequently decreased to 23.12mg dwt m^{-3} (±12.64SD) during March. The longitudinal trend in zooplankton biomass was similar to that of the zooplankton densities during the September and March surveys, with a peak in the lower to middle reaches (Stations 2 and 3) and a decrease in biomass to the head and mouth of the estuary (Figure 4.9). During June no longitudinal trend was evident and during November only the lower reach stations were sampled due to shallow water depths at all other stations (Figure 4.9).

Table 4.25: The average, maximum and minimum zooplankton biomass (mg dwt m^{-3}) recorded within the East Kleinemonde Estuary during all seasons sampled.

	June	September	November	March
Average	17.42	24.52	58.31	23.12
Std Dev.	11.58	20.06	10.64	12.64
Maximum	34.02	58.87	65.83	47.10
Minimum	5.44	4.93	50.79	13.50

The mean zooplankton biomass in the nearshore marine environment adjacent to the Kasouga Estuary demonstrated a temporal pattern, with an increase in biomass from June (82.67mg dwt m^{-3} ±35.42) to November (174.81mg dwt m^{-3} ±299.52), and a continued increase to March (637.98mg dwt m^{-3} ±1633.07) (Table 4.26). The total zooplankton biomass during November and March was significantly higher than the values recorded during the June and September surveys ($p<0.001$; df=44). The total zooplankton biomass during the September and November surveys were highest at stations occupied downstream of the estuary mouth (Figure 4.10). During March the highest biomass was recorded adjacent to the estuary mouth (Transect 2). No clear spatial patterns were evident during the June survey.

Table 4.26: The average, maximum and minimum zooplankton biomass (mg dwt m^{-3}) recorded in the nearshore environment adjacent to the Kasouga Estuary.

	June	September	November	March
Average	82.67	61.86	174.81	637.98
Std Dev.	35.42	63.41	299.52	1633.07
Maximum	153.20	187.47	1059.37	5795.66
Minimum	33.37	10.62	10.71	16.61

The total zooplankton biomass in the nearshore marine environment adjacent to the East Kleinemonde Estuary indicated an accumulation of zooplankton adjacent to the mouth during all seasons (Figure 4.10). During November when the estuary mouth was open the trend was heightened, with increased biomass close inshore along the coast. In addition, a seasonal trend was evident with a steady increase in average zooplankton biomass from a June minimum of 26.28mg dwt m^{-3} (±17.19SD) to a March maximum of 210.58mg dwt m^{-3} (±144.21SD) (Table 4.27). The total zooplankton biomass during the March and November surveys were significantly higher than during the June and September surveys ($p<0.001$; df=44).

Table 4.27: The average, maximum and minimum zooplankton biomass (mg dwt m^{-3}) in the nearshore environment adjacent to the East Kleinemonde Estuary.

	June	September	November	March
Average	26.28	50.90	104.66	210.58
Std Dev.	17.19	23.12	82.52	144.21
Maximum	58.64	98.47	278.84	535.45
Minimum	10.35	22.47	12.77	60.18

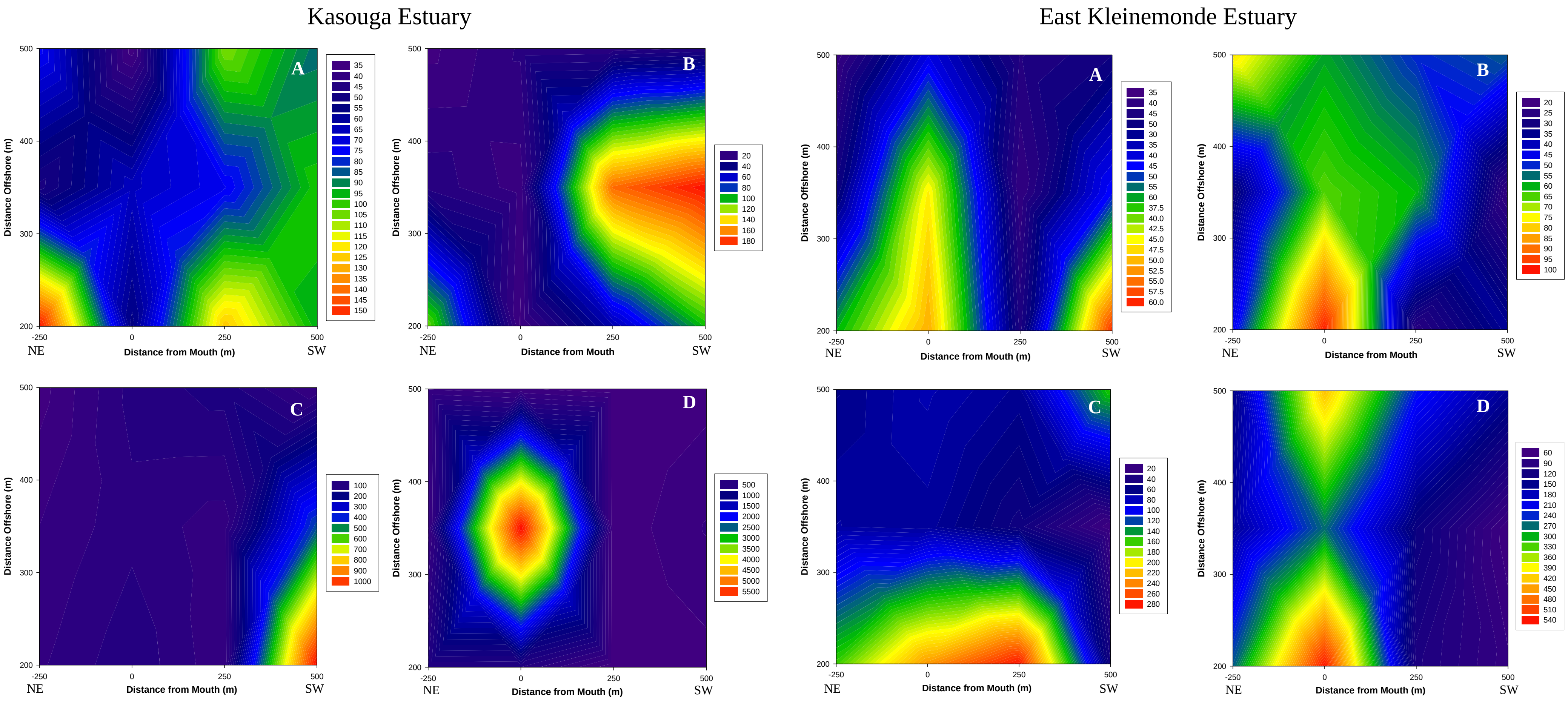


Figure 4.10: The mean zooplankton biomass (mg dwt m^{-3}) recorded in the nearshore environment adjacent to the Kasouga (left) and East Kleinemonde (right) Estuaries during the June 2005 (A), September 2005 (B), November 2005 (C) and March 2006 (D) surveys. Note the different scales on each contour plot. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

4.3.5 Zooplankton community structure and numerical analysis

Seasonal community structure

A total of 44 zooplankton species were recorded within and adjacent to the Kasouga Estuary, while 43 were sampled in and adjacent to the East Kleinemonde Estuary (see Appendix 5 for the recorded species lists). Twenty-six species were recorded within the Kasouga Estuary, while 24 were recorded in the East Kleinemonde Estuary (see Appendix 5 for the recorded species lists). All of the 26 species recorded within the Kasouga Estuary were recorded in the marine environment adjacent to this system. Similarly, all 24 species recorded within the East Kleinemonde Estuary were recorded in the marine environment adjacent to this system. The nearshore environment adjacent to the Kasouga had a higher species richness and diversity relative to the estuary during all seasons (Table 4.28). The opposite was recorded in the East Kleinemonde in terms of species richness, with the estuary having a higher richness during all seasons (Table 4.28).

Table 4.28: The total number of taxonomic groups, species diversity and species richness for the nearshore and estuarine environment during all seasons in both systems studied.

Estuary	Season	Estuary / Nearshore	Number of Species	Margalef's Species Richness	Shannon-Weiner Diversity
Kasouga	June	Estuarine	22	2.44	0.04
		Nearshore	43	7.22	2.53
	September	Estuarine	14	1.53	0.07
		Nearshore	25	4.30	1.26
	November	Estuarine	14	1.48	0.20
		Nearshore	26	4.51	1.84
	March	Estuarine	16	1.62	0.18
		Nearshore	23	2.15	1.69
East Kleinemonde	June	Estuarine	18	1.96	0.17
		Nearshore	10	1.27	0.96
	September	Estuarine	16	4.14	1.24
		Nearshore	12	1.03	0.79
	November	Estuarine	37	5.22	1.56
		Nearshore	30	3.51	1.13
	March	Estuarine	28	3.00	1.48
		Nearshore	24	2.15	1.74

A numerical analysis of each estuary and the adjacent marine stations resulted in separate groupings of estuarine and marine stations during each season. As a result the analysis presented here combines both estuaries on a seasonal basis. The different seasons resulted in similar community groupings occurring when densities from all the sites for both systems were analysed using a Bray-Curtis similarity. During the June and November surveys the separation between the marine and estuarine sites occurred at approximately 30% similarity, while during the September and March surveys the separation occurred at approximately 25% similarity and 45% similarity, respectively (Figure 4.11 to 4.14). A further separation of the marine sites into groups representing the respective estuaries occurred at approximately 60%, 50% and 40% during June, September and November, respectively (Figure 4.11 to 4.13). This separation did not occur in March, with the marine sites adjacent to the estuaries forming a mixed group (Figure 4.14). During the November survey a very different grouping was evident at the East Kleinemonde estuarine sites as they separated from all other sites at approximately 20% similarity.

The dominant groups contributing to the differences between the marine and estuarine stations were *Calanus simillimus* (9.6 to 12% of the dissimilarity during the different seasons), various copepod nauplii (8.7 to 11% of the dissimilarity during the June to November surveys) and *Oithona* sp. (8.3 to 11% dissimilarity during the September to March surveys) (Table 4.29). Four other taxonomic groups which contributed approximately 5% to the dissimilarity during various seasons were *Acartia longipatella*, various zoeae, appendicularians and *Clausocalanus* sp. (Table 4.29).

Combined community structure

A Bray-Curtis Similarity analysis of the combined data for all seasons from both systems gives a similar result to the individual seasons, with the estuarine and marine samples separating at approximately 30% similarity level (Figure 4.15). A notable exception was the Kasouga Estuary mouth sample collected during the June and March surveys, which grouped within the marine stations (Figure 4.15). The Kleinemonde Estuary sites for November grouped with three Kasouga marine stations at approximately 20% similarity, possibly due to some marine species in the East Kleinemonde mouth region due to the open mouth conditions during this season.

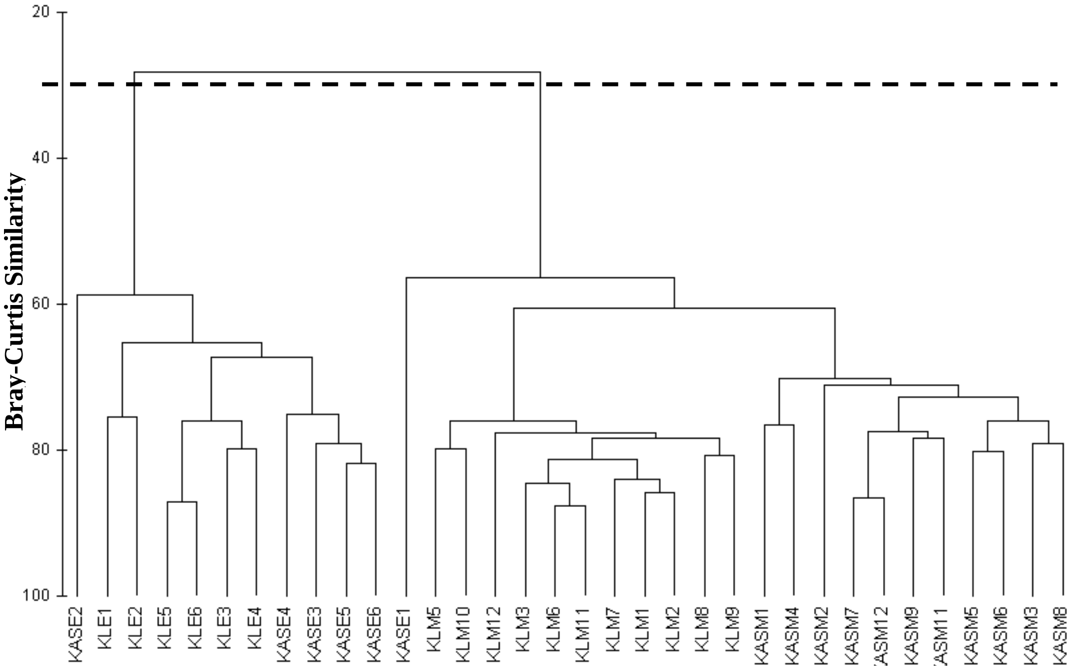


Figure 4.11: Cluster diagram showing the grouping of sites based on the zooplankton abundance data within and adjacent to the Kasouga and East Kleinemonde estuaries during the June 2005 survey. The coding of sites is a river name (KL for East Kleinemonde and KAS for Kasouga), a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line indicates a 30% similarity level.

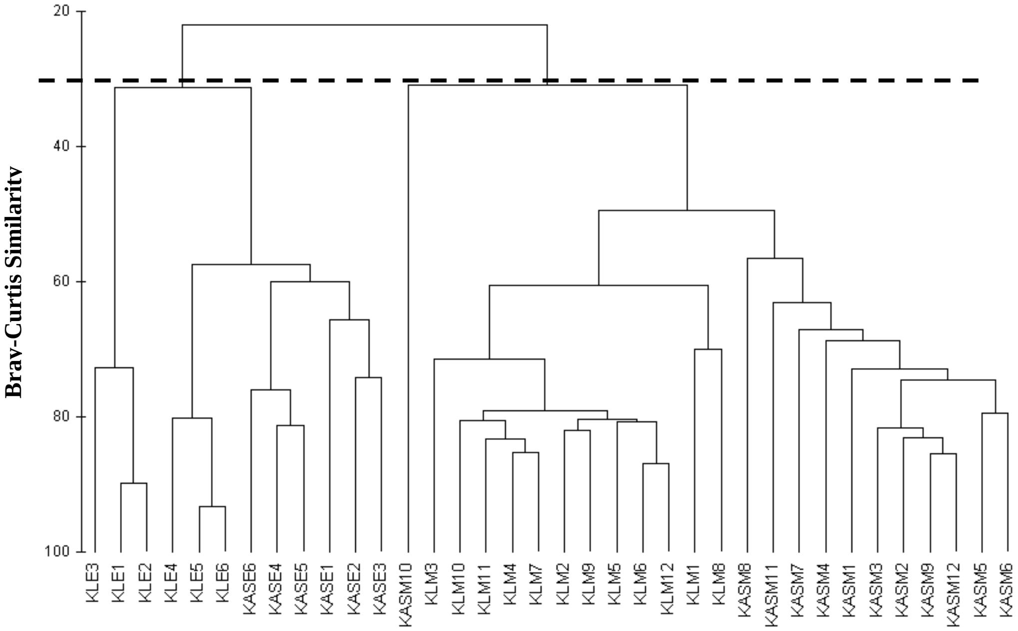


Figure 4.12: Cluster diagram showing the grouping of sites based on the zooplankton abundance data sampled within and adjacent to the Kasouga and East Kleinemonde estuaries during the September 2005 survey. The coding of sites is a river name (KL for East Kleinemonde and KAS for Kasouga), a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line indicates a 30% similarity level.

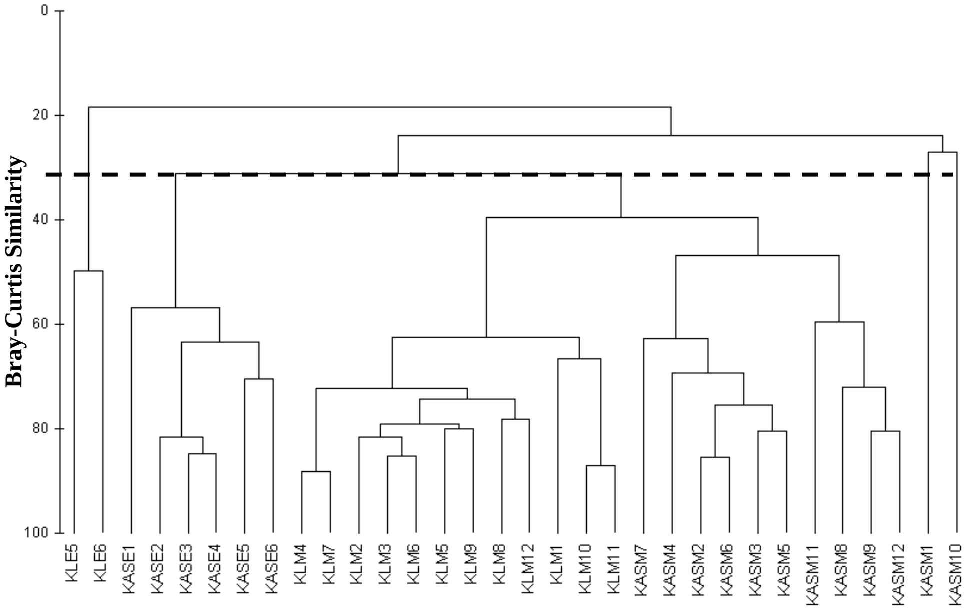


Figure 4.13: Cluster diagram showing the grouping of sites based on the zooplankton abundance data within and adjacent to the Kasouga and East Kleinemonde estuaries during the November 2005 survey. The coding of sites is a river name (KL for East Kleinemonde and KAS for Kasouga), a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line indicates a 30% similarity level.

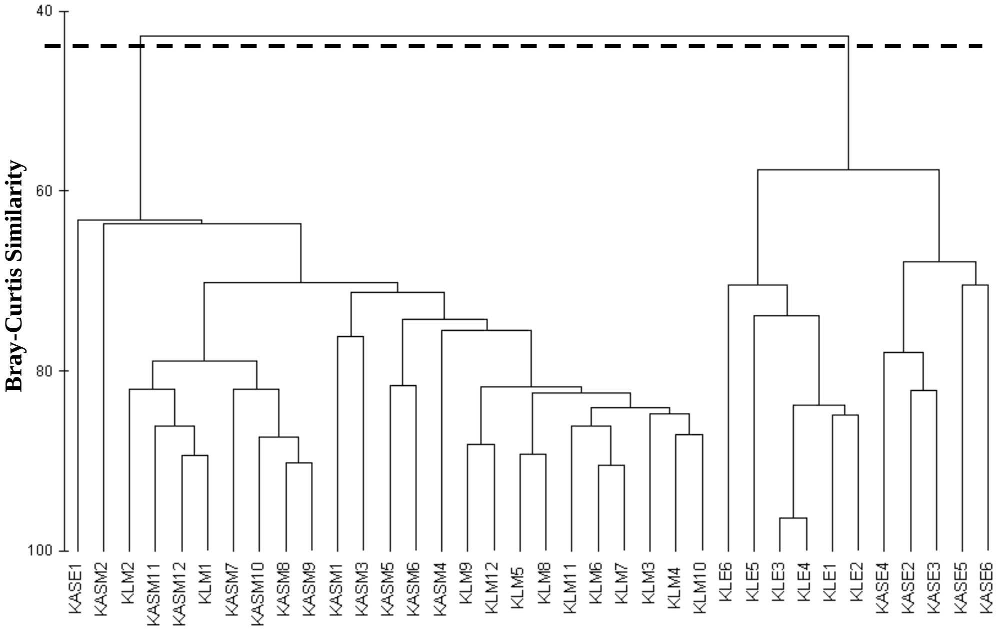


Figure 4.14: Cluster diagram showing the grouping of sites based on the zooplankton abundance data within and adjacent to the Kasouga and East Kleinemonde estuaries during the March 2006 survey. The coding of sites is a river name (KL for East Kleinemonde and KAS for Kasouga), a site number and a notation for estuarine (E) vs marine (M) stations. The dotted line indicates a 45% similarity level.

Table 4.29: The average estuarine and marine abundances and the percentage contribution to dissimilarity observed in the above cluster diagrams for the 14 highest contributing taxonomic groups. The results are from the SIMPER subroutine in PRIMER.

Species		*Calanus simillimus*	*Clausocalanus* sp.	Nauplii	*Oithona* sp.	*Acartia longipatella*	*Pseudodiaptomus hessei*	*Oncaea* sp.	Harpacticoida	Zoeae	*Temora turbinata*	*Limacina* sp.	Mussel Larvae	Barnacle Larvae	Appendicularians
June	Ave Estuarine Abundance	0.8	0.6	5580	0.0	74	1.4	0.7	18	1.6	0.1	6.5	0.3	0.2	0.0
	Ave Marine Abundance	114	44	196	0.0	1.3	0.8	19.5	20	2.3	8.0	3.7	2.9	1.3	9.5
	Percentage Contribution to Dissimilarity	9.6	7.1	8.7	0.0	6.0	1.1	5.6	3.0	1.6	4.1	2.9	2.3	1.5	4.7
September	Ave Estuarine Abundance	0.0	0.0	2703	0.1	14	6.3	0.0	2.5	3.7	0.0	39.3	0.2	0.2	0.0
	Ave Marine Abundance	1070	13.8	190	673	1.9	1.2	24	24.8	6.0	1.3	5.6	7.6	2.3	4.0
	Percentage Contribution to Dissimilarity	11.1	3.7	10.7	11.1	4.5	3.1	6.9	5.0	3.2	1.1	4.7	3.7	2.2	1.9
November	Ave Estuarine Abundance	0.2	0.0	4675	1.1	88	4.3	0.1	3.6	11.8	0.0	1.6	0.1	2.1	0.0
	Ave Marine Abundance	969	17.9	2118	345	360	1.5	43	84	12.7	5.1	29.6	4.2	23	21.3
	Percentage Contribution to Dissimilarity	10.0	3.1	11.0	8.3	7.3	2.6	4.8	4.1	5.5	1.7	3.9	2.2	3.9	3.7
March	Ave Estuarine Abundance	13	11	16981	24.4	9179	3.9	0.0	54	1.5	0.0	0.0	390	3.1	0.0
	Ave Marine Abundance	6833	2269	4063	8764	5305	343	0.0	77	171	1.4	14	14	6.0	299
	Percentage Contribution to Dissimilarity	11.9	11.4	2.7	11.2	6.2	6.4	0.0	2.8	6.7	0.3	2.4	5.1	1.7	6.7

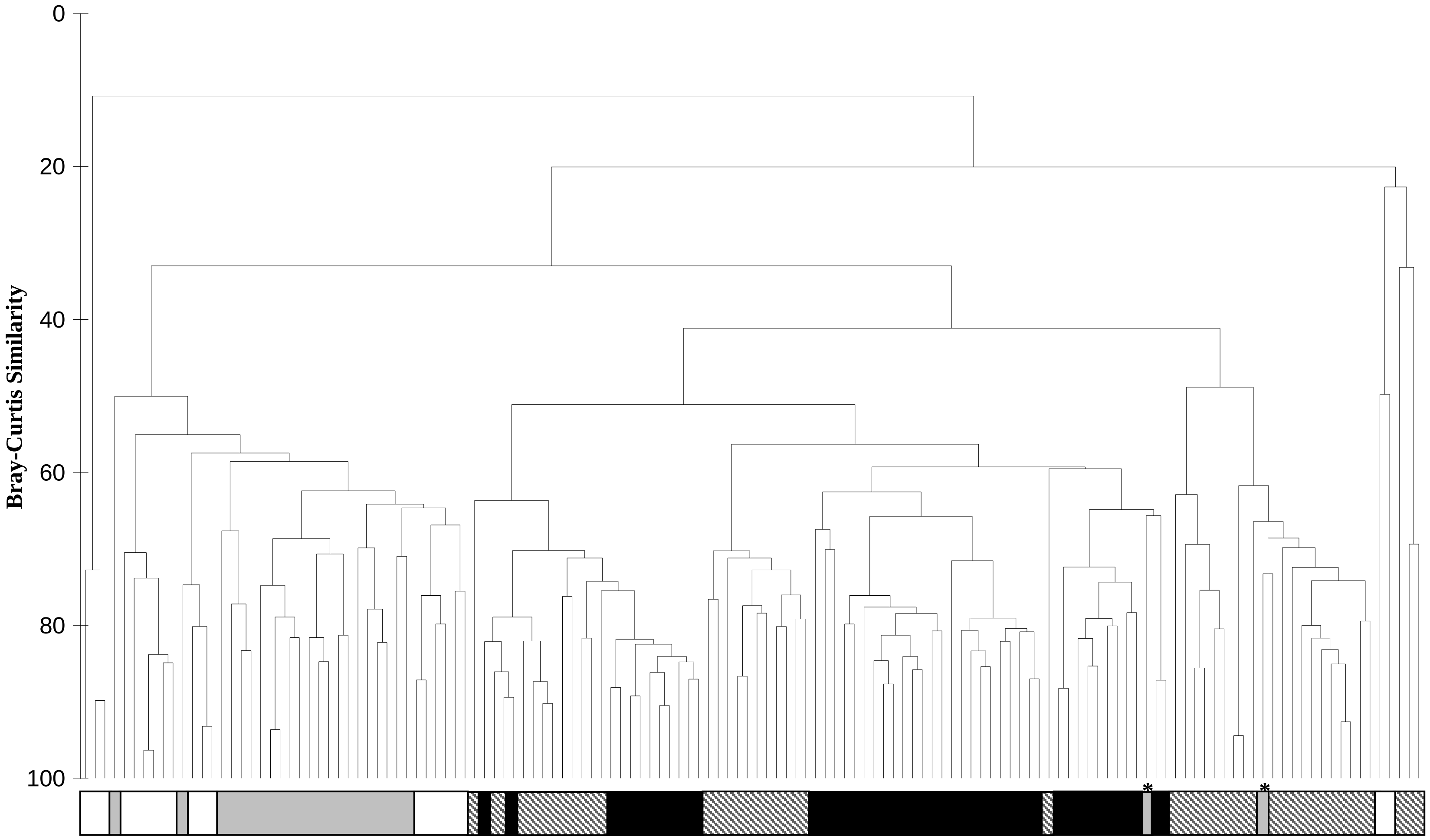


Figure 4.15: Cluster diagram representing all samples from all seasons on both estuaries. White squares indicate East Kleinemonde estuarine samples, black indicates East Kleinemonde nearshore samples, light grey indicates Kasouga estuarine samples, while hatched lines indicate Kasouga nearshore samples. * denotes estuarine samples within a marine grouping.

4.4 DISCUSSION

This study assessed the influence of two temporarily open/closed estuaries (TOCEs) on the adjacent marine environment. Although the two estuaries are similar in size, the mouth status of the two systems differed with the East Kleinemonde breaching in November 2005, while the Kasouga Estuary was separated from the marine environment throughout the study. Overtopping events were recorded in both systems during March 2006 and during November 2005 in the Kasouga. The observed difference in mouth status between the two systems is in agreement with the published literature. Bell *et al.* (2001) suggested that the East Kleinemonde Estuary breached on average 12% of the time over a period of 26 months, while the Kasouga Estuary has reportedly been separated from the marine environment for periods of up to 21 months (Froneman, 2002a and c). The differences in the mouth status of the two systems can be related to a variety of factors including the extent of the sand bar that separates the estuary from the marine environment, catchment size and the land use patterns.

The majority of sampling transects in the marine survey grid were established to the south-west of the mouths of both estuaries due to the prevailing wind speed and direction (Appendix 1, Tables A1.3 and A1.4). The wind patterns were consistently southerly or easterly (blowing towards the north or west) at the time of sampling, and in combination with the south-westerly longshore swash and surfzone currents resulted in the described establishment of the survey grids. This does not preclude the current direction from alternating and turning towards the north-east, however, this situation did not materialise at the time of sampling.

A key characteristic of both systems was the absence of marked horizontal gradients in salinity and temperature within the two estuaries (Figures 4.2 and 4.3). Notable exceptions were recorded in November 2005 and March 2006 in the East Kleinemonde Estuary (Figure 4.2 and 4.3). The presence of the gradients during these months could be attributed to a combination of higher rainfall in the catchment area and the open mouth conditions, which are correlated with higher fresh water inflow into the estuary. The absence of any notable horizontal gradients in salinity and temperature within Eastern Cape TOCEs is now well documented and can be related to, amongst others, small catchment size, which limits fresh water inflow into the estuaries, and strong coastal winds that facilitate both the horizontal and vertical mixing of water within these systems (Cowley and Whitfield, 2001; Froneman, 2002a; Tweddle, 2004; Bernard and Froneman, 2005; Lukey *et al.*, 2006). The extent of the wind induced mixing is exacerbated by the shallow depth and large surface areas of many of these estuaries (Froneman, 2002c). The observed seasonal trends in temperature within the two estuaries is consistent with the published literature (Vorwerk *et al.*, 2001; Froneman, 2004a; Bernard and Froneman, 2005; Lukey *et al.*, 2006). An exception was recorded in November 2005 within the East Kleinemonde Estuary, which could be ascribed to the breaching event that was associated with the inflow of cooler marine waters into the estuary. Variations in salinity did not follow any seasonal patterns.

The total chl-a concentrations and zooplankton abundance and biomass values recorded within both estuaries during this study are in the range reported for TOCEs within the same region (Wooldridge, 1999; Froneman, 2002a and c; Tweddle, 2004; Gama *et al.*, 2005) and indeed for TOCEs in other regions of southern Africa (Perissinotto *et al.*, 2000; Walker *et al.*, 2001; Nozias *et al.*, 2001; Perissinotto *et al.*, 2003). The values are, however, considerably less than those recorded in the Mhlanga and Mdloti estuaries along the east coast of southern Africa (Kibirige *et al.*, 2006). In these systems total chl-a concentrations and zooplankton biomass values may exceed 100mg chl-*a* m^{-3} and 100mg dwt m^{-3}, respectively (Kibirige *et al.*, 2006). The elevated chl-a concentrations and zooplankton biomass values recorded in these estuaries are the result of discharge of effluent into these systems that provides a continuous supply of nutrients.

The importance of fresh water inflow into estuaries in promoting the growth of phytoplankton is now well documented (Adams *et al.*, 1999; Froneman, 2002c). During the present study, total chl-a concentrations in both estuaries attained the highest levels when reduced salinities were evident (i.e. high flow conditions within the catchment areas) (Figure 4.6). A similar result was observed by Gobler *et al.* (2005), who recorded an increase in chl-a in the Mecox Bay Estuary (Long Island) during the closed phase and large reductions in the chl-a concentration upon opening of the inlet. In agreement with a number of previous studies (see for example:

Perissinotto *et al.*, 2000; Froneman, 2002c; Kibirige and Perissinotto, 2003; Froneman, 2004b), the total zooplankton biomass followed similar trends to that of the total chl-a with the highest values recorded during those periods of fresh water inflow into the two estuaries (Figure 4.9). The increase in the total zooplankton abundance and biomass following rainfall is thought to be the result of increased food availability (phytoplankton) (Froneman, 2004a).

The breaching event that occurred in the East Kleinemonde Estuary during November 2005 was associated with a significant decrease in the total chl-a concentrations and the zooplankton abundance and biomass values ($p<0.05$ in all cases). These observed decreases in the chl-a concentrations and zooplankton abundance and biomass following the breaching event is consistent with studies conducted within the same geographic region (Wooldridge and Erasmus, 1980; Perissinotto *et al.*, 2000; Walker *et al.*, 2001; Froneman, 2002a; Froneman, 2004a; Kibirige *et al.*, 2006) and is thought to be the result of the outflow of the biomass rich estuarine waters into the marine environment.

In the marine environment adjacent to both estuaries the possibility of bias in the particulate organic matter (POM) concentrations at the inshore marine stations exists due to wave action at these sites. However, as recorded in the contour plots the only occasion were the inshore sites maintained the highest POM concentrations along the length of the coast sampled was adjacent to the Kasouga in June 2005.

In agreement with the study conducted in the sea adjacent to the fresh water deprived Kariega Estuary within the same geographic region (Chapter 3), the salinities and temperatures in the marine environment adjacent to the two TOCEs demonstrated no clear vertical stratification during the four surveys (Appendix 4, Figures A4.1 – A4.4, A4.5 – A4.8). The marine water temperatures exhibited an expected seasonal pattern with the highest values recorded in summer and the lowest in winter. A consistent spatial pattern in both salinity and temperature was observed within the marine environment, with the lowest values recorded immediately adjacent to or upstream of the mouths of the two TOCEs. The presence of this lower salinity water in the sea adjacent to both TOC systems suggests an unidentified source of fresher water. A previous study conducted in the Alexandria dune fields located some 100km south-west of the study estuaries, demonstrated that fresh water is discharged from the dunes into the sea at a rate of ≈1m^3 per running metre of the beach per day (McLachlan and Illenberger, 1985; Campbell and Bate, 1998). Due to the moderately-sized dunefields surrounding the study estuaries it is likely that the less saline water observed in the marine environment adjacent to the estuaries was derived from a combination of seepage of water through the sandbars that separate the systems from the sea and groundwater from the surrounding dunefields. Unfortunately, there are no data available to establish the exact source of the lower saline water observed adjacent to the mouth of the estuaries.

The spatial patterns in delta σ_t values adjacent to the Kasouga Estuary did not correspond to the observed salinities (Figures 4.2 and 4.4) with limited evidence of any density variations in the region opposite the mouth or upstream (relative to the Agulhas Current) of the mouth. Adjacent to the East Kleinemonde the observed spatial pattern in delta σ_t values did show moderate stratification near the mouth of the estuaries during June, September and November (Figure 4.4). The spatial pattern during June and November was likely a result of groundwater seepage as well as estuarine water seepage through the berm of the system. During September the more extensive low density plume adjacent to the East Kleinemonde Estuary was a result of fresh water outflow through the open mouth of the estuary.

The total chl-a concentrations and zooplankton abundance and biomass values within the marine environments adjacent to the two estuaries did not demonstrate any clear stratification (Appendix 4, Figures A4.13 – A4.16; Figures 4.7, 4.9, 4.15 and 4.17). Similarly to the physico-chemical variables, a region of increased total chl-a concentration and zooplankton biomass was observed in the seawaters adjacent to the mouth of the East Kleinemonde Estuary. This trend was amplified following the November breaching event, with the higher zooplankton biomass and density extending further downstream in the inshore area. The observed spatial pattern in the biology appears largely to be in response to the low salinity, higher nutrient content waters which would likely promote the growth of marine phytoplankton (Campbell and Bate, 1998; Adams *et al.*, 1999). The mechanisms responsible for generating and retaining these patterns in the biology are not clear, although it is likely to be similar to those described for large estuarine fronts opposite permanently open systems (Chapter 3; Largier, 1993). The accumulations of zooplankton appear to be a response to increased phytoplankton productivity resulting from nutrient rich fresh water entering the marine environment (Largier, 1993).

The results of the numerical analyses conducted with the zooplankton abundance data indicated that the zooplankton communities within the two estuaries and the adjacent marine environments were distinct from one another (Figures 4.11 – 4.15). This clear separation is not surprising in light of the fact that the two environments were separated from one another by the presence of a sandbar at the mouth. The breaching event that was observed within the East Kleinemonde Estuary during November 2005, resulted in a greater separation between the estuarine and marine zooplankton groupings despite the fact that a link was established between the estuary and the sea (Figure 4.13). The clear separation between the marine and estuarine grouping during November 2005 was largely the result of dramatic decrease in the zooplankton abundance values within the estuary, which could be ascribed to the outflow of estuarine waters with high plankton biomass into the sea following the breaching event (see above). Although Froneman (2004a) demonstrated that the inflow of seawater into TOCEs during overtopping events coincided with a shift in the zooplankton community from an estuarine to a more marine dominated plankton community, this pattern was not evident during the present study. Overtopping events were, however, associated with increases in zooplankton biomass and density at stations occupied near the mouth of both estuaries (Figures 4.7 and 4.9).

4.4.1 Conclusions

It is interesting to note that along this short stretch of coastline (≈200km) Whitfield (2000) recorded 27 TOCEs, which often breach simultaneously in response to large rainfall events (*pers. obs.*). The combined effect of this large pulse of biomass into the marine environment is unknown at this stage, but can only be assumed to contribute to enhanced biological activity in the nearshore marine environment. Lukey *et al.* (2006) discussed similar trends when examining the fish population of the Grants Valley Estuary, which occurs within the same region. Lukey *et al.* (2006) described a large build-up of ichthyofaunal biomass within the estuary during the closed phase, which would subsequently be released to the marine environment upon breaching.

The marine environment adjacent to estuaries showed evidence of an estuarine or groundwater influence on salinities and temperature directly adjacent to the estuary. In addition, a biological response, in terms of the chlorophyll-a concentrations and zooplankton biomass, was observed in the marine environment adjacent to the East Kleinemonde Estuary during all seasons, even when the mouth was closed. The marine environment adjacent to the Kasouga did not indicate the same trends, with a reduced biological response in the nearshore adjacent to this system. The geographic extent of the influence of these estuaries was also shown to differ depending on the mouth status of the respective estuary, with a greater biological response evident opposite the mouth of the East Kleinemonde during the open phase.

The observed response adjacent to the East Kleinemonde was likely due to seepage water from the estuary channel or adjacent groundwater sources and was magnified during the recorded breaching event. Rainfall, fresh water flow into the estuary and seepage are inextricably linked, with the volume of seepage from both the estuary channel and groundwater sources reliant on the gravitational head of water. Chlorophyll-*a* concentrations and zooplankton biomass and density appear related to the peaks in rainfall recorded prior to June and November although they do not correlate statistically ($P>0.05$). The predicted relationship is one of increased chlorophyll-*a* concentrations and zooplankton biomass in the nearshore adjacent to an estuary as the rainfall or fresh water inflow into the estuary and therefore the seepage from the system and surrounding groundwater sources increases (Figure 4.16).

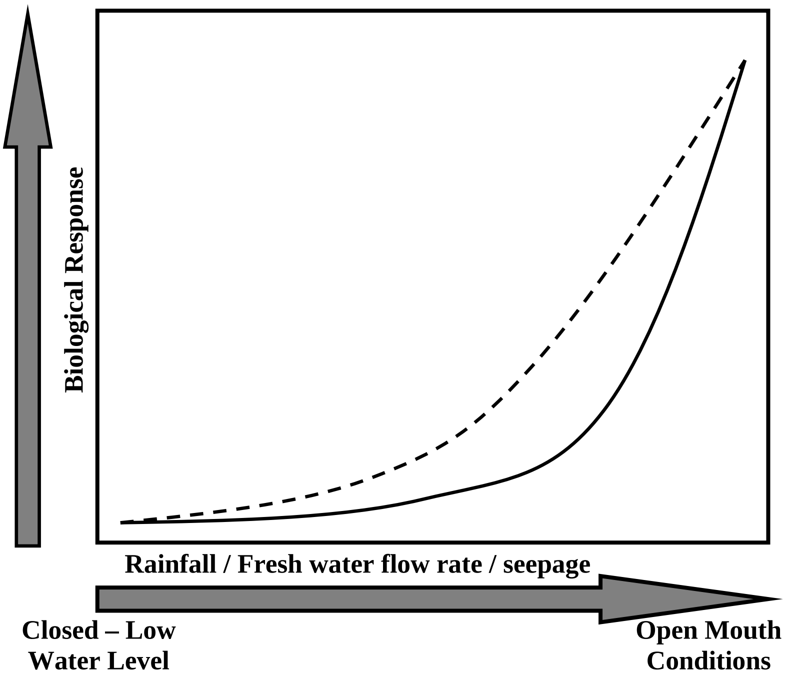


Figure 4.16: Stylised relationship between biological response in the nearshore marine environment adjacent to the East Kleinemonde Estuary and the related variables of rainfall, fresh water flow rate, seepage and mouth conditions. The dashed line indicates chlorophyll-*a* response and the solid line indicates zooplankton response.

CHAPTER 5

THE IMPORTANCE OF ESTUARINE DERIVED CARBON FOR THE NEARSHORE MARINE ENVIRONMENT: A STABLE CARBON ISOTOPE APPROACH ON TWO PERMANENTLY OPEN EASTERN CAPE ESTUARIES

5.1 INTRODUCTION

The use of stable isotopes as a means of determining various ecological pathways in both terrestrial and aquatic systems has gained prominence since the 1970's (Peterson and Fry, 1987). Stable isotopes of many elements occur in differing amounts in the natural environment, forming a very small part of the global pool of an element and being slightly atomically heavier due to additional neutrons on the isotopic atoms (Robinson, 2001). Due to the different atomic weights, isotopes behave differently in biogeochemical processes relative to the normal elements and are preferentially retained by an organism (Peterson and Fry, 1987). The elements most commonly used to trace food webs and food sources are carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). These elements are considered light isotopes and the proportion of $\delta^{15}N$ and $\delta^{13}C$ in biological tissues is influenced by biological processes (Rubenstein and Hobson, 2004). All of these isotopes in consumer tissues reflect the isotope ratio in their food sources with some degree of enrichment by trophic level and are therefore useful tracers of food webs.

5.1.1 Derivation of isotopes

Different biological and biogeochemical factors influence the natural abundance of the different isotopes (Michener and Schell, 1994). For example ^{13}C abundance is influenced by the type of photosynthetic pathway, whether C_3, C_4 or CAM, while ^{15}N abundance is influenced by the means of nitrogen fixation, whether by a symbiotic bacteria or directly from the atmosphere (Rubenstein and Hobson, 2004). Additionally, in the different environments, i.e. terrestrial, marine and to a degree estuarine, different factors influence the different elements' isotope ratios. In the terrestrial environment, mesic habitats are more enriched in ^{13}C and ^{15}N than xeric habitats if the C_3 photosynthetic pathway is employed (Rubenstein and Hobson, 2004). Similarly in the marine and estuarine environments, benthic sources are more enriched in ^{13}C than pelagic sources.

5.1.2 Potential problems and pitfalls in stable isotope analysis

Stable isotope analysis is not a completely flawless method of tracing organic pathways, but if knowledge of the potential flaws is considered this method becomes a highly useful tool for ecological analyses. Some of the potential pitfalls include differential uptake of isotopes by different tissue types (e.g. lipid versus muscle), the collection and storage of isotope samples prior to analysis (Hobson *et al.*, 1997) and the requirement to identify all potential food sources for an accurate analysis (Fry and Sherr, 1984). The necessity for identifying all potential sources of isotopes is due to the potential to misinterpret the resultant data if a limited number of sources are known (Fry and Sherr, 1984).

An additional potential pitfall with isotope analysis is the possibility of fractionation by different tissues and metabolites, such as lipids relative to muscle or bone (Michener and Schell, 1994). For many animal groups, the preferred tissue which is most representative of the organisms diet can be found in the scientific literature as laboratory studies on this phenomenon have been carried out (DeNiro and Epstein, 1978; Fry and Sherr, 1984; Peterson and Fry, 1987). This problem arises due to biochemical fractionation after the consumer has digested its food source, with the most significant problem being that of preferential uptake of ^{15}N and ^{13}C by lipids within consumers (Peterson and Fry, 1987). An example is that reported by Pinnegar and Polunin (1999), who observed a significant difference in $\delta^{13}C$ and $\delta^{15}N$ of tissues of juvenile trout that still contained lipids. However, after lipid removal these tissues were statistically indistinguishable in terms of $\delta^{13}C$ and $\delta^{15}N$ content. In contrast, DeNiro and Epstein (1978) reported that experimenting with different tissues and biochemical fractions indicated that whole animal isotope analysis provided a more accurate means of identifying the $\delta^{13}C$ and $\delta^{15}N$ of the animal and its diet.

Sample preservation and storage is an additional potential source of error for stable carbon and nitrogen isotope analysis. Hobson *et al.* (1997) carried out an investigation looking at a variety of storage media and techniques and identified the most accurate methods being that of immediate freezing or if this is not possible then storage in 70%

ethanol. Due to the relatively short duration of day trips and the accessibility of liquid nitrogen and dry ice, this should not be a complication for the current study.

5.1.3 Stable isotope uses

The use of stable isotopes in the aquatic, and particularly the marine environment, has mostly been directed at describing food webs and tracing food sources. There are several examples of research articles using isotopes for this in both estuaries (Kwak and Zedler, 1997; Chong *et al.*, 2001; Bouillon *et al.*, 2002) and the marine environment (Davenport and Bax, 2002; Mutchler *et al.*, 2004; Schmidt *et al.*, 2004). Other uses include the tracing of pollutants (McClelland *et al.*, 1997; Morrissey *et al.*, 2004) and if using other stable isotopes such as strontium and oxygen, authors have been able to establish the different temperatures and salinities that fish have moved through by analysing their otoliths (Elsdon and Gillanders, 2002; Martin *et al.*, 2004).

The use of stable isotopes in South African estuarine research is a relatively new tool, with only a handful of researchers having employed this technique to assess trophic relationships within these food webs. Jerling and Wooldridge (1995) employed stable isotopes to identify the carbon sources used by mesozooplankton (mainly copepods) in the permanently open Sundays River Estuary on the south-east coast of southern Africa. Paterson and Whitfield (1997) similarly used stable carbon isotopes as a tool for identifying the food web structure in the permanently open Kariega Estuary in the same region. Their efforts were, however, concentrated on the ichthyofauna. Several authors have subsequently used carbon and nitrogen stable isotopes as a means of assessing trophic pathways within the plankton communities of a variety of estuaries (Schlacher and Wooldridge, 1996b; Froneman, 2001b; Froneman, 2002a; Kibirige *et al.*, 2002; Perissinotto *et al.*, 2003). To date no studies have used stable carbon isotopes to examine the biotic links between estuaries and the marine environment in southern Africa.

Several authors have hypothesised that due to the direction of water flow through estuaries into the marine environment, the bulk of estuarine productivity and biota are exported from these systems into the adjacent marine environment (Odum, 1980; Dame and Allen, 1996; Roegner and Shanks, 2001). This hypothesis suggests that the food webs in the marine environment adjacent to estuaries will be driven by estuarine derived productivity and biotic material rather than autochthonous marine sources.

This study was conducted within, and adjacent to, two permanently open estuaries with contrasting fresh water flow regimes along the south-eastern coast of South Africa. The two estuaries studied were the fresh water dominated Great Fish Estuary (see 2.2.1 in Chapter Two for details) and the marine dominated Kariega Estuary, which is fresh water deprived (see 2.2.2 in Chapter Two for details). The aim of the study was to assess the importance of estuarine derived carbon to the nearshore marine ecosystem and highlight any differences in the estuaries resulting from altered flow regimes.

5.2 MATERIALS AND METHODS

5.2.1 Sample collection

Due to the continuous recycling of nitrogen within estuarine ecosystems, this study only focused on carbon stable isotopes (Fry and Sherr, 1984; Peterson and Fry, 1987; Mutchler *et al.*, 2004). The study was conducted in autumn to minimise any possible seasonal effects on the isotope signatures of the biota. Sampling of various vegetation types (three replicates per vegetation type), particulate organic matter (POM) and zooplankton was undertaken to obtain carbon stable isotope signatures for the dominant components of the estuarine and marine biota in these groups. In both the Kariega and Great Fish estuaries, three replicate samples were taken at three stations within each of the upper and lower reaches. The upper reaches corresponded to the upper half of the estuary, above the direct influence of seawater, while the lower reaches corresponded to the bottom half of the estuary where seawater exchange occasionally occurred. In the adjacent marine environment five replicate samples were taken at each interval along the coast from the estuary mouth downstream relative to the Agulhas Current (Figure 5.1).

The vegetation sampled included the dominant riparian vegetation in each estuary as well as salt marsh vegetation and submerged macrophytes. All vegetation samples were washed in distilled water or GF/F filtered estuarine water (depending on origin) to remove any excess salts. The collection of POM samples involved returning five litres of estuarine or marine water for each replicate to the laboratory for subsequent filtering through precombusted (500ºC) GF/F filters and removing of any faunal matter manually using a dissecting microscope.

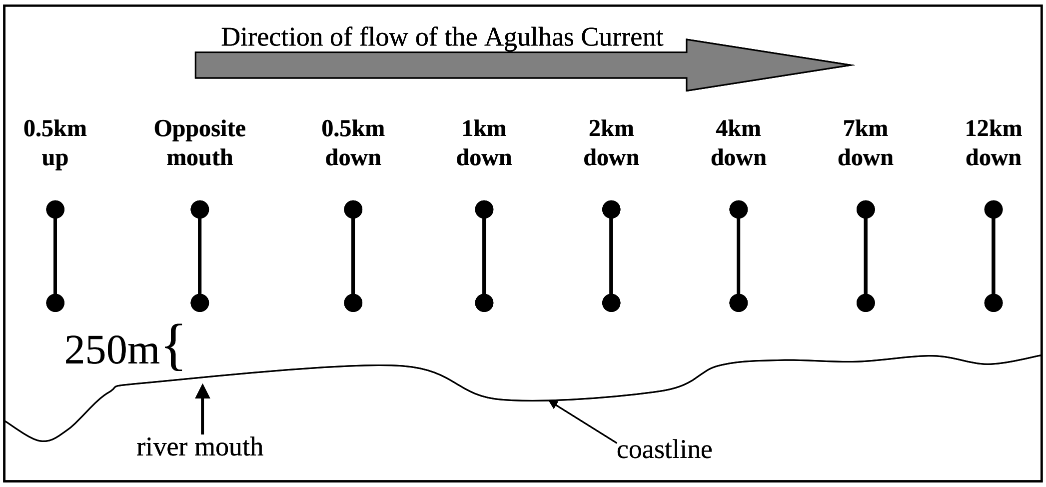


Figure 5.1: A stylised diagram of the sampling stations in the adjacent marine environment. The notation of “up” or “down” indicates each transect’s position relative to the estuary mouth and the Agulhas Current. Adjacent to the Kariega Estuary stations were only occupied for 4km downstream of the mouth.

Filter feeders, either unidentified sponges or *Pyura stolonifera* (Heller, 1878) (red bait), were collected in the marine environment adjacent to the two estuaries by free-diving the samples off rocky reefs. Both sponges and *P. stolonifera* samples were used, as neither type of animal was available at all sites. The range of isotope values for animals from both groups from closely related stations showed no significant difference. For the *P. stolonifera* samples body muscle tissue was utilised for the sample. The collection of different taxon was necessitated as any individual taxon did not occur on all the reefs at the different distances from the estuary mouth. These samples were frozen and transported to the laboratory. Zooplankton were collected from all sites during the day in a series of surface tows using a WP-2 net (0.17m^2 mouth area) with a mesh size of 60µm. Samples were immediately frozen and returned to the laboratory for separation into taxonomic groups. Individual zooplankters were combined (±500 individuals for the copepods and ±10individuals for the mysids) to provide sufficient dry weight to allow stable isotope analysis.

5.2.2 Sample preparation

All samples were oven dried at 60ºC for a period of 24hrs. Subsequent to drying, all zooplankton and filter feeder samples were defatted in a solution of chloroform, methanol and water (2:1:0.8) according to the method of Bligh and Dyer (1959). This process was carried out to remove any isotope variations that may have resulted from differences in the proportions of fatty acids within the fauna (Peterson and Fry, 1987; Gannes *et al.*, 1997). All samples were again oven dried for 24hrs at 60ºC prior to being ground in a mortar and pestle.

5.2.3 Stable isotope analysis

Sample analysis was conducted in an online Carlo-Erba NA1500 preparation unit and $\delta^{13}C$ determination was performed in a MAT 252 stable light isotope mass spectrometer in the Department of Archaeology at the University of Cape Town, South Africa. Merck gelatine was used as an internal standard, calibrated against several IAEA reference materials. The results were expressed as $\delta^{13}C$ signatures in units of parts per thousand (‰) relative to the Pee Dee Belemnite solution using the following formula (Peterson and Fry, 1987):

$$\delta X = \left(\left[\frac{R_{sample}}{R_{standard}} \right] - 1 \right) \times 1000$$

where x = element concerned (in this case carbon) and *R* = ratio of the heavy over the light isotope (^{13}C:^{12}C).

A two source mixing model (Phillips and Gregg, 2001) was utilised to attempt to identify the particulate organic matter (POM) source being fed on by the filter feeders and zooplankton directly adjacent to the mouths of the two estuaries as well as the contribution of estuarine and upstream POM to that adjacent to the estuary mouth. The inputs were the mean δ13C ratios (and standard deviations) of the sources and the consumers or derived POM. The assumption with this mixing model is that the two sources provided are the only ones being utilised by the consumers.

5.2.4 Statistical analysis

The post hoc Tukey Test was performed to identify whether there were any significant differences in the isotopic signatures at different locations within the different biotic groups. The Statistica software package (Statsoft, Inc., 2004) was used to conduct the analysis.

5.3 RESULTS

5.3.1 The Kariega Estuary and adjacent marine environment

Primary producers and particulate organic matter (POM)

The riparian vegetation sampled demonstrated a δ^{13}C ratio of between -28.05‰ and -21.07‰, while the salt marsh and littoral vegetation covered a greater range from -29.97‰ to -14.29‰ (Figure 5.2 and Table 5.1). The most depleted δ^{13}C signatures were recorded for the salt marsh plant *Sarcocornia perennis* (Mill. Scott, 1978) (-29.97‰) and the riparian plant *Sideroxylon inerme* (Linaeus, 1753) (-28.05‰). The most enriched signatures were recorded for the eelgrass, *Zostera capensis* (Setchell) (-16.88‰), and salt marsh plant, *Sporobolus virginicus* (Kunth, 1829) (-14.29‰) (Table 5.1 and Figure 5.2). A post hoc Tukey Test resulted in two major groupings, the first including all the riparian vegetation and the salt marsh *Chenolea diffusa*, while the second group comprised the salt marsh and littoral plants, with the exclusion of the highly depleted *S. perennis* and moderately depleted *C. diffusa*.

Table 5.1: δ^{13}C values (‰) of the primary producers collected from the Kariega Estuary in April 2005. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 8).

Species	Habitat Type	Mean δ^{13}C	St Dev.	Maximum	Minimum	Grouping according to Tukey Test
Sarcocornia perennis	Salt marsh	-29.97	1.50	-28.91	-31.03	A
Sideroxylon inerme	Riparian	-28.05	0.25	-27.87	-28.22	C
Sporobolus virginicus	Salt marsh	-14.29	0.92	-13.64	-14.94	D
Rhus sp.	Riparian	-27.11	1.19	-26.26	-27.95	C
Chenolea diffusa	Salt marsh	-26.70	1.27	-25.80	-27.59	BC
Schotia affra	Riparian	-26.12	0.72	-25.61	-26.63	C
Portulacaria affra	Riparian	-21.07		-21.07	-21.07	CD
Spartina maritima	Salt marsh	-24.28	0.82	-23.70	-24.86	D
Zostera capensis	Littoral	-16.88	1.33	-15.94	-17.83	D

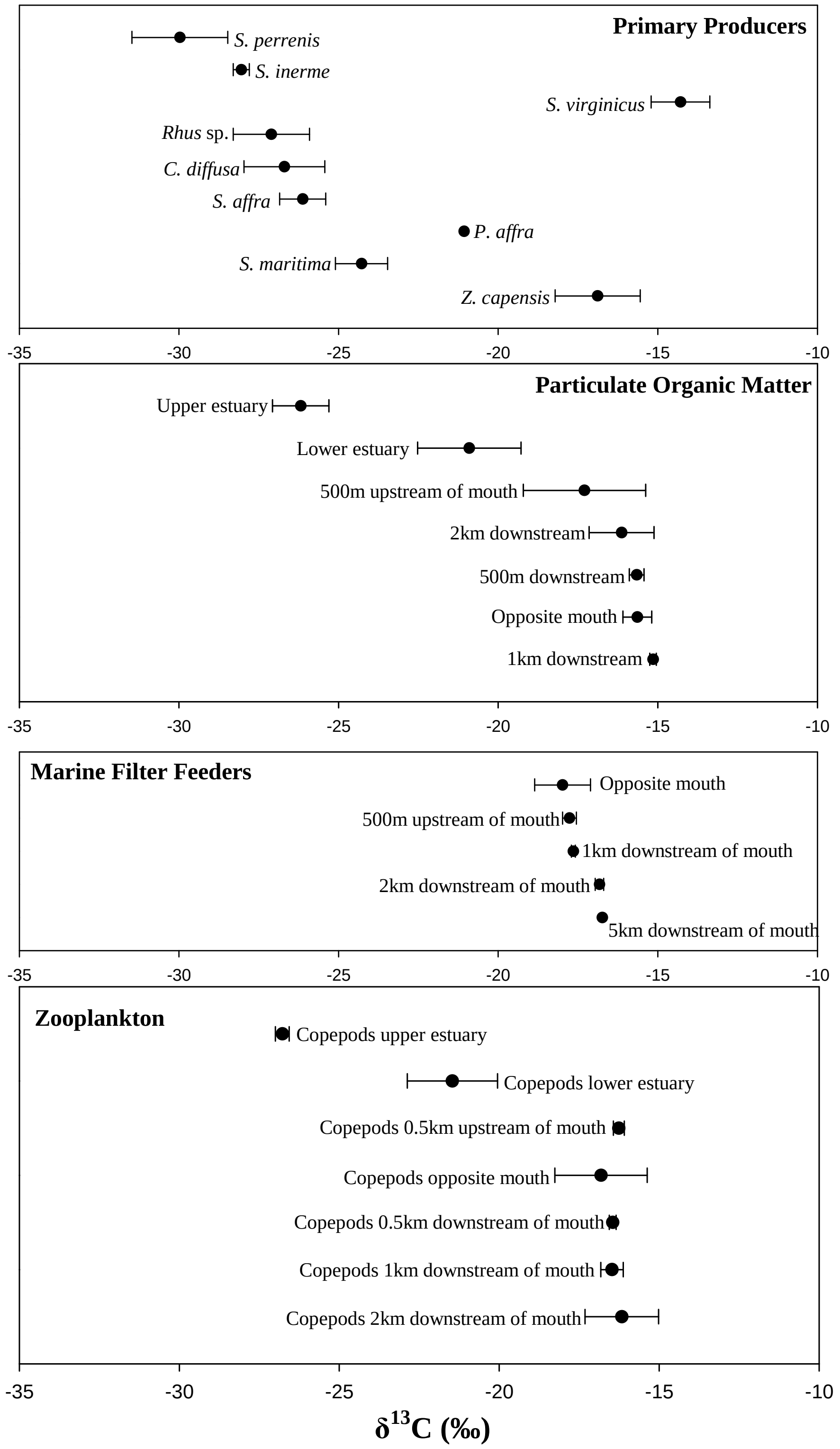


Figure 5.2: The δ^{13}C (‰) ratios and standard error for the primary producers, POM, marine filter feeders (sponges and *P. stolonifera*) and zooplankton collected from the Kariega Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with distances upstream (east) and downstream (west) of the estuary mouth relative to the Agulhas Current.

The $\delta^{13}C$ signature of the particulate organic matter (POM) in the estuary was dependent on the reach, with the upper reaches' POM signatures being more depleted (-26.19‰) than the lower reaches (-20.90‰) (Figure 5.2 and Table 5.2). The $\delta^{13}C$ ratios for the POM from the adjacent marine environment were more enriched than that from the estuary, ranging from -15.15‰ near the mouth to -17.30‰ upstream of the mouth (Table 5.2). The POM signatures in close proximity to the estuary mouth (opposite and within 1km downstream) were more enriched than the POM signatures upstream of the mouth and further downstream (2km) (Figure 5.2). The $\delta^{13}C$ signatures for the upper estuarine POM were significantly different ($p<0.01$; df = 10) from all other samples, while the $\delta^{13}C$ ratios of the lower estuary POM grouped with the sites upstream of the estuary mouth. The post hoc Tukey Test resulted in a final grouping of $\delta^{13}C$ signatures for the POMs of all the marine stations (Table 5.2). Mixing models demonstrated that the POM opposite the Kariega Estuary mouth was almost entirely derived from the POM in the adjacent marine environment (100% ±0.47SE).

Consumers (zooplankton and filter feeders)

The marine filter feeders collected were either *P. stolonifera* (red bait) or an unidentified sponge species. A post hoc Tukey Test identified two significantly different groupings, with the $\delta^{13}C$ ratios of the filter feeders near the estuary mouth being more depleted than those further along the coast (Table 5.3). This was confirmed by a trend of increased enrichment with increased distance from the estuary (Figure 5.2).

The $\delta^{13}C$ ratios for the copepods (predominantly *Calanus agulhensis* and *Clausocalanus* sp.) ranged from highly depleted in the upper reaches of the estuary (-26.78‰) to moderately depleted values in the lower reaches of the system (-21.46‰). In the marine environment the $\delta^{13}C$ signatures of the copepods were moderately enriched and ranged from -16.26‰ to -16.82‰ (Table 5.4 and Figure 5.2). A Tukey Test identified two significantly different groups, the estuarine copepods and the marine copepods (Table 5.4).

Table 5.2: $\delta^{13}C$ ratios (‰) of the POM collected from the Kariega Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with a distance up or downstream of the mouth, which is relative to the Agulhas Current. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 10).

Location	Mean $\delta^{13}C$	St Dev.	Maximum	Minimum	Grouping according to Tukey Test
Upper Estuary	-26.19	0.88	-25.56	-26.81	A
Lower Estuary	-20.90	1.62	-19.76	-22.05	B
0.5km upstream of mouth	-17.30	1.92	-16.00	-19.50	BC
Opposite mouth	-15.64	0.45	-15.14	-16.01	C
0.5km downstream of mouth	-15.66	0.23	-15.40	-15.84	C
1km downstream of mouth	-15.15	0.10	-15.07	-15.22	C
2km downstream of mouth	-16.13	1.02	-15.34	-17.28	C

Table 5.3: $\delta^{13}C$ values (‰) of the filter feeders (sponges and *P. stolonifera*) collected from the Kariega Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with a distance up or downstream of the mouth, which is relative to the Agulhas Current. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 11).

Location	Mean $\delta^{13}C$	St Dev.	Maximum	Minimum	Grouping according to Tukey Test
Opposite mouth	-17.98	0.88	-16.93	-19.03	A
0.5km upstream of mouth	-17.77	0.22	-17.51	-17.91	A
1km downstream of mouth	-17.64	0.06	-17.60	-17.69	A
2km downstream of mouth	-16.82	0.13	-16.71	-16.94	B
5km downstream of mouth	-16.74		-16.74	-16.74	B

Two source mixing models identified that the filter feeder $\delta^{13}C$ ratios opposite the mouth were derived from a combination of the POM adjacent to the estuary mouth (56% ±0.12SE) and that in the lower estuary (44% ±0.12SE). The copepod $\delta^{13}C$ values adjacent to the estuary mouth were derived predominantly from the POM adjacent to the system (78% ±0.17SE) and to a lesser extent from the estuarine POM (22% ±0.17SE).

Table 5.4: $\delta^{13}C$ values (‰) of the zooplankton collected from the Kariega Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with a distance up or downstream of the mouth, which is relative to the Agulhas Current. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 30).

Taxon	Location	Mean $\delta^{13}C$	St Dev.	Maximum	Minimum	Grouping according to Tukey Test
Copepod	Upper Estuary	-26.78	0.22	-26.62	-26.93	A
Copepod	Lower Estuary	-21.46	1.41	-20.49	-23.08	A
Copepod	0.5km upstream of mouth	-16.26	0.17	-16.14	-16.38	B
Copepod	Opposite mouth	-16.82	1.45	-15.12	-18.19	B
Copepod	0.5km downstream of mouth	-16.45	0.11	-16.32	-16.58	B
Copepod	1km downstream of mouth	-16.47	0.35	-16.12	-16.82	B
Copepod	2km downstream of mouth	-16.44	1.25	-14.54	-18.05	B

5.3.2 The Great Fish Estuary and adjacent marine environment

Primary producers and particulate organic matter (POM)

The vegetation sampled in the Great Fish Estuary separated into two distinct groups, one with highly depleted $\delta^{13}C$ ratios (-29.94‰ to -26.88‰) and the other comprising only *S. virginicus* (-14.43‰) (Figure 5.3 and Table 5.5). The highly depleted group was a mix of riparian species, reeds and sedges, and one salt marsh species (*S. perennis*). The riparian vegetation covered the full range of $\delta^{13}C$ ratios (-29.94‰ to -26.88‰) in the initial grouping, while the reeds, sedges and salt marsh vegetation covered a greater range, incorporating *S. virginicus* (-29.60‰ to -14.43‰) (Table 5.5).

The $\delta^{13}C$ ratio for the POM (-19.22‰) recorded within the Great Fish Estuary was enriched relative the vegetation sampled, with the exception of *S. virginicus* (Table 5.6). The $\delta^{13}C$ ratios for the POM in the adjacent marine environment ranged between a depleted -20.16‰ upstream of the estuary mouth to an enriched ratio of -18.25‰ 12km downstream of the estuary mouth (Table 5.6 and Figure 5.3). The $\delta^{13}C$ signatures of the POM from the adjacent marine environment fluctuated around the recorded value for the estuarine environment and demonstrated a trend of slight enrichment with distance from the estuary mouth (Table 5.6; Figure 5.3). This was confirmed by mixing models demonstrating that the $\delta^{13}C$ ratios of the POM adjacent to the estuary was derived from an approximately equal mix of estuarine derived (46% ±0.55SE) and marine derived POM (54% ±0.55SE).

Table 5.5: $\delta^{13}C$ values (‰) of the primary producers collected from the Great Fish Estuary in April 2005. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 8).

Species	Habitat type	Mean $\delta^{13}C$	St dev	Maximum	Minimum	Grouping according to Tukey Test
Acacia sp.	Riparian	-29.28	0.37	-29.02	-29.54	A
Brachylena elliptica	Riparian	-29.33	3.49	-26.87	-31.80	A
Brachylena illiciflora	Riparian	-29.94	1.99	-28.54	-31.34	A
Erythrina sp.	Riparian	-26.88	2.40	-25.19	-28.58	A
Juncus kraussi	Reed/Sedge	-29.60	0.39	-29.32	-29.88	A
Phragmites australis	Reed/Sedge	-26.88	0.05	-26.85	-26.92	A
Sarcocornia perennis	Salt Marsh	-27.67	0.75	-27.14	-28.20	A
Sporobolus virginicus	Salt Marsh	-14.43	0.22	-14.27	-14.59	B

Table 5.6: $\delta^{13}C$ ratios (‰) of the POM collected from the Great Fish Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with a distance up or downstream of the mouth, which is relative to the Agulhas Current. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 29).

Location	Mean $\delta^{13}C$	St dev	Maximum	Minimum	Grouping according to Tukey Test
Estuarine	-19.22	0.34	-18.88	-19.53	AB
0.5km upstream of mouth	-20.16	1.11	-19.36	-21.77	A
Opposite mouth	-19.73	0.64	-19.23	-20.85	AB
0.5km downstream of mouth	-19.42	0.67	-18.63	-20.26	AB
1km downstream of mouth	-18.46	0.19	-18.32	-18.60	AB
2km downstream of mouth	-18.76	0.33	-18.52	-18.99	AB
4km downstream of mouth	-18.75	0.56	-18.15	-19.35	AB
7km downstream of mouth	-18.86	0.97	-17.87	-20.23	AB
12km downstream of mouth	-18.25	0.81	-17.30	-19.50	AB

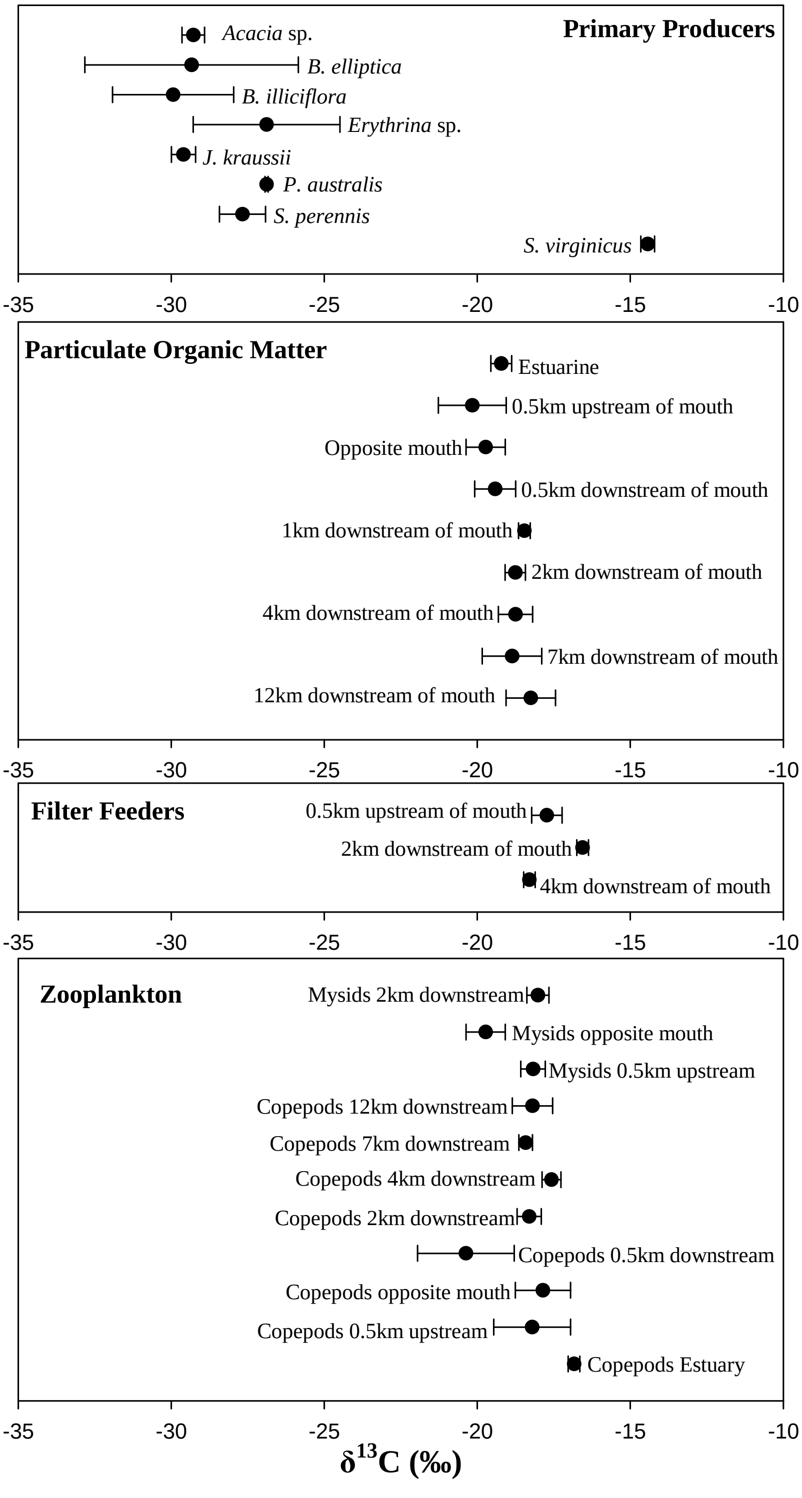


Figure 5.3: The $\delta^{13}C$ (‰) ratios and standard error for the primary producers, POM, marine filter feeders (sponges and *P. stolonifera*) and zooplankton collected from the Great Fish Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with distances upstream or downstream of the mouth, which is relative to the Agulhas Current.

Consumers (zooplankton and filter feeders)

There were relatively few rocky reefs adjacent to the Great Fish Estuary and therefore the collection of filter feeders for each transect was not possible. The three samples that were collected demonstrated no real trends, with the most enriched $\delta^{13}C$ signature recorded 2km down the coast and the most depleted value recorded 4km down the coast (Table 5.7 and Figure 5.3). Upstream of the estuary mouth a $\delta^{13}C$ ratio of -17.73‰ was recorded for *P. stolonifera* samples.

Table 5.7: $\delta^{13}C$ ratios (‰) of the filter feeders (sponges and *P. stolonifera*) collected from the Great Fish Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with a distance up and downstream of the mouth, which is relative to the Agulhas Current. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 6).

Location/Habitat type	Mean $\delta^{13}C$	St dev	Maximum	Minimum	Grouping according to Tukey Test
0.5km upstream of mouth	-17.73	0.49	-17.21	-18.19	A
2km downstream of mouth	-16.56	0	-16.56	-16.56	B
4km downstream of mouth	-18.30	0.19	-18.14	-18.51	A

There were no significant differences in the $\delta^{13}C$ signatures of the zooplankton between the Great Fish Estuary and marine samples ($p>0.05$; Table 5.8). The $\delta^{13}C$ signatures for copepods (predominantly *Calanus agulhensis*) ranged from -20.37‰ to -16.84‰, while the signatures for mysids (predominantly *Rhopalophthalmus terranatalis*) ranged between -18.02‰ and -19.73‰ (Table 5.8). The $\delta^{13}C$ ratios of the copepods collected within the Great Fish Estuary were more enriched (-16.84‰) than any of the zooplankton collected in the adjacent marine environment, while the $\delta^{13}C$ signatures for copepods collected at all marine sites, except 0.5km downstream of the mouth, fell within a range of less than 1‰ (Table 5.8 and Figure 5.3). The $\delta^{13}C$ ratios for mysids collected opposite the estuary mouth (-19.73‰) were slightly depleted relative to the $\delta^{13}C$ signatures of mysids collected 2km downstream (-18.02‰) and 0.5km upstream (-18.18‰) of the estuary (Table 5.8).

Table 5.8: $\delta^{13}C$ values (‰) of the zooplankton collected from the Great Fish Estuary and adjacent marine environment in April 2005. The samples in the marine environment are designated with a distance up or downstream of the mouth, relative to the Agulhas Current. Different letters in the Tukey Test (post hoc test after ANOVA was performed) indicate significantly different groups ($p<0.05$; df = 31).

Species	Location	Mean $\delta^{13}C$	St dev	Maximum	Minimum	Grouping according to Tukey Test
Copepod	Estuary	-16.84	0	-16.84	-16.84	A
Copepod	0.5km upstream of mouth	-18.21	1.26	-15.90	-19.59	A
Copepod	Opposite mouth	-17.85	0.90	-17.01	-19.37	A
Copepod	0.5km downstream of mouth	-20.37	1.58	-18.78	-21.73	A
Copepod	2km downstream of mouth	-18.30	0.40	-17.75	-18.65	A
Copepod	4km downstream of mouth	-17.58	0.31	-17.36	-17.79	A
Copepod	7km downstream of mouth	-18.42	0.22	-18.09	-18.64	A
Copepod	12km downstream of mouth	-18.20	0.66	-17.41	-18.80	A
Mysids	0.5km upstream of mouth	-18.18	0.40	-17.90	-18.46	A
Mysids	Opposite mouth	-19.73	0.64	-19.23	-20.85	A
Mysids	2km downstream of mouth	-18.02	0.36	-17.76	-18.27	A

Mixing models demonstrated that the $\delta^{13}C$ ratios of the copepods adjacent to the Great Fish Estuary were feeding almost entirely on estuarine POM, while, not surprisingly, the carnivorous mysids adjacent to the estuary mouth were feeding entirely on copepods.

5.3.3 Comparison between Kariega and Great Fish $\delta^{13}C$ isotope values

Primary producers and particulate organic matter (POM)

The comparative results from primary producers that occurred in the riverine vegetation adjacent to both estuaries demonstrated a minimal variability between the two systems (Figure 5.4). The observed variability in $\delta^{13}C$ values for *S. perennis* samples was 2.3‰ (Kariega: -29.97‰; Great Fish: -27.67‰), while the variability in *S. virginicus* was only 0.2‰ (Kariega: -14.29‰; Great Fish: -14.43‰).

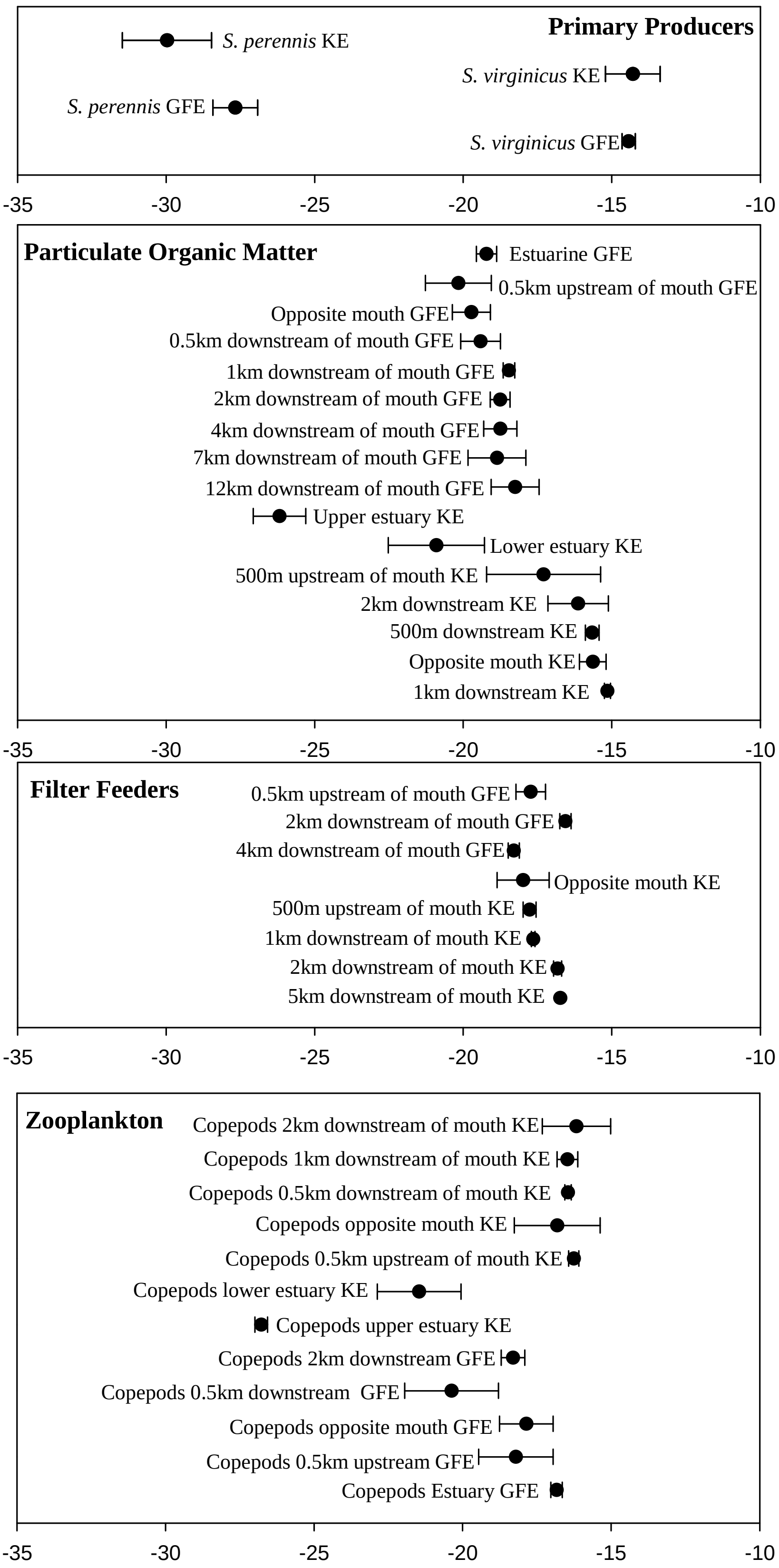


Figure 5.4: The comparative $\delta^{13}C$ (‰) ratios and standard error for specific samples that were collected in and adjacent to both estuaries in April 2005. The samples in the marine environment are designated with distances upstream or downstream of the mouth, which is relative to the Agulhas Current.

Consumers (zooplankton and filter feeders)

The ranges of δ^{13}C values for the filter feeders occurring in the adjacent marine environment were similar (Figure 5.4). The δ^{13}C values of the filter feeders occurring adjacent to the Kariega Estuary ranged between -16.74‰ and -17.9‰, while those adjacent to the Great Fish Estuary ranged between -16.56‰ and -18.30‰ (Figure 5.4). Alternatively, the δ^{13}C values of the copepods in the marine environment adjacent to the Kariega (range: -16.17‰ to –16.82‰) were consistently more enriched than those occurring adjacent to the Great Fish Estuary (range -17.85‰ to –20.37‰). The δ^{13}C values of the copepods within the estuary demonstrated a large variation, with the δ^{13}C values of the copepods within the Kariega Estuary being –26.78‰ (upper estuary) and –21.46‰ (lower estuary) and the δ^{13}C values of the Great Fish copepods being –16.84‰ (Figure 5.4).

5.4 DISCUSSION

Results of previous studies have demonstrated that the main carbon source assimilated by primary and secondary consumers within southern African estuaries appears to be dependent on the volume of fresh water flowing into the system (De Villiers, 1990; Jerling and Wooldridge, 1995; Schlacher and Wooldridge, 1996b; Froneman, 2002b). In those systems characterised by sustained fresh water inflow, phytoplankton appear to be the main carbon source used by the zooplankton (Jerling and Wooldridge, 1995). Alternatively, in those estuaries which are regarded as fresh water deprived, the plankton food web is sustained by detrital carbon or microphytobenthic algae (Schlacher and Wooldridge, 1996b).

5.4.1 The Kariega Estuary

The results of stable isotope analysis within the Kariega Estuary indicated two distinct carbon pathways that were spatially separated from one another. The δ^{13}C signatures of the POM in the upper reaches of the estuary were closely linked to the δ^{13}C signatures of the group of plants comprising the riparian vegetation, while in the lower reaches the δ^{13}C signatures of POM were closely related to *Spartina maritime* (Fernald, 1916), *Z. capensis* and *S. virginicus* (Figure 5.2). Assuming an enrichment of 1 – 1.5‰ per trophic level (DeNiro and Epstein, 1978; Monteiro *et al.*, 1991; Sholto-Douglas *et al.*, 1991), it appears that the zooplankton within the upper reaches of the estuary are largely consuming POM derived from riparian vegetation (Figure 5.2). In the lower reaches of the system, the copepods appear to be assimilating carbon derived mainly from the extensive salt marshes within the region (Figure 5.2).

The identification of two separate carbon pathways within the Kariega Estuary concurs with Paterson and Whitfield (1997), who also found two carbon pathways that they termed “channel” and “littoral” within this system. The channel pathway they identified is similar to the upper reach pathway recorded in this study, being derived from riparian vegetation. The littoral pathway they describe is similar to the lower reach pathway identified in this study as they both rely on macrophytes and salt marsh vegetation for the majority of carbon. Froneman (2002b) and Froneman (2001b) also identified two carbon pathways when investigating the Kariega Estuary, except that he found that the channel or upper reach pathway was reliant on carbon derived from benthic algae rather than phytoplankton. Tweddle (2004) similarly identified a benthic algae driven food web in the neighbouring temporarily open/closed Kasouga Estuary, which is supported by the results of studies by Kibirige *et al.* (2002) and Perissinotto *et al.* (2003) in estuaries along the south coast of southern Africa.

The different pathways identified within the Kariega Estuary can be explained by a combination of food preference and food availability (Doi *et al.*, 2005), as, although the same primary consumers were sampled at different sites, the changes in δ^{13}C ratios may be due to selective feeding at either of the sites, rather than different food availability. International studies have described both pathways identified by this study within the Kariega Estuary. The importance of macrophytes as carbon sources for estuarine fauna has been identified in studies conducted by Loneragan *et al.* (1997) and Créach *et al.* (1997) in tropical Australia, while Smit *et al*. (2005) and Bouillon *et al.* (2002) identified autochthonous inputs such as benthic and pelagic macroalgae as the main carbon source for food webs, despite the availability of extensive seagrass beds and terrestrially derived carbon.

The δ^{13}C ratios of the POM in the marine environment adjacent to the Kariega Estuary demonstrated a strong association with *Z. capensis* (Figure 5.2). This pattern can likely be attributed to the fact that large volumes of detached *Z. capensis* are exported to sea during the outgoing tide (unpublished data). However, despite this strong correlation, mixing model results indicate that the POM adjacent to the estuary is derived primarily from marine POM sources and not an estuarine or *Z. capensis* source. The two marine POM signatures least likely to be influenced by an estuarine source, namely the site upstream (relative to the Agulhas Current) and the site furthest downstream from the estuary mouth, demonstrated the most depleted $\delta^{13}C$ signatures of the marine POM (Figure 5.2). The observed depletion of POM $\delta^{13}C$ ratios with distance from the estuary mouth indicates the inclusion of additional unidentified carbon sources, which are most likely a variety of macro-algal species which occur along the coast in this region. Deegan and Garritt (1997) have reported that ocean sources are typically enriched in ^{13}C due to the dissolution of dissolved inorganic carbon into seawater and it is therefore unlikely that it is an open ocean source that is causing the depletion. Similarly, Megens *et al.* (2001) identified the extent of mixing between near/offshore waters as having a large effect on suspended particulate matter composition. The low flow rates within the Kariega Estuary suggest that export of estuarine derived carbon to the marine environment is likely to be restricted to the region immediately adjacent to the mouth of the estuary. With increasing distance from the mouth, the POM is likely to be comprised of a mixture of carbon derived from estuarine, marine and rocky shore sources.

The POM derived from the lower reaches of the Kariega Estuary appeared to be the main carbon source assimilated by the marine filter feeders and copepods adjacent to the mouth of the estuary (Figure 5.2). With increased distance from the estuary mouth the $\delta^{13}C$ ratios of the filter feeders and copepods became increasingly enriched, indicating an as yet unidentified carbon source playing a more important role in their diet. Authors have identified different isotope ratios for different species feeding on the same diet, which could have contributed partially to the difference between estuarine and marine samples. However, considering that the samples in both the estuarine and marine stations were comprised predominantly of *C. agulhensis* and *Clausocalanus* sp. the variation derived from this component should be minimal.

5.4.2 The Great Fish Estuary

Similarly to the Kariega Estuary, the vegetation sampled within the Great Fish Estuary grouped into a highly depleted group (-29.94‰ to -26.88‰) and a group comprising the relatively enriched *S. virginicus* (-14.43‰) (Figure 5.3). The highly depleted group was comprised of riparian vegetation and two species of reeds as well as the salt marsh plant *S. perennis*. The $\delta^{13}C$ ratio values of the POM within the estuary (-19.22‰) appeared to be closely aligned with that of the terrestrial vegetation (Figure 5.3). However, previous studies have demonstrated that the residence time of water within the estuary is less than one day (Jennings, 2005), indicating that the POM within the system is unlikely to be derived from terrestrial vegetation. In addition, a number of studies conducted within the estuary have demonstrated that chl-*a* concentrations within the system may attain levels up to 200mg chl-*a* m^{-3}, with values >20mg chl-*a* m^{-3} not uncommon (Grange and Allanson, 1995; Grange *et al.*, 2000). Analyses of the published literature indicates that the $\delta^{13}C$ values for fresh water phytoplankton are highly variable (ranging from -5 to -30‰) reflecting seasonality, species composition, nutrient availability and dissolved inorganic carbon sources (Fry and Sherr, 1984; De Villiers, 1990; Michener and Schell, 1994; Jerling and Wooldridge, 1995). All of these factors indicate that the food web within the Great Fish Estuary is maintained by allochthonously derived fresh water phytoplankton that is transported into the estuary via the interbasin transfer scheme. This is supported by a previous study within the estuary which demonstrated that phytoplankton were the primary source of carbon consumed by the numerically dominant zooplankton within the system (Mesher, 2005).

The absence of any significant difference in $\delta^{13}C$ POM signatures between the marine and estuarine environments suggests a similar source of carbon for the POM signatures from these different areas (Figure 5.3). The $\delta^{13}C$ signatures of the marine POMs demonstrate a trend of increasing enrichment with distance from the estuary mouth, which implies mixing between the POM derived from the estuary and an unidentified, enriched carbon source. This is supported by the mixing model results, which indicate that the POM adjacent to the estuary is derived from approximately equal contributions of estuarine and marine sources. Hill *et al.* (2006) recorded the inshore POM in this region being in the range of -15‰ to -17‰. The $\delta^{13}C$ ratios recorded for the copepods in the adjacent marine environment demonstrate a similar trend to that of the POM in the marine environment, with slight enrichment with distance from the estuary mouth (Figure 5.3).

The concept of the Great Fish Estuary food web being sustained by allochthonous carbon (riverine phytoplankton) is supported by an international study. Melville and Connoly (2005) identified high productivity in Australian estuaries being supported by imported organic matter.

5.4.3 General discussion

The food webs within the two estuaries investigated in this study appear to be sustained by different carbon sources. In the Great Fish Estuary the zooplankton appear largely to be sustained by allochthonous phytoplankton derived from the greater riverine inflow. This result is in agreement with work by Froneman (2002b) and Mesher (2005) within this system. Furthermore, results are consistent with a study on the nearby Sundays River Estuary, a permanently open system with moderate flow rates, which also identified phytoplankton as the main carbon source for primary consumers (Jerling and Wooldridge, 1995). In the fresh water deprived Kariega Estuary, carbon derived from a combination of autochthonous phytoplankton and allochthonous vegetation sources appears to sustain the plankton food web.

The generally more enriched $\delta^{13}C$ values for POM offshore of the Kariega Estuary relative to the Great Fish is evidence of a reduced estuarine influence, due to oceanic carbon sources being traditionally more enriched than terrestrial or coastal sources (Deegan and Garritt, 1997). Results of a mixing model showed that the POM adjacent to the Great Fish Estuary was derived from a mixture of estuarine and marine sources, while that adjacent to the Kariega Estuary was derived entirely from marine POM sources. The influence of estuarine derived carbon on the adjacent marine environment has been extensively studied by Darnaude (2005) and Darnaude *et al.* (2004), who identified that the productivity of higher trophic levels, such as secondary consumers, in the marine environment adjacent to the Rhone River is affected by the riverine flow rates. High flow rates were associated with higher productivity due to increased prey (filter and detrital feeding polychaetes) biomass attributable to raised concentrations of riverine POM. A similar result was recorded by Cauwet *et al.* (1990), with large contributions to the organic carbon pool in the adjacent marine environment by the Rhône River and fluctuations in these contributions being related to varying flow rates. A study by Chong *et al.* (2001) showed that estuarine derived detritus formed up to 25% of the diet of marine prawns up to 2km away from the estuarine source. Finally, Loneragan *et al.* (1997) identified estuarine and terrestrial sources as supporting the penaeid prawn populations within and adjacent to estuaries in tropical Australia.

5.4.4 Final conclusions

The outwelling hypothesis states that due to the direction of water flow through estuaries into the marine environment, estuarine productivity and biota are exported from these systems into the marine environment (Odum, 1980; Dame and Allen, 1996; Roegner and Shanks, 2001). This has led researchers to assume that food webs in the marine environment directly adjacent to estuaries are sustained by estuarine derived productivity and biotic material. This hypothesis seems to be validated by this study, with a reliance on estuarine derived POM of both the zooplankton and filter feeders in the marine environment adjacent to, and up to 12km from, the Great Fish Estuary. The high flow rates (in excess of $8m^3.s^{-1}$) recorded within this estuary create a flow through system, transporting riverine POM and chlorophyll-*a* into the adjacent marine environment. Alternatively, in the Kariega Estuary, the carbon is derived from a variety of sources due to the longer water residence times allowing degradation of a variety of plant material as well as autochthonous phytoplankton production. Although some export of estuarine derived POM to the marine environment adjacent to the Kariega Estuary was evident, due to the low flow rates, it was restricted to the sites in the vicinity of the estuary mouth.

Further study is required to clarify the processes occurring adjacent to these large permanently open estuaries. Components that need clarification include studies incorporating other isotopic elements, particularly sulphur (MacAvoy and Macko, 1998; Herzka, 2005), which would allow a better separation between marine, estuarine and terrestrial carbon sources, and a higher spatial and temporal resolution study in the marine environments adjacent to both these estuaries to identify potential marine sources of carbon.

CHAPTER 6

TIDAL IMPORT OF MACROZOOPLANKTON INTO A FRESH WATER DEPRIVED, PERMANENTLY OPEN EASTERN CAPE ESTUARY

6.1 INTRODUCTION

Estuarine faunal communities comprise species with a variety of life history patterns, including those that complete their entire life cycle within estuaries, and those that have a marine or fresh water phase in their life cycle (reviews by Whitfield, 1998; Wooldridge, 1999; Able, 2005). The use of estuaries as a nursery environment by a range of ichthyofaunal (Potter *et al.*, 1990; Neira and Potter, 1992; Whitfield, 1992b; Ray, 1997; Strydom *et al.*, 2003) and invertebrate (Forbes *et al.*, 1994; Cyrus and Forbes, 1996; Kemp and Froneman, 2004; Bernard and Froneman, 2005) species is now well documented. To date, however, limited effort has been applied to determining the recruitment trends of invertebrates from the marine environment into estuaries.

The South African scientific literature indicates limited information available about the temporal recruitment patterns of invertebrate species into estuaries. Forbes and Benfield (1986a and b) demonstrated no diurnal trends in the densities of the penaeid prawn, *Penaeus indicus* (H. Milne Edwards, 1837), recruiting into estuaries along the east coast of southern Africa (KwaZulu-Natal). Contrasting results were reported by Wooldridge and Loubser (1996), who showed a significant nocturnal increase in the mud-prawn, *Upogebia africana* (Ortmann, 1894), larvae recruiting into estuaries along the south coast of southern Africa (Eastern Cape). Researchers do, however, agree that densities of recruiting larvae on flood tides are significantly higher than on ebb tides (Forbes and Benfield, 1996a and b; Wooldridge and Loubser, 1996; De Villiers *et al.*, 1999). Records of seasonal trends in recruitment indicate that for the penaeid species, highest densities of larval recruits are evident entering estuaries during late summer or early autumn (Forbes and Cyrus, 1991; Forbes *et al.*, 1994). Evidence exists indicating that larvae accumulate adjacent to southern African estuaries in response to an unknown cue, thought to be salinity or turbidity gradients (Whitfield, 1989a; Cowley *et al.*, 2001).

The current research on recruitment mechanisms in invertebrates indicates that their ability to enter estuaries is due to vertical migrations in response to changing tidal pressures (Epifanio, 1988; Rothlisberg *et al.*, 1995; Dame and Allen, 1996; De Villiers *et al.*, 1999). Rothlisberg *et al.* (1995) demonstrated that as pressure increased, penaeid prawns migrated to surface waters, presumably to use the incoming tidal currents to enter estuaries.

Anthropogenic influences have been credited with reducing the ability of invertebrate and vertebrate fauna to recruit into South African estuaries. For example, Wooldridge (1994) attributed the reduced *U. africana* populations within the Great Brak Estuary, along the south-east coast of southern Africa, to limited recruitment opportunities due to the extended closure of the mouth resulting from impoundments. Similarly, Hanekom and Baird (1992) attributed the limited recruitment of *U. africana* into a permanently open system within the same region, to reduced olfactory and turbidity cues entering the marine environment as well as the periodic inlet closure as a result of impoundments in this system's catchment. In terms of ichthyofaunal recruitment, similar results have been recorded, particularly with respect to alterations in mouth phase of estuaries (Whitfield and Bruton, 1989; Bennett, 1989; Whitfield and Wooldridge, 1994; Russell, 1996; Vorwerk *et al.*, 2003).

South Africa is considered an arid region, receiving approximately half the world average rainfall of ≈450mm.yr^{-1} (DWAF, 2004a). To meet the ever increasing demands for fresh water to sustain socio-economic development, large impoundments have been constructed along the main channel of the majority of the large river systems in the region. This has contributed to a decrease in the magnitude of fresh water flowing into southern African estuaries. While considerable research has been conducted on the biological consequences of the reduced fresh water inflow within estuaries (Whitfield and Bruton, 1989; Whitfield and Wooldridge, 1994; Grange and Allanson, 1995; Ter Morshuizen *et al.*, 1996b; Strydom *et al.*, 2002), no studies have assessed the influence of these reductions on recruitment of marine invertebrates into these systems. The main aim of this study was to examine the recruitment patterns in the macrozooplankton (>1cm) entering the Kariega Estuary (see section 2.2.2 of Chapter Two for details), a fresh water deprived, permanently open estuary along the south-east coastline of southern Africa.

6.2 MATERIALS AND METHODS

6.2.1 Sample collection

Samples were collected from a station occupied in the middle channel at the mouth of the estuary using a net with a $0.5m^2$ mouth area and a mesh size of approximately 500µm funnelled to a removable cod-end with a 100µm mesh size. The net was fitted with a General Oceanics analogue flow meter to calculate filtered volumes. The net was anchored to the estuary floor in mid-channel, 150m from the mouth facing in a seaward direction. See Figure 6.1 for a stylised diagram of the equipment.

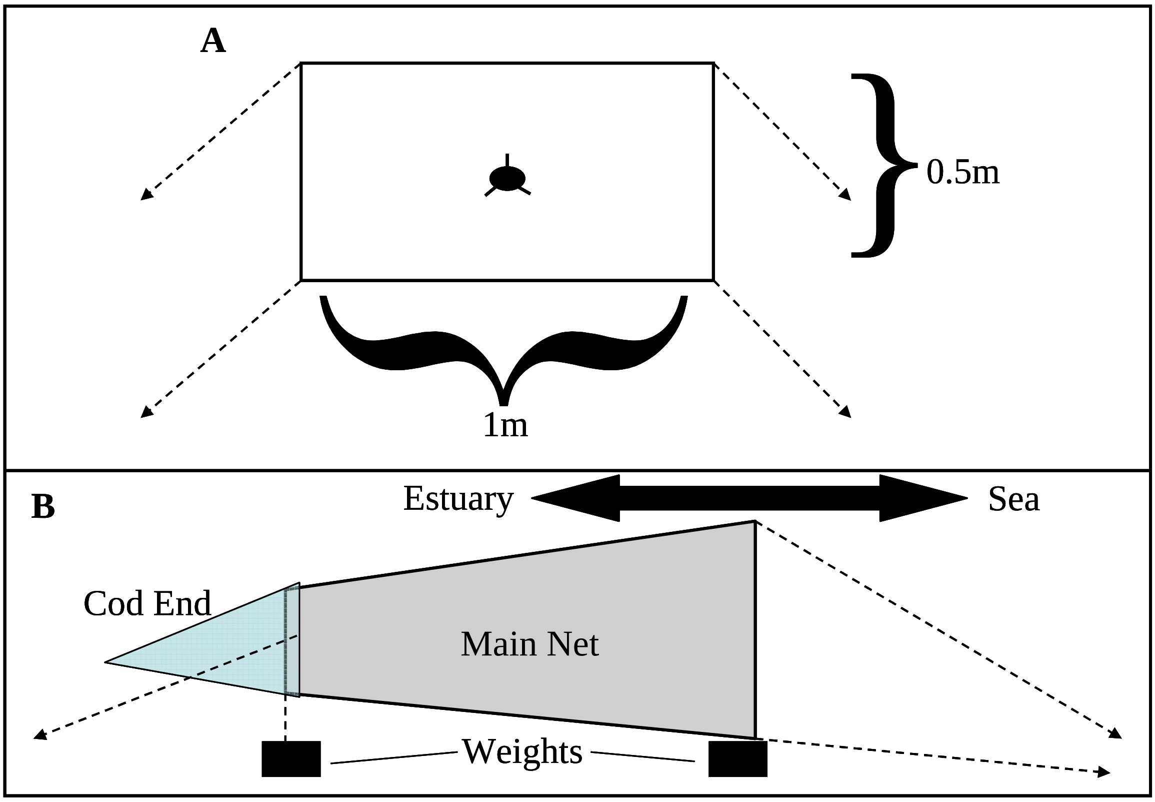


Figure 6.1: Schematic diagram of the net design from the front (A) and the side (B). Dashed lines represent anchor ropes.

Sampling took place monthly over a one year period. During each sampling trip, samples were collected every two hours during the incoming tide (timed to coincide with the change in tidal regime) for a period of 24hrs to establish diurnal as well as seasonal variations in recruitment of macroinvertebrates into the estuary (see Table 6.1 for the sampling dates and tide type). Tide direction (ebb or flood) was determined by the direction of flow of water at the site. After each two hour period, the cod end was removed and the flow meter readings noted. The samples were filtered through a 300µm mesh to remove excess sediment and then placed in a sample jar and fixed with 10% buffered formalin for analyses of the zooplankton community structure and biomass in the laboratory. Salinity was recorded at each two hour interval using an optical refractometer.

Table 6.1: The dates that sampling was conducted including the tidal situation (spring or neap tide and whether full or new moon on the spring tides).

Month	Date	Tide	Season
March	1 March 2006	Neap	Austral Autumn
April	31 March 2006	Spring New Moon	
May	15 May 2005	Spring Full Moon	
June	1 June 2005	Neap	Austral Winter
July	19 July 2005	Spring Full Moon	
August	17 August 2005	Spring Full Moon	
September	2 September 2005	Spring New Moon	Austral Spring
October	14 October 2005	Spring Full Moon	
November	1 November 2005	Spring New Moon	
December	7 December 2005	Neap	Austral Summer
January	13 January 2006	Spring Full Moon	
February	3 February 2006	Neap	

6.2.2 Laboratory analysis

An Olympus dissecting microscope, operated at a magnification of 100 to 200, was used to identify and count the invertebrates collected. All mysids and decapods were identified to the species level using Boltovsky (1999), Gibbons (2001) and Branch *et al.* (1999). Biomass was determined by weighing sub-samples on a Sartorius microbalance. Values were expressed as ind.m^{-3} and mg wwt m^{-3} (milligrams wet-weight per metre cubed), respectively.

6.2.3 Data analysis

Species richness and diversity during each sampling trip were calculated according to the Margalef's and Shannon-Weiner equations presented in Chapter 3, Section 3.2.4.

After Log transforming the data and testing for normality using a Kolmogorov-Smirnov Test, an ANOVA was used to test for significant differences between seasonal and diel recruitment. Samples collected during night and daytime were pooled to allow diel comparisons in recruitment. Similarly, data for each season was pooled to allow for a seasonal comparison in recruitment patterns. All analyses were conducted using the computer package Statistica version 6 (Statsoft Inc., 2004). A Spearman Correlation was conducted in MS Excel to determine if observed temporal patterns related to recorded salinity or temperature.

6.3 RESULTS

Salinity was measured on every occasion that the cod-end was removed throughout the sampling period and ranged between 35 and 41psu. The average salinity over the sampling period was 35.60psu ±1.44. All correlations between physico-chemical variables (temperature and salinity) and the observed temporal trends were not significant ($p>0.05$).

6.3.1 Recruitment analysis

Twenty macrozooplankton species were recorded recruiting into the Kariega Estuary between April 2005 and March 2006. The highest number of species in any one month was recorded during autumn (13 during May) (Table 6.2). The highest species richness (10.64) and diversity (0.82) values were similarly recorded during the autumn and winter months. During spring and summer the number of species sampled ranged between five and eight, with species richness less than 1.6 and diversity only exceeding 0.45 on one occasion (Table 6.2). A total of 46 341 macrozooplankton were captured recruiting into the Kariega Estuary during the sampling period. The total wet weight of these macrozooplankton totalled 77.46g.

Table 6.2: The number of species sampled, Margalef's species richness and Shannon-Weiner Diversity recorded for each month during the sampling period.

	Number of Species	Margalef's Richness	Shannon Weiner Diversity
March	7	1.57	0.26
April	9	1.84	0.82
May	13	2.48	0.37
June	12	10.64	0.49
July	8	1.41	0.04
August	11	1.25	0.26
September	8	1.59	0.55
October	6	0.56	0.25
November	6	0.68	0.31
December	5	0.86	0.43
January	8	1.34	0.13
February	5	0.59	0.3

The single most numerous species in the samples collected during this study was the mysid, *Gastrosaccus brevifissura* (Tattersall, 1952), with an average monthly density of 931.18ind.m^{-3} (±1 889.07SD), which represented approximately 80% of the average monthly catch (Table 6.3). The other dominant species included the surf shrimp, *Macropetasma africanum* (Balss, 1913) (76.66ind.m^{-3} ±250.42SD), the penaeid prawn, *P. indicus* (31.79ind.m^{-3} ±67.78SD), the mysid, *Mesopodopsis wooldridgei* (Wittmann, 1992) (39.06ind.m^{-3} ±59.25SD) and the swimming prawn, *Metapenaeus monoceros* (Fabricius, 1798) (23.83ind.m^{-3} ±74.70SD). The contribution of any of these species on any one occasion did not exceed 7% of the total invertebrates sampled (Table 6.3).

In terms of biomass, the dominant species recruiting into the Kariega Estuary was *G. brevifissura* (average monthly biomass 1 457.85mg wwt m^{-3} ±3 250.90SD). Other species that were recorded recruiting in high biomasses included *P. indicus* (176.17mg wwt m^{-3} ±474.24SD), *Gastrosaccus psammodytes* (Tattersall, 1958) (97.13mg wwt m^{-3} ±335.80SD) and *M. africanum* (78.52mg wwt m^{-3} ±265.20SD) (Table 6.3). Not many individuals of *Solenocera comatum* (Stebbing, 1915) were recorded, but they contributed a relatively high monthly average of 42.41mg wwt m^{-3} (±85.62SD) to the recorded biomass due to their large body size.

Table 6.3: The average monthly density and biomass for macrozooplankton collected during the study. Day and night abundances and biomasses are also presented with standard deviation.

Species	Average Monthly Density (ind.m^{-3})						Average Monthly Biomass (mg.m^{-3})					
	Total		**Day**		**Night**		**Total**		**Day**		**Night**	
	Ave	**Std Dev.**	**Ave**	**Std Dev.**	**Ave**	**Std Dev.**	**Ave**	**Std Dev.**	**Ave**	**Std Dev.**	**Ave**	**Std Dev.**
Callianassa kraussi	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.09	0.00	0.00	0.03	0.09
Euphasid sp.	2.32	6.95	0.01	0.04	2.31	6.95	11.68	37.95	0.01	0.03	11.67	37.95
Gastrosaccus brevifissura	931.18	1889.07	0.44	1.31	930.74	1887.82	1457.85	3250.90	0.45	1.38	1457.40	3249.62
Gastrosaccus olivae	1.90	4.30	0.00	0.00	1.90	4.30	0.75	1.92	0.00	0.00	0.75	1.92
Gastrosaccus psammodytes	8.40	25.47	0.00	0.00	8.40	25.47	97.13	335.80	0.00	0.00	97.13	335.80
Gonodactylus chiragra	0.00	0.01	0.00	0.00	0.00	0.01	0.20	0.69	0.00	0.00	0.20	0.69
Leptochela robusta	3.28	11.04	0.00	0.00	3.28	11.04	2.08	7.11	0.00	0.00	2.08	7.11
Lucifer penicillifer	0.51	1.74	0.00	0.00	0.51	1.74	0.00	0.01	0.00	0.00	0.00	0.01
Macrobrachium sp.	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.26	0.00	0.00	0.08	0.26
Macropetasma africanum	76.66	250.42	2.48	8.59	74.17	250.88	78.52	265.20	0.00	0.00	78.52	265.20
Mesopodopsis wooldridgei	39.06	59.25	5.24	11.87	33.82	51.80	14.92	34.86	0.17	0.50	14.75	34.41
Metapenaeus monoceros	23.83	74.70	0.36	1.24	23.47	74.79	20.45	62.93	0.15	0.50	20.30	62.97
Ogyrides saldanhae	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.15	0.00	0.00	0.04	0.15
Palaemon peringueyi	6.13	20.70	0.00	0.00	6.13	20.70	20.85	66.27	0.00	0.00	20.85	66.27
Penaeus indicus	31.79	67.78	0.58	1.45	31.21	67.41	176.17	474.24	1.99	5.96	174.18	474.07
Pontophilus megalocheir	2.48	8.59	2.48	8.59	0.00	0.00	0.02	0.05	0.00	0.00	0.02	0.05
Rhopalophthalmus terranatalis	1.34	4.64	0.00	0.00	1.34	4.64	0.74	2.55	0.00	0.00	0.74	2.55
Solenocera comatum	12.50	21.61	0.26	0.64	12.24	21.09	42.41	85.62	1.05	3.16	41.36	84.89
Thysanopoda sp.	0.01	0.03	0.00	0.00	0.01	0.03		0.00	0.02	0.00	0.00	0.00
Upogebia africana	0.02	0.06	0.00	0.00	0.02	0.06		0.04	0.13	0.00	0.00	0.04

6.3.2 Diurnal cycle

A comparison of the densities of recruiting macrozooplankton during incoming day-time versus night-time tides resulted in significant differences on a seasonal basis (F=22.35; p<0.001) (Figure 6.2). Similarly, the biomass recorded recruiting during daylight hours was significantly lower (F=21.59; p<0.001) than that recorded recruiting during the night during all seasons (Figure 6.3).

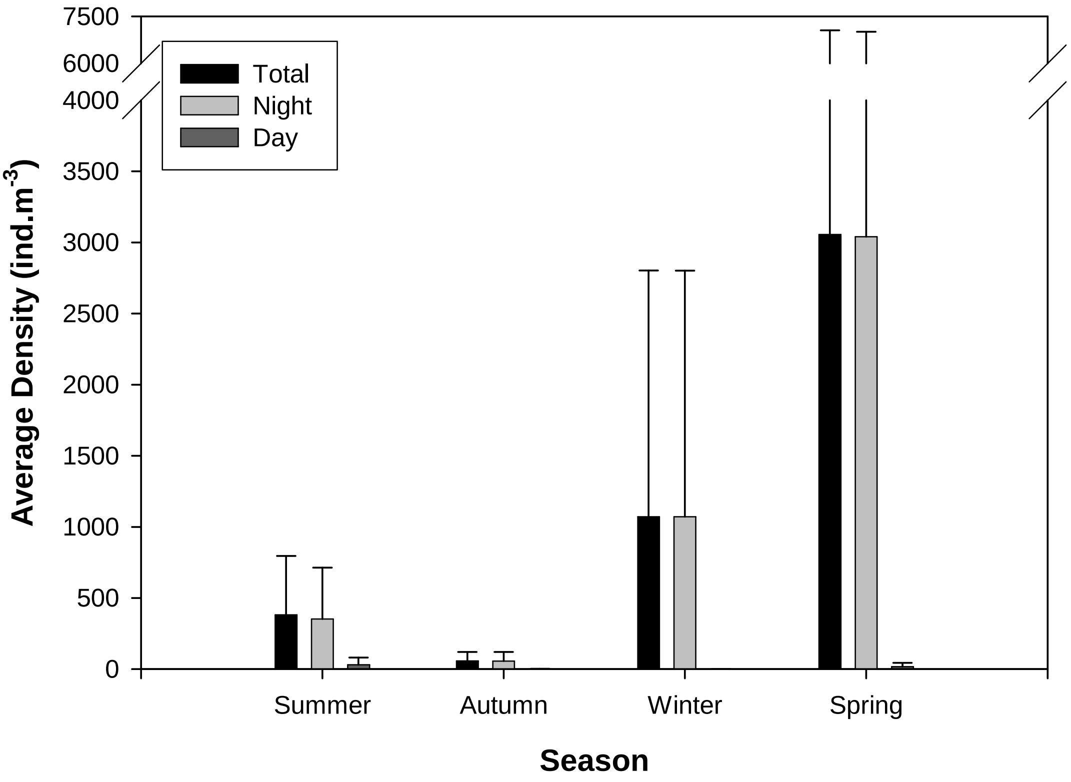


Figure 6.2: The average seasonal densities of recruiting macrozooplankton into the Kariega Estuary (n=3 for each period). Total densities and densities for daylight and night-time hours are presented.

Figures 6.4 and 6.5 indicate that the monthly diurnal trends concur with the seasonal trends, with maximum recruiting densities and biomass being recorded during darkness. Only September is anomalous, with recruiting biomass during daytime hours being higher than after dark for this month. This was due to a swarm of large-bodied *P. indicus* juveniles recruiting into the estuary at dawn (≈06h00).

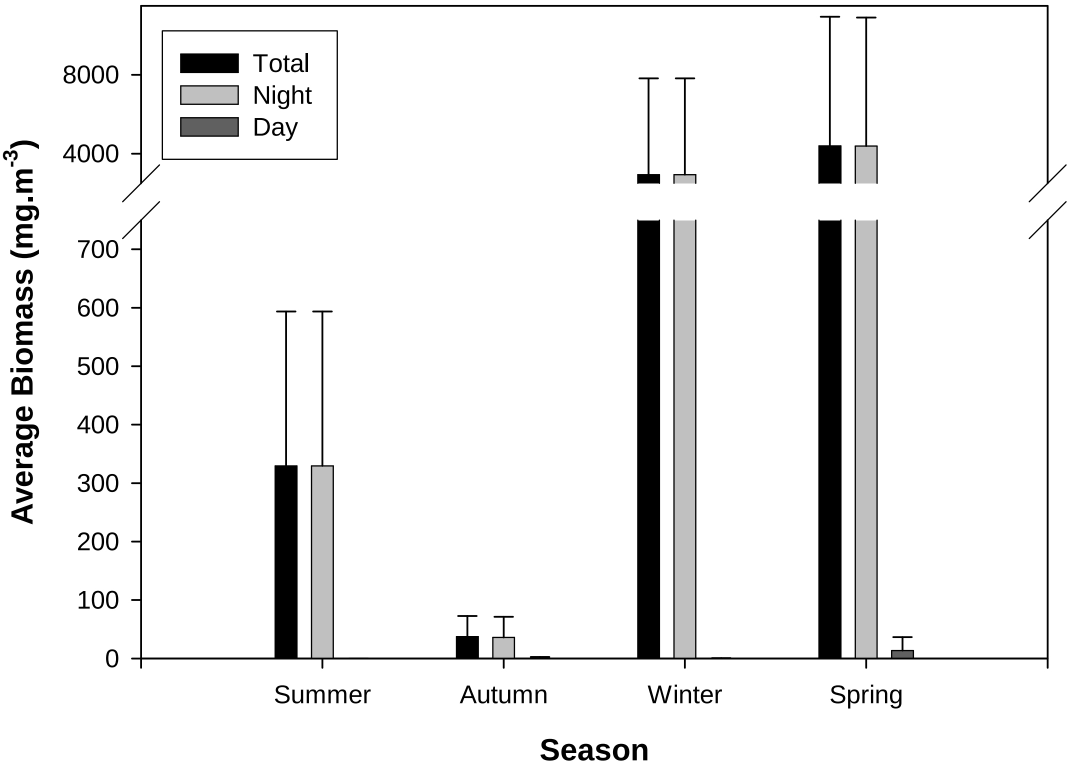


Figure 6.3: The average seasonal biomass of macrozooplankton recruiting into the Kariega Estuary (n=3 for each period). Average total biomass, daytime biomass and nocturnal biomasses are presented.

6.3.3 Monthly trends

The general monthly trends in recruitment densities were less than 190ind.m^{-3} from December through to July (range: 2.86ind.m^{-3} to 186.37ind.m^{-3}), with increasing densities (>1 400ind.m^{-3}) recorded from August to November (range: 1 483.83ind.m^{-3} to 3 067.96ind.m^{-3}) (Figure 6.4). Anomalies included a slightly elevated recruitment during February (856.31ind.m^{-3}) and reduced recruitment during September (82.55ind.m^{-3}).

Similar monthly trends were recorded in terms of biomass, with relatively low values ranging between 0.22mg wwt m^{-3} and 334.86mg wwt m^{-3} recorded from December to July and higher biomasses between 582.67mg wwt m^{-3} and 11 952.25mg wwt m^{-3} recorded from August to November (Figure 6.5). Similarly to the densities, February was anomalous, with a relatively high biomass being recorded (590.76mg wwt m^{-3}).

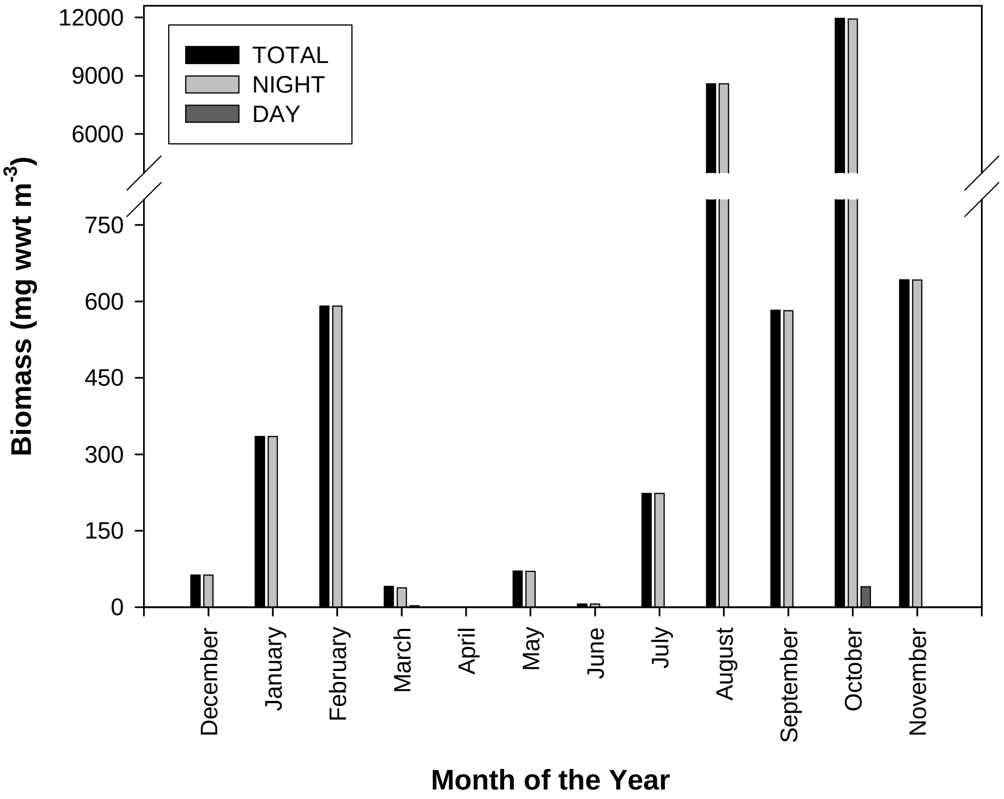


Figure 6.4: The monthly densities recorded during daylight hours, during darkness and overall.

6.3.4 Seasonal trends

The seasonal trends in recruitment indicate low average densities during summer (381.73ind.m^{-3} ±413.13SD) and autumn (57.18ind.m^{-3} ±63.18SD), with an increasing trend through winter (1 071.23ind.m^{-3} ±1 730.64SD) and spring (3 055.47ind.m^{-3} ±3 997.59SD) (Figure 6.2). The observed increase in winter is mainly due to the higher densities recorded in August (Figure 6.4). Due to the high degree of variability in recruitment patterns observed during the study, there were no significant seasonal trends in recruitment of invertebrates into the estuary ($p>0.05$).

The seasonal trends in biomass are similar to those recorded for the densities during each season, with lowest values recorded during summer (329.54mg wwt m^{-3} ±263.92SD) and autumn (37.29mg wwt m^{-3} ±35.47SD), with an increasing trend through winter (2 936.63mg wwt m^{-3} ±4 888.74SD) and spring (4 392.36mg wwt m^{-3} ±6 547.13SD) (Figure 6.3). The summer biomass is relatively high compared to the density, as a result of a large swarm of adult *G. brevifissura* recruiting into the estuary during February (Figure 6.5). A similar result occurred in winter due to a large swarm of *G. brevifissura* adults and *P. indicus* juveniles recruiting during August. Similarly to the seasonal densities, no significant differences in seasonal biomass were detected using an ANOVA due to large variability in each season (p>0.05).

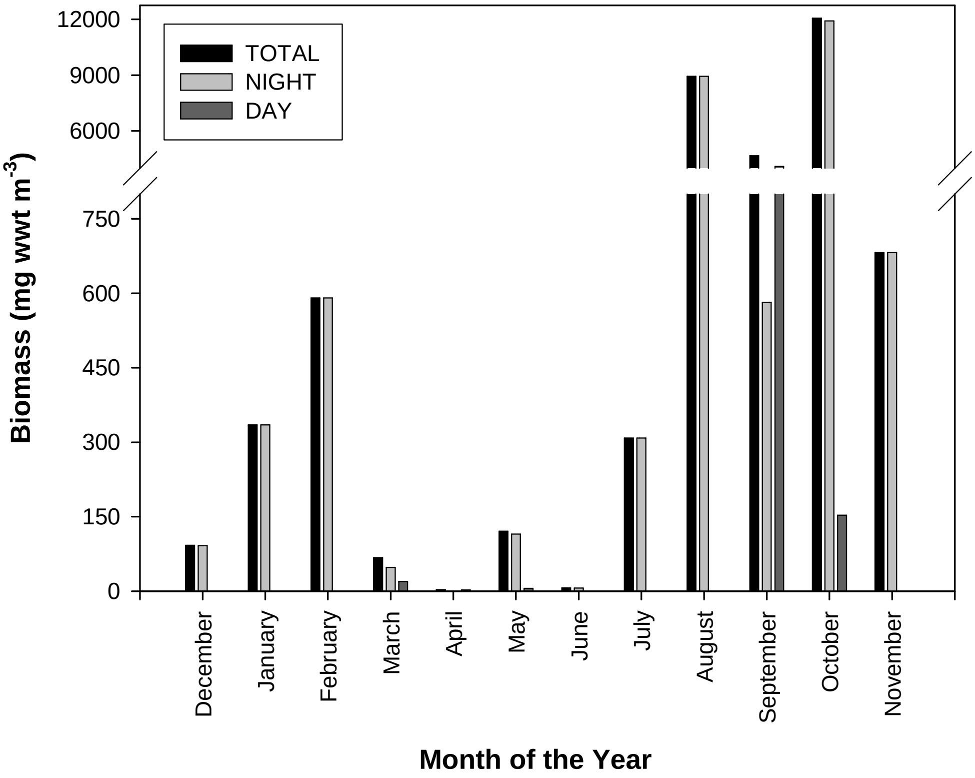


Figure 6.5: The monthly biomass recorded during daylight hours, during darkness and overall.

6.4 DISCUSSION

The trends in macrozooplankton recruitment into the Kariega Estuary indicate a spring, nocturnal peak in recruitment (Figures 6.2). The peak in recruiter densities observed during the spring months is similar to that observed for macrozooplankton in other estuaries in southern Africa, with several authors identifying a bimodal recruitment pattern of late summer/early autumn and spring (Forbes *et al.*, 1994; De Villiers *et al.*, 1999; Forbes and Demetriades, 2005). Crocos and Kerr (1983) related the bimodal pattern in penaeid recruitment to the peak spawning periods for these species. Emmerson (1986) identified a slightly different pattern when examining the caridean shrimp, *Palaemon peringueyi* (Stebbing, 1915). The peak in recruitment of this species occurred during summer in three Eastern Cape estuaries. This study identified a corresponding peak period of recruitment for this species in December.

The relatively high winter and summer recruiter densities (Figures 6.2 and 6.4) recorded during this study can be attributed to a single shoal of the mysid, *G. brevifissura* in selected months. In winter they recruited during a two hour period in August, which accounted for more than 85% of the total catch by density during that month, while in summer they recruited during February, contributing ≈75% of the total catch in that month. The high recruitment densities recorded during October and November could be attributed to a combination of species, including *G. brevifissura* and *G. psammodytes,* which accounted for ≈80% of recruiters during both months. Large shoals of mysids such as those reported above have been previously recorded, with authors reporting shoals of up to 20 000ind.m^{-3} recruiting into estuaries on nocturnal flood tides (Wooldridge, 1983). There was no relationship between temperature and recruiter densities or biomass, with the intermediate densities and biomass occurring during the two seasons with temperature extremes, i.e. summer and winter.

The fluctuations in seasonal recruiter biomass can similarly be attributed to single shoals of species recruiting into the Kariega Estuary. The relatively high average winter biomass (Figures 6.3 and 6.5) was a result of a swarm of adult *G. brevifissura*, and to a lesser extent, *P. indicus*, recruiting into the estuary during August. Swarms of adult *G. brevifissura* recruiting during January and February similarly resulted in a high average biomass, relative to density, being recorded during summer (Figure 6.5). Alternatively, the high average biomass recruiting during spring was contributed to by a variety of species across all three of the respective months.

The abovementioned dominance of most months by one or two species is reflected in the low calculated diversity indices (Table 6.2). This is a result of diversity indices considering the distribution of individuals across the recorded species (Zar, 1996). The slightly higher diversity recorded during December, March and April was as a result of additional species (e.g. *Rhopalophthalmus terranatalis* [Wooldridge, 1986] and *Gastrosaccus olivae* [Bacescu, 1970]) contributing to the recorded densities. Margalef’s Species Richness considers primarily the number of species recorded and secondly the densities recorded (Zar, 1996). This interaction accounts for the relatively high richness recorded during April and June despite these months not dominating in terms of species numbers (Table 6.2).

Some of the species recorded recruiting into the Kariega Estuary during this study are beyond their natural range (e.g. *P. indicus* and *M. monoceros*). Both species are recorded in the current literature as subtropical species, while the study estuary is considered to be in a warm-temperate biogeographic zone (Branch *et al.*, 1999). The recruitment of these individuals is most likely a result of warm water pulses into the region through the Agulhas Current, which flows from the tropical northern Mozambique coastline down the eastern coast of southern Africa.

In all months, with the exception of September, daytime recruitment densities and biomasses were significantly lower than those recorded during the night time ($p<0.05$; Figure 6.2 and 6.3). The anomalous result during September was attributed to a swarm of *P. indicus* recruiting into the estuary shortly after sunrise. Wooldridge (1991) and Wooldridge and Loubser (1996) recorded maximum recruiter densities during nocturnal hours for *P. peringueyi* and *U. africana*, respectively. Alternatively, Forbes and Benfield (1986b) recorded two different nocturnal patterns in *Penaeus japonicus* (Bate, 1888) and *P. indicus*, with *P. japonicus* recruitment being recorded predominantly during the night-time, while *P. indicus* occurred in similar numbers during both the daytime and night-time samples. This concurs with the results observed during this study, with the only large daytime recruiting event being recorded for *P. indicus* (Table 6.3).

Few studies examining invertebrate recruitment into South African estuaries have been conducted to date. Wooldridge (1991) and Wooldridge and Loubser (1996) examined the tidal exchange of *P. peringueyi* and *U. africana* across the mouth inlets of two east coast estuaries, the Swartvlei and Gamtoos, respectively. The study by Wooldridge and Loubser (1996) identified a maximum of approximately 90ind.m^{-3} of *U. africana* postlarvae entering the Gamtoos Estuary on the flood tide, while Wooldridge (1991) recorded a maximum of 8ind.m^{-3} of *P. peringueyi* and 9ind.m^{-3} of *U. africana* entering the Swartvlei Estuary. This study has identified a similar number of *P. peringueyi* entering the Kariega Estuary at a monthly average of 6.79ind.m^{-3} (Table 6.3). Other decapods, however, were recorded recruiting at substantially higher densities, e.g. *P. indicus* (47.12ind.m^{-3}), *M. monoceros* (30.07ind.m^{-3}) and *M. africanum* (76.70ind.m^{-3}).

Due to the lack of salinity cues from the Kariega Estuary, this high recruitment of a number of decapod species indicates that salinity is not the primary cue that triggers recruitment of these species into estuaries. It is worth noting that a recent study showed that the recruitment of the sparid, *Rhabdosargus holubi* into southern African estuaries is the result of cues other than salinity (James, 2006). Selection experiments demonstrated that this fish species had a preference for terrestrial and estuarine water over marine water despite standardising of salinity (James, 2006). Alternatively it is possible that the recruitment of macrozooplankton into the estuary is the result of passive movement of individuals through the mouth of the estuary on tidal currents.

Previous studies on specific species, have recorded the majority of recruitment occurring on incoming tides (Forbes and Benfield, 1986b; Epifanio, 1988; Dame and Allen, 1996; Wooldridge and Loubser, 1996; Forbes and Demetriades, 2005). This is explained by the theory of tidal pressure induced responses in zooplankton assisting these animals in recruitment into estuaries. Forbes and Benfield (1986b) and Rothlisberg *et al.* (1995) have reported a pressure induced response in the penaeid prawns as postlarvae near the coast. The response involves a greater relative difference in pressure between ebb and flow tides, allowing the animals to identify in which direction the water is flowing. As pressure increases the postlarvae move into faster flowing surface waters, which results in a greater likelihood of the postlarvae being imported into estuaries (Little and Epifanio, 1991; Rothlisberg *et al.*, 1995).

6.4.1 Final conclusions

This study has presented results on a variety of different temporal scales, including seasonal and diurnal scales, which indicate different controlling factors that interact in terms of macrozooplankton recruitment to cause an overall maximum during nocturnal spring tides. Temperature and spawning season influences the seasonal patterns (Wooldridge, 1999; De Villiers *et al.*, 1999), resulting in a spring maximum in recruitment. Additionally, the diel trends indicate a general preference for nocturnal recruitment amongst the majority of species, which is suggested to be a predator avoidance mechanism (Grindley, 1972; Hart and Allanson, 1975; Jerling and Wooldridge, 1992; Wooldridge, 1999).

CHAPTER 7

GENERAL DISCUSSION

The aquatic habitats in the Coastal Transition Zone (CTZ) include the nearshore marine environment and the estuaries along the coastline (Schaefer, 1972). These habitats are considered important both anthropogenically and biologically due to this zone providing both ecosystem and human services out of proportion of its areal extent (Costanza *et al.*, 1997; Levin *et al.*, 2001). Productivity within the CTZ accounts for approximately 20% of all oceanic production, with 30% of this productivity being used by human fisheries (Pauly and Christensen, 1995; Liu *et al.*, 2000). Approximately 60% of the world's human population live within 100km of the coastline, and the economic value of ecological and human services that the CTZ provides is estimated to be US$12.568 trillion per annum globally (Costanza *et al.*, 1997; Vitousek *et al.*, 1997; Talley *et al.*, 2003). Due to the above mentioned high use of the CTZ, it is imperative that a better understanding is gained of the ecological links in this zone (Costanza *et al.*, 1997; Levin *et al.*, 2001; Talley *et al.*, 2003).

In South Africa the ecological functioning of the CTZ has come under threat directly from human activity in this area, and indirectly due to modifications of the riverine systems that feed estuaries and the adjacent marine environment with fresh water (Morant and Quinn, 1999; Grange *et al.*, 2000). Human activity in the CTZ includes a variety of recreational, commercial and subsistence services (Bruton, 1988; Breen *et al.*, 2004). In addition, there has been an increase in impoundments as well as several inter-basin transfers on some of South Africa's rivers due to the high anthropogenic demand for fresh water (DWAF, 2004a).

Due to the generally uni-directional flow of water through estuaries, it has been hypothesised that there is a net export of biological productivity to the marine inshore area (Dame and Allen, 1996; Roegner and Shanks, 2001). International studies have demonstrated differential biological export and import between estuaries and the marine environment in the form of chlorophyll-*a* and larval and adult invertebrates and fish (Sanchez-Velasco *et al.*, 1996; Roegner, 1998; Roegner and Shanks, 2001; Espinosa-Fuentes and Flores-Coto, 2004). Studies of this nature have not been conducted in South Africa to date, or indeed internationally in similar sized estuaries, and our understanding of the biological links between estuaries and the marine environment is, therefore, limited. The lack of information, in particular baseline data is a matter of serious concern as estuaries and their water supplies come under increasing developmental pressures (Avis, 1998).

7.1 FINDINGS FROM THIS STUDY

The “Outwelling Hypothesis” by Odum (1968; 1980) states that the productivity in estuaries is too high to be used within these systems and therefore excess production will be exported to the adjacent marine environment. No research has been carried out examining the impact of biological export from estuaries on the marine environment in the southern African region to date. The international literature has begun to examine this effect, but the research efforts have been concentrated on relatively large estuaries in the Americas and Europe. South African rivers are relatively small, with no large or navigable systems in the region and the river runoff totalling less than half the flow of the Zambezi River (DWAF, 2004a). Other regions in the world with comparable estuaries include Australasia and a few systems on the west coast of South America (Potter *et al.*, 1990). To date only one study of this nature has been conducted on any estuary within these regions, examining the effect of the temporarily open/closed (TOC) St Lucia Estuary on the fish communities in the adjacent marine environment on the north-east coast of South Africa (Harris *et al.*, 2001). Due to the relatively low fresh water flow rates entering the estuaries along the South African coastline, the applicability of the outwelling hypothesis in terms of biotic components of estuaries is uncertain.

This study is the first to examine the effect of biotic export from both permanently open and temporarily open/closed estuaries (TOCE) with low fresh water flow rates. The study took place along a short stretch (≈60km) of the Eastern Cape coastline in South Africa. The permanently open systems examined included the Great Fish Estuary, which is regarded as a fresh water dominated system, and the fresh water deprived Kariega Estuary. In addition, two TOCEs were also studied, namely the Kasouga and East Kleinemonde estuaries.

The examination of the biotic interactions between the marine environment and the permanently open estuaries (Chapter 3) identified export of chlorophyll-*a* and particulate organic matter (POM) from both estuaries during all seasons. The fresh water dominated Great Fish Estuary did, however, provide a greater contribution to the marine environment than the fresh water deprived Kariega Estuary. Similarly, zooplankton congregations were noted adjacent to the mouths of both these estuaries during all seasons, but they were in greater concentrations adjacent to the Great Fish. A similar finding was noted by Espinosa-Fuentes and Flores-Coto (2004), who identified a variety of fish communities in the nearshore environment off different rivers and coastal lagoons in the Gulf of Mexico. The extent and distribution of the different communities was found to be dependent on the volume of fresh water outflow from each individual system (Espinosa-Fuentes and Flores-Coto, 2004). This result is in agreement with that presented by Harris *et al.* (2001) for the TOC St Lucia Estuary, where separate fish communities were identified at different distances offshore relating to changes in salinity and turbidity during the open mouth phase of this system. Roegner (1998) and Roegner and Shanks (2001) identified contrasting results in terms of chlorophyll-*a* flow between the marine environment and Eel River (Nova Scotia) and the marine environment and South Slough (Oregon). The Eel River was characterised by higher flow rates and continually exported chlorophyll-*a* to the marine environment (Roegner, 1998). Alternatively, in South Slough Estuary chlorophyll-*a* was imported into the system due to the high chlorophyll-*a* concentrations, derived from upwelling, in the adjacent marine environment (Roegner and Shanks, 2001).

An isotope study (Chapter 5) conducted within, and adjacent to the two permanently open systems, indicated a contribution of estuarine derived biological material to the adjacent marine environment. The distance along the coastline that the estuary influenced was highly dependent on the magnitude of fresh water flowing into the estuary. The $\delta^{13}C$ signature from the Great Fish Estuary POM and vegetation could be detected in filter feeders and the marine inshore POMs up to 12km downstream of the estuary mouth. Alternatively, the $\delta^{13}C$ values of the POM and vegetation from the Kariega Estuary were traced in the inshore marine environment for less than 1km from the mouth. These results are supported by international studies which have identified different export rates of terrestrially derived POM under varying flow regimes (Darnaude *et al.*, 2004; Darnaude, 2005). Darnaude (2005) indicated that terrestrially derived biotic material was crucial to productivity in European coastal waters. Mulkins *et al.* (2002) similarly related seasonal changes in the $\delta^{13}C$ ratios of mysids in Cow Bay (British Columbia) to changes in diet due to variability in fresh water flow rates of the adjacent creeks affecting the availability of terrestrial food sources.

An examination of the interactions between the TOCEs and the inshore marine environment (Chapter 4) demonstrated that during the closed phase, these systems had a reduced impact on the adjacent marine environment. During the open phase this interaction increased significantly. While the TOCEs were separated from the marine environment there was some evidence to suggest that they had an influence on the biology in the adjacent marine environment due to the increase in chlorophyll-*a* concentrations and zooplankton biomass and density directly adjacent to the East Kleinemonde Estuary mouth. This is likely due to seepage of nutrient rich water along the bedrock of the estuary causing a localised increase in biological activity adjacent to the estuary mouth. No studies have been conducted on the potential export or import of biotic material from estuaries of this size and longer term work is needed to provide greater clarity on the seasonal fluctuations in these interactions. In addition, the impoundment of many river systems in the southern African region may result in a change in the nature of the associated estuaries, causing longer term closure of these systems and therefore reduced direct interactions with the marine environment (Whitfield and Wooldridge, 1994; Schlacher and Wooldridge, 1996a; Whitfield, 2005). A greater understanding of the role of these estuaries in inshore marine ecology is needed prior to altering these systems. Harris *et al.* (2001) represents the only study of biotic marine-estuarine interactions on a TOCE, albeit a very large system, unlike the small estuaries examined in this study. The study did not examine the biological components of chlorophyll-*a* and particulate organic matter, but the findings indicated that during the open phase, the St Lucia estuarine lake influenced the composition of fish communities in the adjacent marine environment, with four different communities forming at different distances from the estuary, related to salinity and turbidity variations (Harris *et al.*, 2001).

One stochastic feature which seems to override the production exported into the adjacent nearshore environment by estuaries is coastal upwelling. The biological activity recorded in the nearshore environment after an upwelling event is substantially greater than that derived by the export of nutrients and biological matter from the estuaries themselves. The overriding influence of an upwelling event was evident in this study during the March 2005 marine survey on the permanently open estuaries, with higher chlorophyll and zooplankton biomass and densities occurring off both the Kariega and Great Fish Estuaries (Chapter 3). Proof of an upwelling event is evident in satellite imagery for that period (www.rsmarinesa.org.za), which demonstrates water temperatures 3 – 4ºC lower than average three days prior to the survey. Similar results have been identified in North America, with larger estuarine embayments importing chlorophyll-*a* from the marine environment due to high upwelling derived productivity occurring adjacent to the estuary (Roegner and Shanks, 2001). Due to the large spatial separation of upwelling cells along the east coast of South Africa and the unpredictable nature of these cells, their contribution to coastal primary productivity is uncertain. There are two main upwelling cells along the east coast of South Africa, one in northern KwaZulu-Natal, and the second centred on Port Alfred (Lutjeharms *et al.*, 1989b; Lutjeharms, 1998; Lutjeharms, 2005). The periodicity of these upwelling events is continually being reviewed, but the current literature indicates that upwelling or its effects are evident in the Port Alfred region on 45% of days (Lutjeharms *et al.*, 2000). The biotic matter exported to the inshore marine environment adjacent to the Great Fish and the fresh water deprived Kariega Estuary likely supports the biota in the intervening periods between upwelling events.

In addition, although TOCEs do not continuously supply nutrients and biotic material to the marine inshore environment, this type of estuary is numerically dominant along the east coast of South Africa, with 27 occurring along a 150km stretch of coastline between Woody Cape and East London (Whitfield, 2000). The proliferation of these estuaries combined with their simultaneous breaching, results in an overall pulse of nutrients and biotic matter into the marine environment that is likely to be substantial. This agrees with similar comments by Lukey *et al.* (2006) when observing the mass export of sub-adult fish into the marine environment upon breaching of TOCEs.

The recruitment of larval macrocrustaceans into the Kariega Estuary was examined monthly over a period of one year (Chapter 6). Several macrozooplankton species were recorded recruiting into the estuary that were not expected due to the lack of any records of these species in the region. These southern range extensions may be due to biota being trapped in warm water cells moving down the east coast in the Agulhas Current (Norton, 2005; Teske *et al.*, 2006). Surveys along the entire length of the Kariega Estuary did not demonstrate persisting communities of many of the species that were recorded recruiting into the system. Anecdotal information from fishermen supports the recorded data due to reports of occasional schools of these larger species occurring in the upper reaches of the estuary. However, this study indicated that the recruitment of macrocrustaceans of all species occurs throughout the year, with peak densities recruiting during the spring months. Additionally, the majority of recruitment occurs during nocturnal hours and on the incoming tides, and is likely to be a passive process, with the juveniles and larvae moving into the surface waters after dark and being imported into the estuary on flood tidal currents. The large numbers of individuals recorded recruiting into the Kariega Estuary and not being subsequently recorded supports the notion that the food web within this system may be driven by both marine and estuarine sources, with these recruiting crustaceans most likely being predated upon by fish using the estuary as a nursery area.

The interactions between estuaries and the inshore marine environment are complex and dependent on the volume of fresh water entering the study estuary as well as coastal processes. Largier (1993) has described estuarine fronts in the marine environment as being very important to both commercial and recreational fishes due to the high productivity associated with these zones. Adjacent to the large permanently open estuaries with high fresh water flow rates along the South African coast, this is likely to be even more applicable due to the otherwise temporally variable nutrient sources available in the marine inshore zone.

Harrison (2004) has related the physico-chemical characteristics and mouth status of estuaries to the catchment size and biogeographic region in which they occur. Similarly, the importance of terrestrially derived (estuarine) contributions to inshore marine ecology most likely varies with geographic region along the South African coast due to the varied width of the continental shelf and the frequency of river mouths along the coastline. On the west coast of South Africa there are relatively few estuaries (Whitfield, 2000; Harrison *et al.*, 2000) and a narrow continental shelf, with frequent shelf-wide upwelling events extending right into the inshore environment (Lutjeharms, 2005). Alternatively, along the south coast of the country the continental shelf extends for up to 200km, moving the Agulhas Current and associated upwelling events offshore (Lutjeharms, 1998), and thereby increasing the importance of estuarine contributions to the nearshore marine ecology. On the east coast (north of Port Elizabeth) the frequency of estuaries increases substantially (Whitfield, 2000; Harrison, 2004) and the continental shelf narrows to approximately 30km wide, but there are only two recorded upwelling cells, one positioned off Port Alfred and the other in the Natal Bight (Lutjeharms *et al.*, 2000; Meyer *et al.*, 2002). The upwelling cells located off Port Alfred and in the Natal Bight result in increased nutrient concentrations in the surface waters, which promote production during an upwelling event (Lutjeharms, 1998; Meyer *et al.*, 2002; Lutjeharms, 2005). However, these upwelling cells represent a relatively small area of the coastline and are substantially more stochastic in nature than the upwelling that occurs on the west coast. Estuarine derived biological matter is therefore likely to be of greater importance in the marine inshore zone on the south and east coast of South Africa relative to the west coast of the country due to the predominance of estuaries and reduced frequency of upwelling in these regions. Along the west coast of the country, the frequency and volume of upwelling derived biotic matter in the inshore marine environment supersedes the importance of terrestrially derived biotic material for this region.

7.2 MANAGEMENT IMPLICATIONS

In South Africa the economic benefits of the CTZ have only been analysed in terms of fisheries. Lamberth and Turpie (2003) reported that estuarine and estuarine-dependent ichthyofaunal fisheries yielded approximately R1.251 billion ($181.30 million) during the 2002 financial year and De Villiers *et al.* (1999) estimated the value of the estuarine-dependent penaeid prawn fishery to be approximately R10 million ($1.45 million) per year. As of yet there are no real economic estimates for the financial benefits of the tourism and recreational industries that are prolific along South Africa’s coastline.

The implications for environmental managers resulting from this study relate to the water resources in South Africa. A DWAF report in 1986 reported that approximately 90% of Mean Annual Runoff in South Africa does not reach the coastal zone (DWAF, 1986). The true degree of this impact was described by Davies *et al.* (1993) in the following statement: “There are few rivers in southern Africa that have not been over-exploited, degraded, polluted, or regulated by impoundments, and we know of many that were once perennial, but which now flow only seasonally or intermittently”. Due to the water poor nature of South Africa, impoundments are required to meet the future anthropogenic water needs of the country. The National Water Act of 1998 protects the water resource and recognises the natural environment as a legitimate water user. This recognition of the natural environment as a water user leads to the management implications of this study.

The future establishment of impoundments and regulation of fresh water supplies to estuaries and therefore to the adjacent marine environment will have to take into consideration these downstream ecological users. This study demonstrates that the marine environment is reliant on the nutrients and biotic input derived from estuaries and the impacts of reducing fresh water must be considered for these ecological water users.

The results from this study on the Kariega Estuary demonstrated that despite substantial fresh water abstraction this system still results in increased biological activity in the adjacent marine environment due to its mouth being kept open by tidal currents and the rocky substrate (Chapter 3). However, the impact of the Kariega Estuary on marine inshore biology is considerably reduced relative to the other permanently open study estuary, the Great Fish. The results from this study have demonstrated that the influence on marine biology is similar to that recorded during the breaching of the nearby, substantially smaller, temporarily open/closed East Kleinemonde Estuary (Chapter 3, Chapter 4).

If in the future water is abstracted from most of the country’s permanently open estuaries, it seems unlikely that the ecological functions they provide can be maintained by the TOCEs along our coastline. This is due to the stochastic nature of the breaching of TOCEs, which does not provide the same continual supply of nutrients and biotic material to maintain the marine inshore environment. Further work is required to establish if during dry years or excessively wet years this will change, but the present study indicates that it would be preferential for inshore marine ecological functioning to abstract water from TOCEs than from permanently open estuaries. However, this has not considered the nursery functions that the TOCEs provide, but only considers the current knowledge of the impact of these systems on inshore marine biological activity.

7.3 FUTURE RESEARCH

Costanza *et al.* (1997), Talley *et al.* (2003) and Vitousek *et al.* (1997) have stated that the understanding of the connectivity of different habitats within the CTZ is fundamental to the ongoing maintenance of the ecological services that this zone provides. In addition, Gillanders *et al.* (2003) have stated that the understanding of the connectivity of juvenile and adult habitats is crucial for the long term conservation of species, as it will allow for more targeted management strategies.

In attempting to address some of these issues, this study has started addressing the interaction between fresh water input and the marine environment as well as indicating the potential importance of estuarine derived biological material for the marine environment. South African researchers are beginning to investigate the use of different habitats within the CTZ by individual species (Naesje *et al.*, 2005; Kerwath *et al.*, 2005; Potts *et al.*, 2005). To better appreciate the complex biological linkages between estuaries and the marine environment, and thereby allow better management of South Africa’s water resources, the following work should be conducted.

- Potts *et al.* (2005), Naesje *et al.* (2005) and Kerwath *et al.* (2005) are currently concentrating on species that are of fisheries importance and this work should be expanded to include additional species that move between CTZ habitats.
- The study described in this dissertation only examined permanently open estuaries at the extremes of fresh water flow. This work needs to be expanded to include permanently open estuaries throughout the continuum of flow regimes to enable water managers to better understand the implications for the nearshore marine environment of altering the flow regime of any individual system.

- In addition, permanently open estuaries in a variety of biogeographic zones should be investigated to identify if the response in the inshore marine environment differs within the various biogeographic zones along the southern African coastline.
- Current research is investigating the link between temporarily open/closed estuary (TOCE) flow rates and breaching frequency, with several studies indicating the importance of mouth opening events to maintaining natural communities in these systems (Whitfield and Bruton, 1989; Wooldridge, 1991; Whitfield and Wooldridge, 1994; Wooldridge, 1994; Wooldridge and Loubser, 1996; Whitfield, 1998; Froneman, 2002a). The work conducted during this study indicates that the biological and nutrient export from TOCEs may be important to the inshore marine biology. Further work should be conducted adjacent to different TOCEs in a variety of biogeographic zones to identify if there are different responses in the marine environment in the various biogeographic zones.
- Additional stable isotope studies including isotopes such as sulphur ($\delta^{34}S$) should be conducted on the biotic and detrital components of estuaries and the adjacent marine environment to enable a more detailed explanation of the links between estuaries and the nearshore marine environment. An analysis using sulphur isotopes was not possible due to financial constraints during this study, but sulphur has been identified as providing a better separation of marine derived sources from estuarine/fresh water derived sources and a study of this nature is therefore crucial.
- An examination of the productivity of estuarine/marine frontal systems in the inshore zone needs to be conducted in southern Africa as there is a general paucity of information on the functioning of these systems within the marine environment and their role in energy dynamics on the continental shelf.

7.4 FINAL CONCLUSIONS

This study is the first to examine the biotic links between the marine inshore zone and relatively small estuaries with relatively low flow rates. Similar work to date in the scientific literature has focused on large systems with relatively high flow volumes (e.g. Sanchez-Velasco *et al.*, 1996; Roegner, 1998; Roegner and Shanks, 2001;

Espinosa-Fuentes and Flores-Coto, 2004). This study identified a relationship between estuaries and the marine inshore zone in terms of the biological processes occurring in these ecosystems. The influence of estuarine water on the biology in the adjacent marine environment is determined by the volume of water transferred between the two habitats, whether tidally or by riverine output. The seepage of water through the sand berm that separates temporarily open/closed estuaries from the marine environment also appeared to influence the marine biological activity directly adjacent to these systems. Although both temporarily open/closed and permanently open estuaries have been shown to influence the marine inshore biological activity, stochastic upwelling events override this influence for short periods by contributing a large pool of nutrients to the marine inshore zone. However, permanently open estuaries produce a continuous supply of nutrients and biotic detritus to the marine inshore zone and are therefore important in bridging the periods between upwelling events. The biological activity in the inshore marine environment appears to be driven by a combination of upwelling events, continuous export from permanently open estuaries, and pulses of nutrients from temporarily open/closed estuaries, all of which play an important role in maintaining the high productivity associated with the inshore marine zone.

This study has indicated fresh water input as being important to the ability of estuaries, both permanently open and temporarily open/closed, to influence the biological activity in the marine inshore zone. This should therefore be taken into consideration by water managers in South Africa before reducing fresh water supplies to coastal ecosystems. The impact of reducing fresh water supplies to these ecosystems could be detrimental to a variety of ecosystem and anthropogenic functions they serve. Managers need to make decisions as to which ecological functions, if any, can be removed from individual estuaries and thereby determine how they will meet the growing anthropogenic water needs of future generations.

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APPENDIX 1

THE WIND SPEED AND DIRECTION ON THE SAMPLING DATE AND EVENING PRIOR TO THE MARINE SURVEYS OFF THE GREAT FISH, KARIEGA, KASOUGA AND EAST KLEINEMONDE ESTUARIES

Table A1.1: The wind speed ($m.s^{-1}$) and direction (compass point source) on the sampling dates (at 08h00) and evening prior to sampling (at 21h00) off the Great Fish Estuary (according to South African Weather Service Data for Port Alfred).

Survey Season	Date	On sampling date		Evening prior to sampling date	
		Wind Speed	**Wind Direction**	**Wind Speed**	**Wind Direction**
June	22/06/2004	3.0	East	0.0	North
September	21/09/2004	3.3	West	2.8	East
December	01/12/2004	3.1	East	5.9	West
March	08/03/2005	1.4	North-east	1.6	East

Table A1.2: The wind speed ($m.s^{-1}$) and direction (compass point source) on the sampling dates (at 08h00) and evening prior to sampling (at 21h00) off the Kariega Estuary (according to South African Weather Service Data for Port Alfred).

Survey Season	Date	On sampling date		Evening prior to sampling date	
		Wind Speed	**Wind Direction**	**Wind Speed**	**Wind Direction**
June	24/06/2004	2.4	East	1.7	East
September	23/09/2004	4.2	East	3.5	East
December	03/12/2004	0.3	East	4.2	West
March	09/03/2005	0.0	South	4.1	East

Table A1.3: The wind speed ($m.s^{-1}$) and direction (compass point source) on the sampling dates (at 08h00) and evening prior to sampling (at 21h00) off the East Kleinemonde Estuary (according to South African Weather Service Data for Port Alfred).

Survey Season	**Date**	**On sampling date**		**Evening prior to sampling date**	
		Wind Speed	**Wind Direction**	**Wind Speed**	**Wind Direction**
June	07/06/2005	2.9	East	2.2	East
September	08/09/2005	2.7	East	2.0	South-east
November	17/11/2005	4.2	East	7.7	South
March	28/02/2006	3.7	East	1.3	South

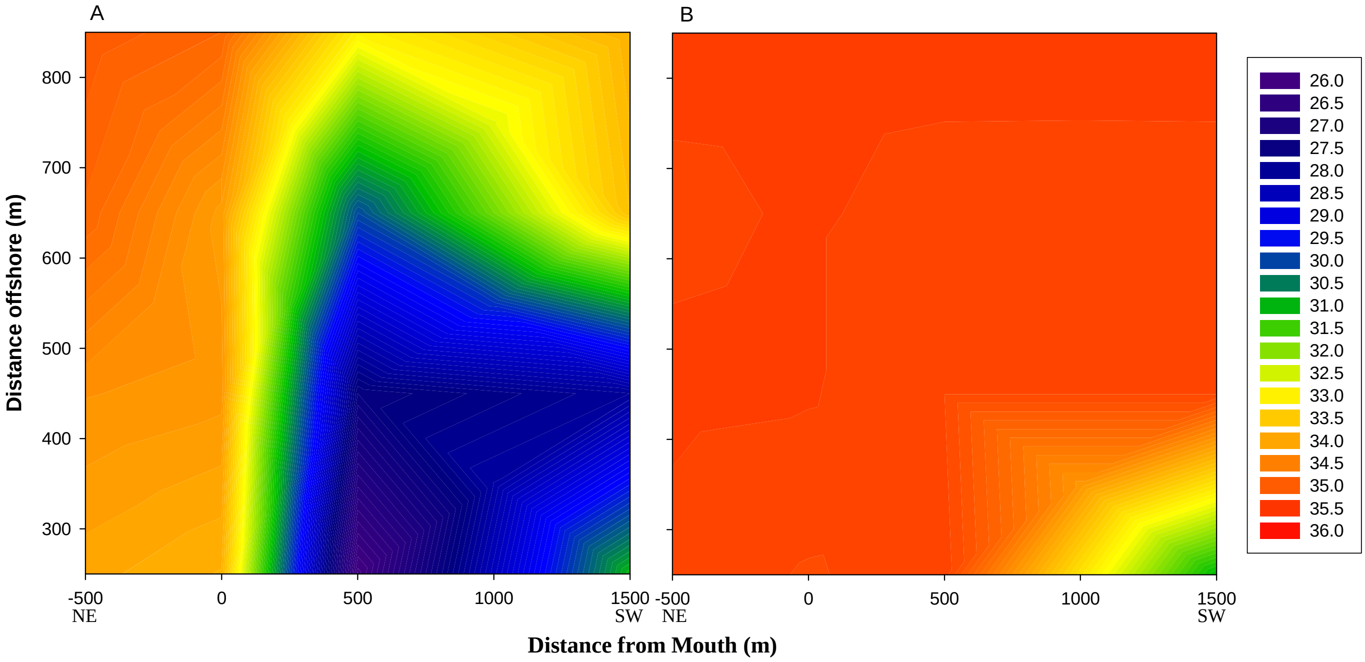
Table A1.4: The wind speed ($m.s^{-1}$) and direction (compass point source) on the sampling dates and evening prior to sampling off the Kasouga Estuary according to observations on the coast in Port Alfred.

Survey Season	**Date**	**On sampling date**		**Evening prior to sampling date**	
		Wind Speed	**Wind Direction**	**Wind Speed**	**Wind Direction**
June	21/06/2005	3.3	South-east	1.8	East
September	08/09/2005	2.7	East	2.0	South-east
November	17/11/2005	4.2	East	7.7	South
March	28/02/2006	3.7	East	1.3	South

APPENDIX 2

CONTOUR PLOTS OF THE PHYSICAL AND BIOLOGICAL DATA FROM THE MARINE ENVIRONMENT ADJACENT TO THE GREAT FISH AND KARIEGA ESTUARIES

Great Fish Estuary



Kariega Estuary

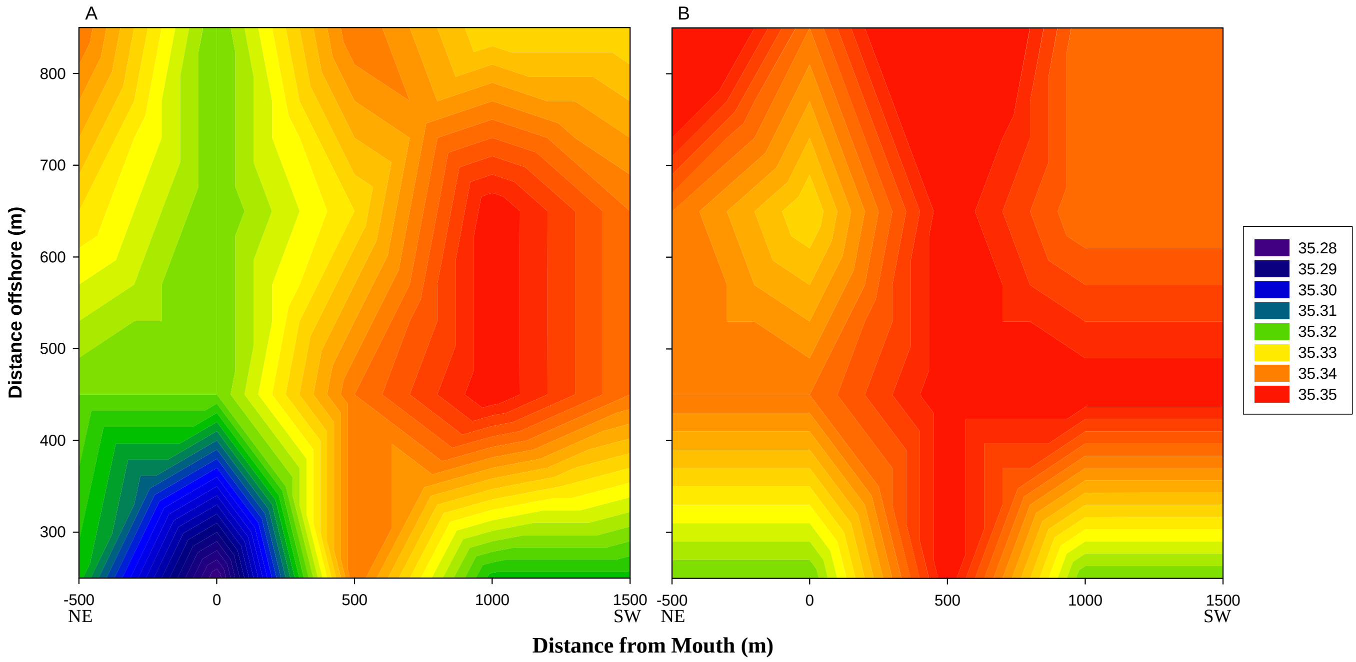
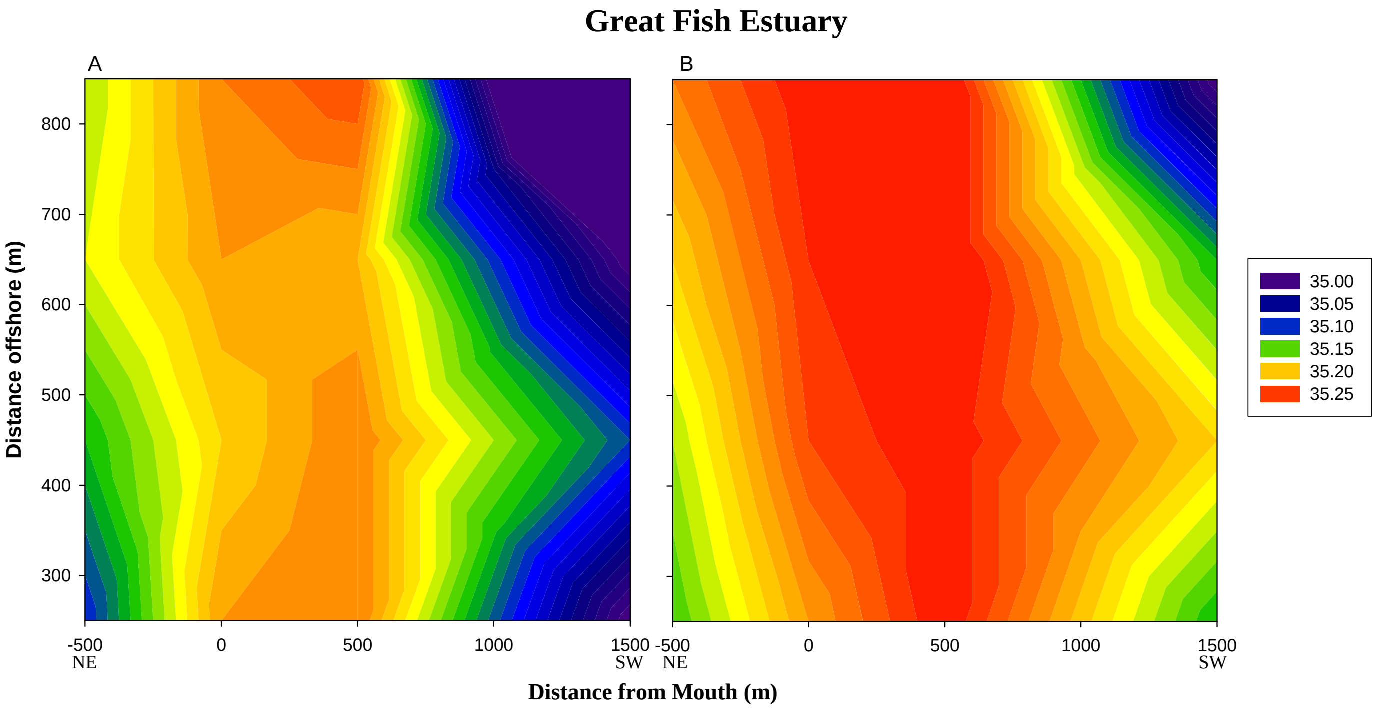


Figure A2.1: Salinity (practical salinity units) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during June 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.



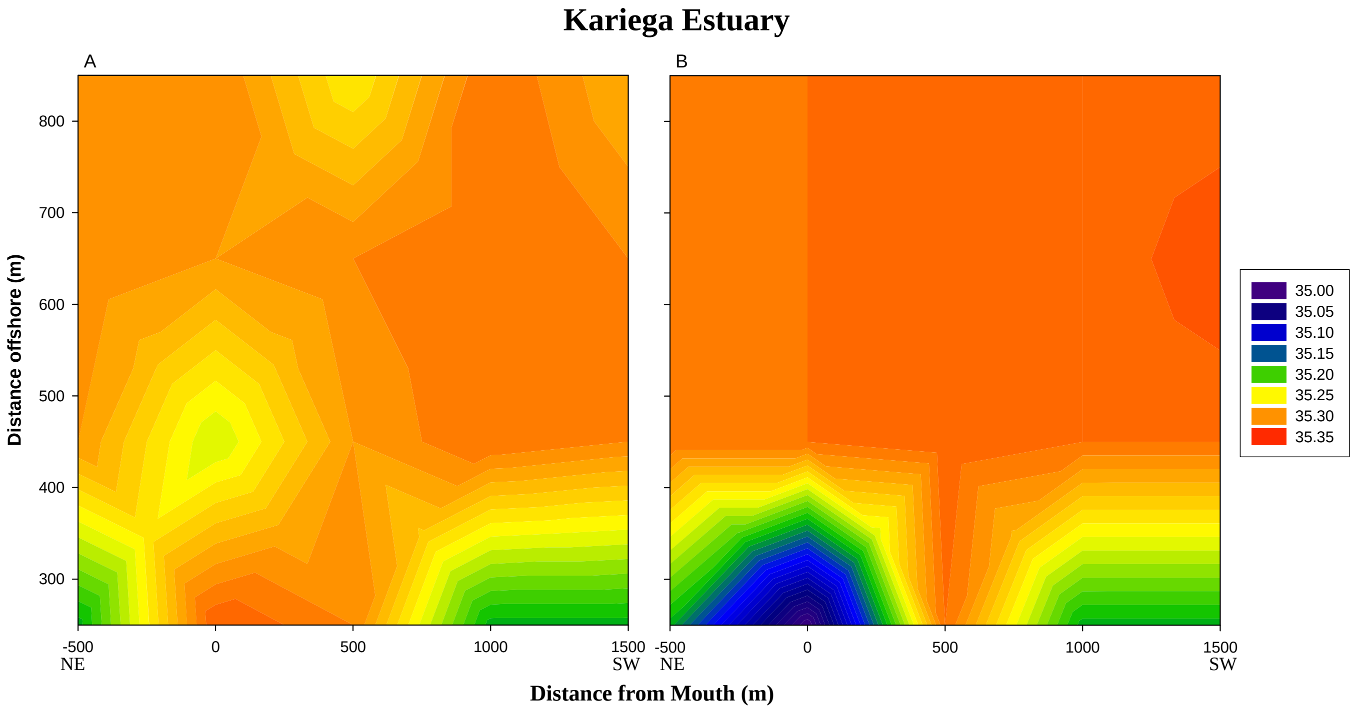
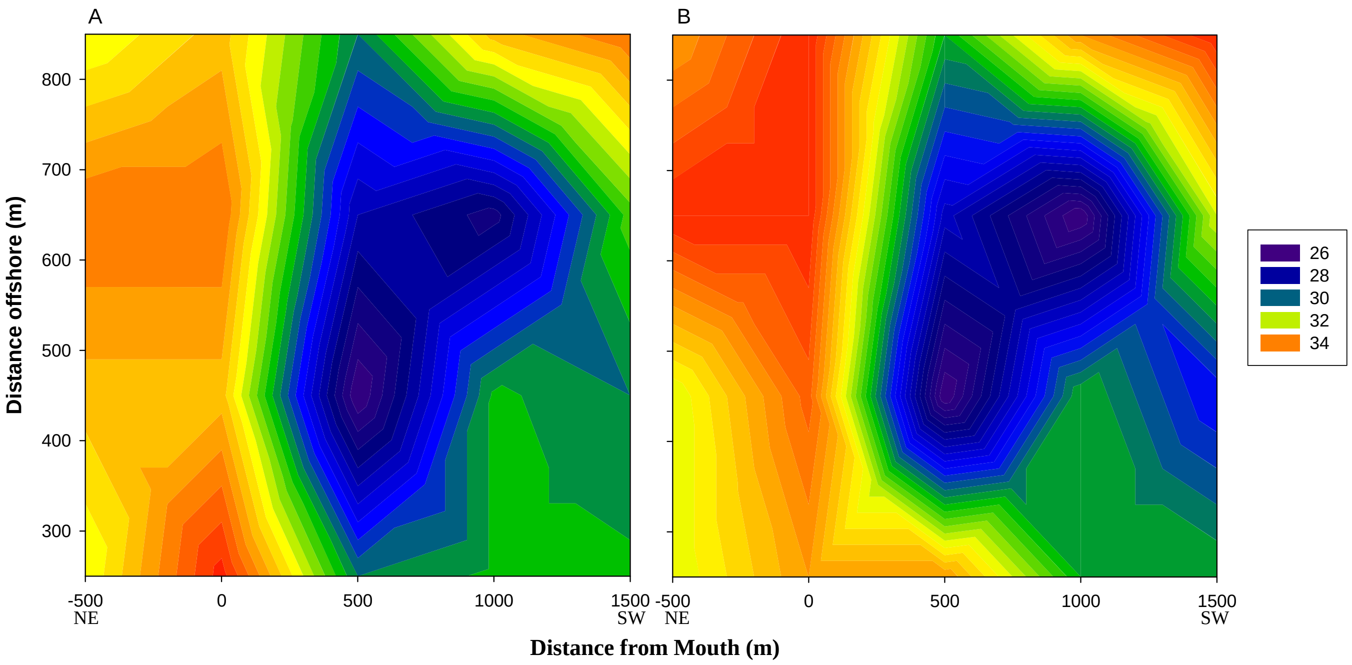


Figure A2.2: Salinity (practical salinity units) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during September 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

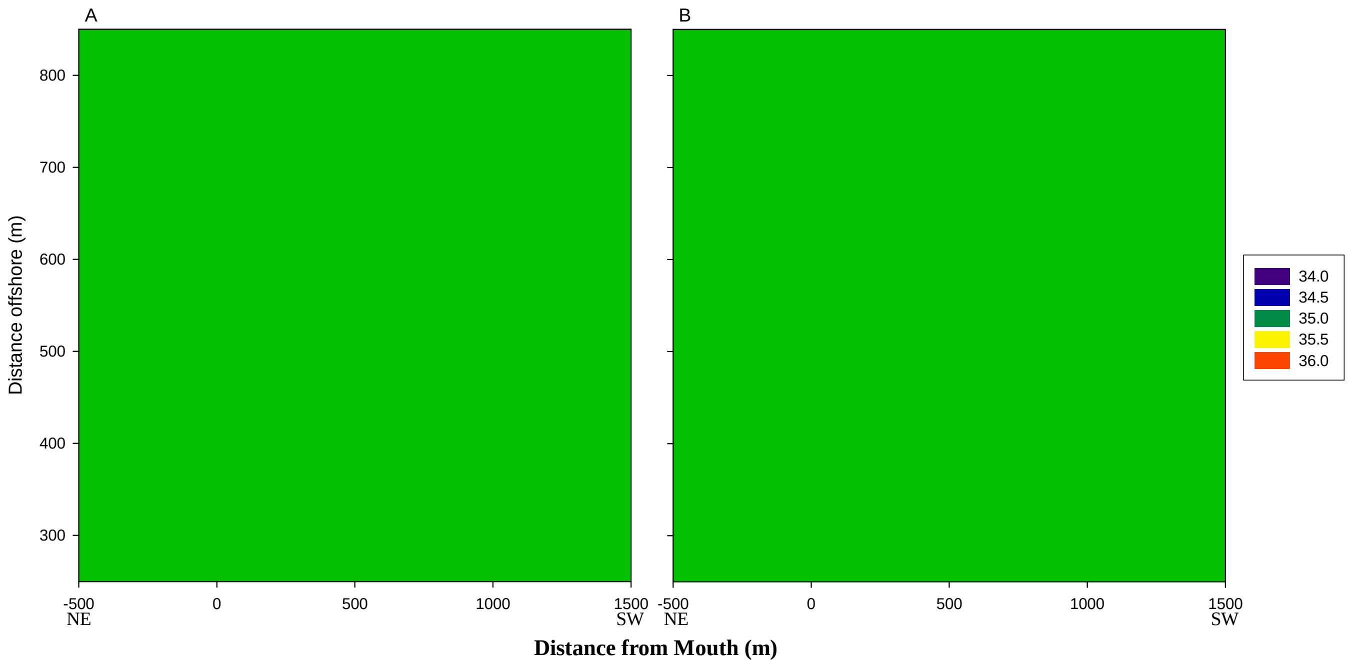


Figure A2.3: Salinity (practical salinity units) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during December 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

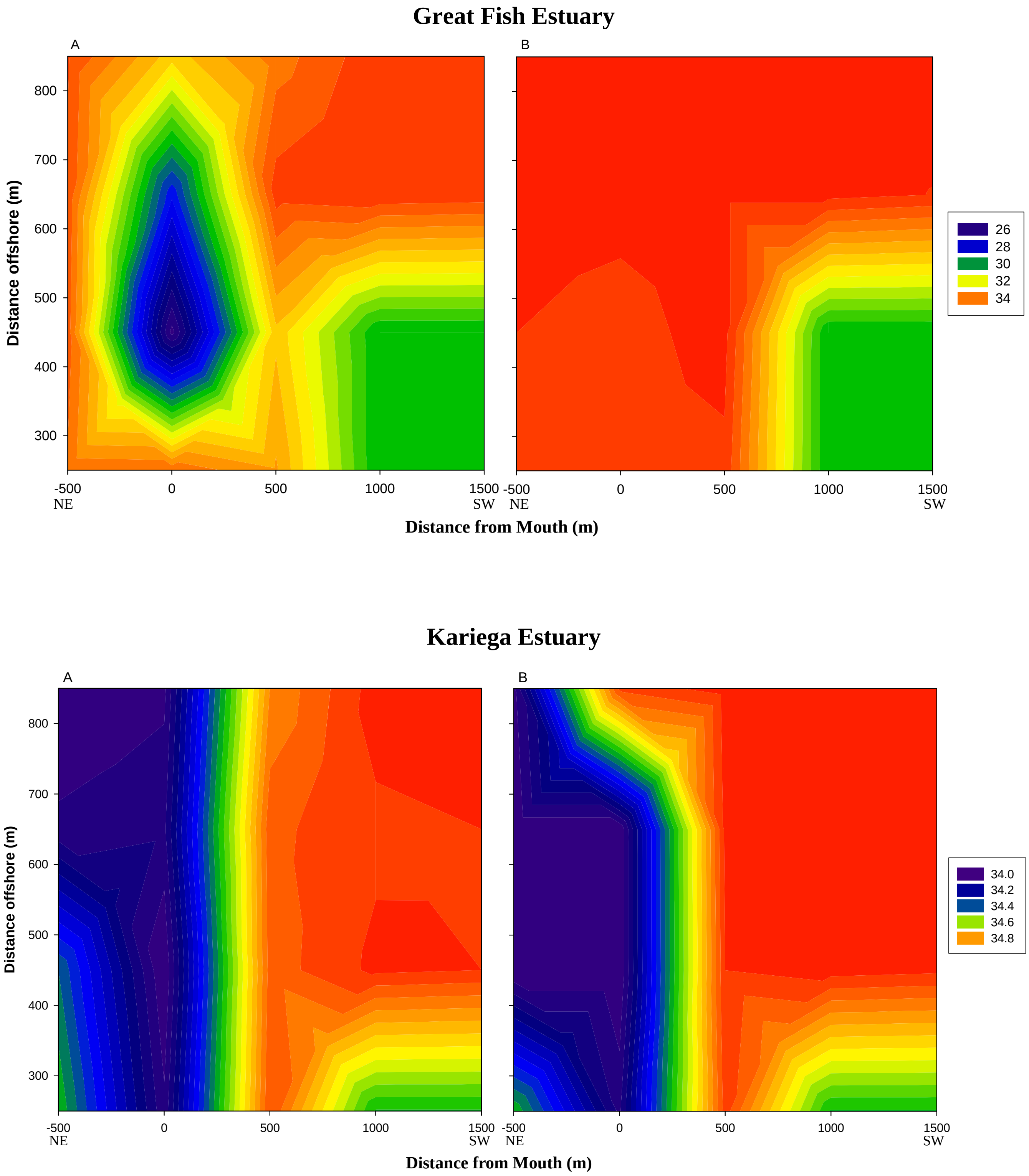
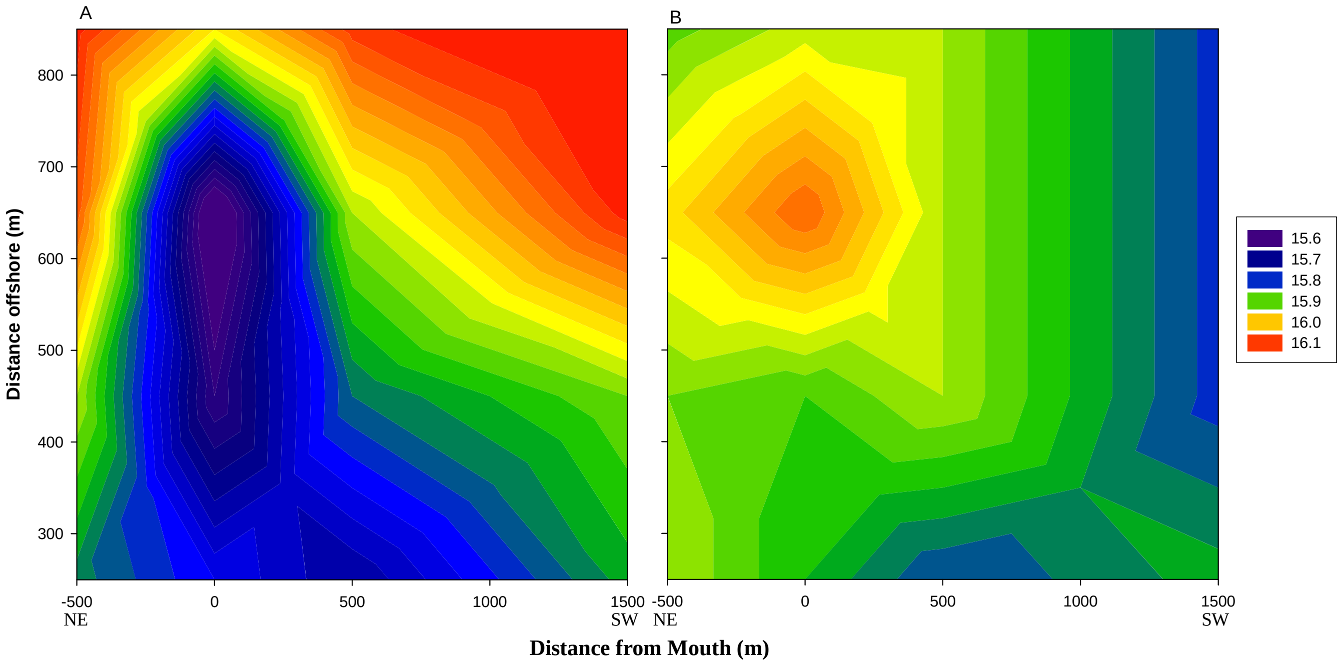


Figure A2.4: Salinity (practical salinity units) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during March 2005. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

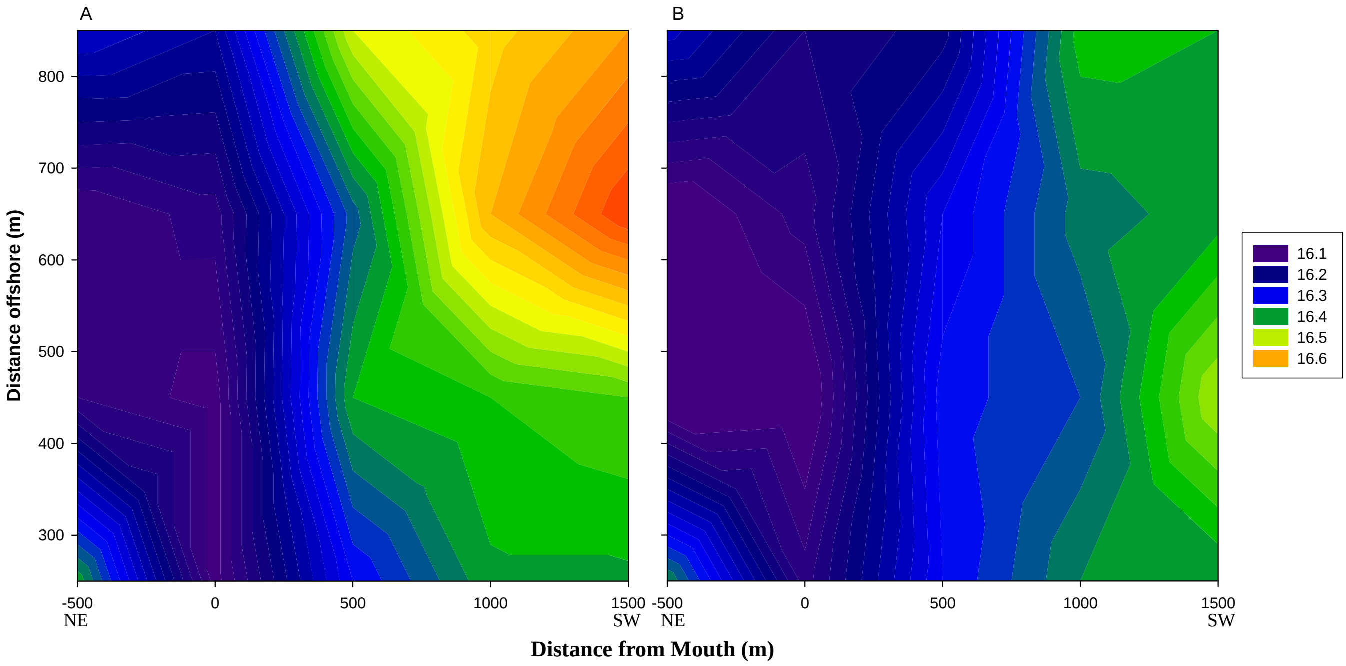
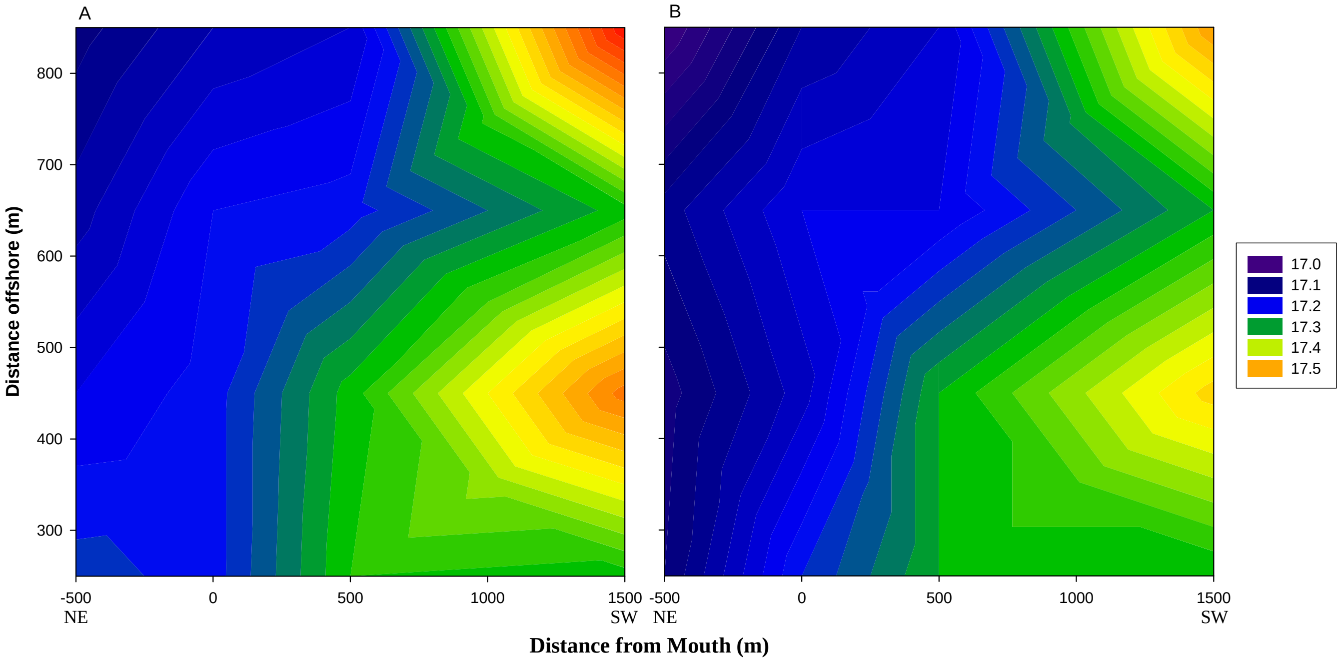


Figure A2.5: Water temperature (ºC) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during June 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

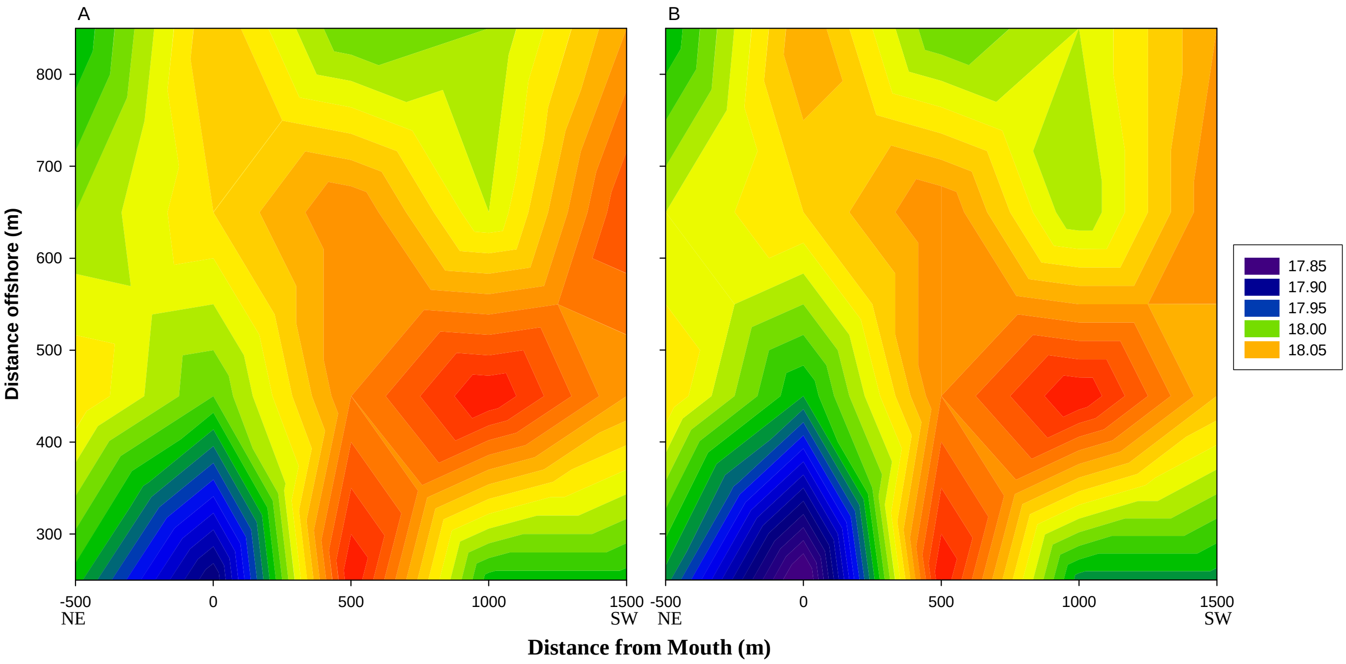
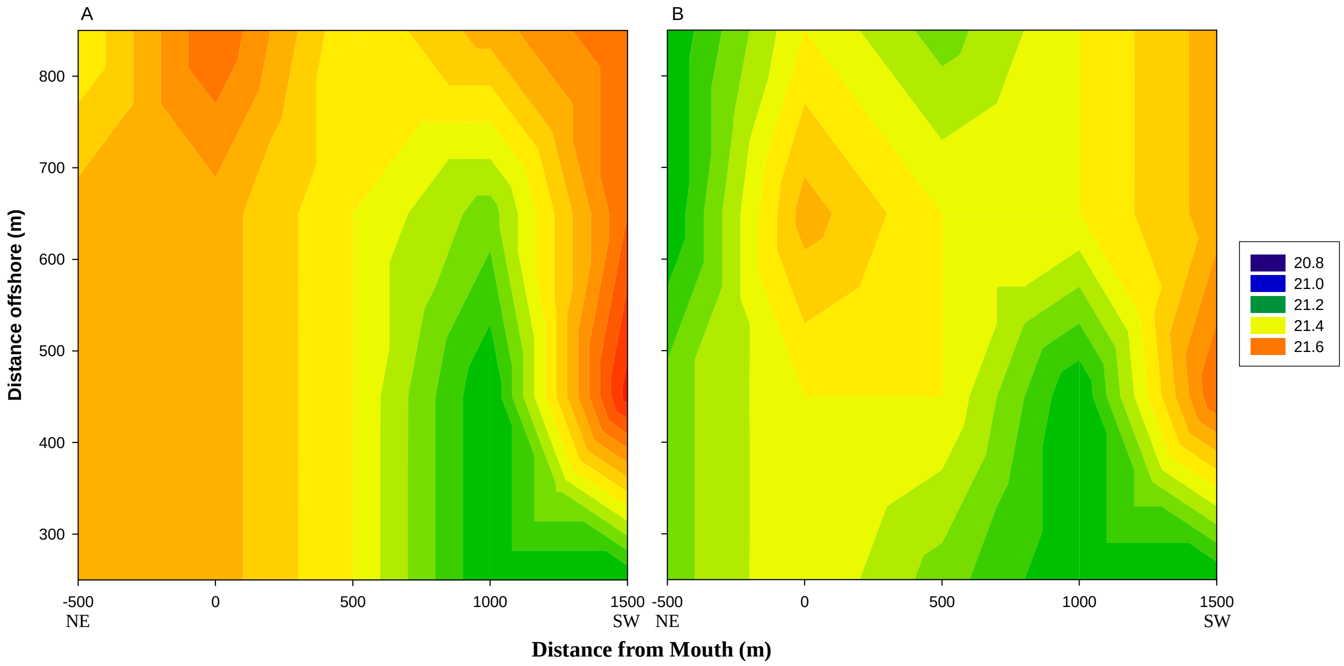


Figure A2.6: Water temperature (°C) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during September 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

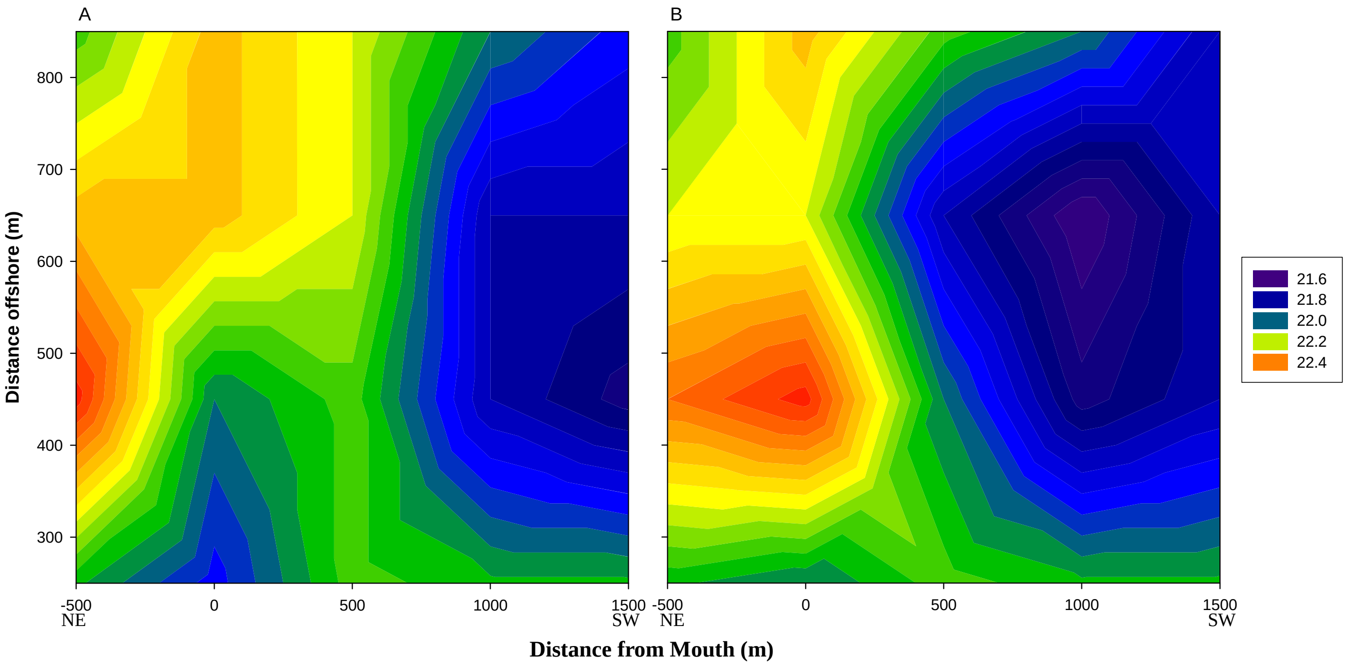
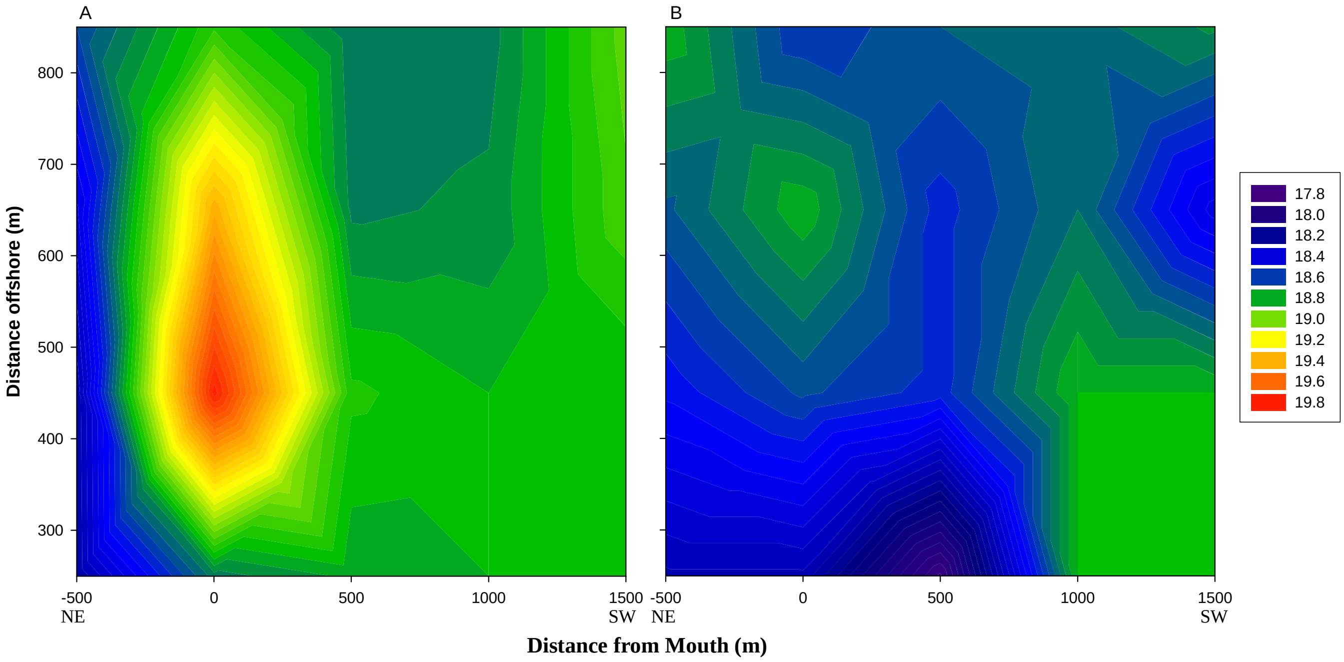


Figure A2.7: Water temperature (°C) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during December 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

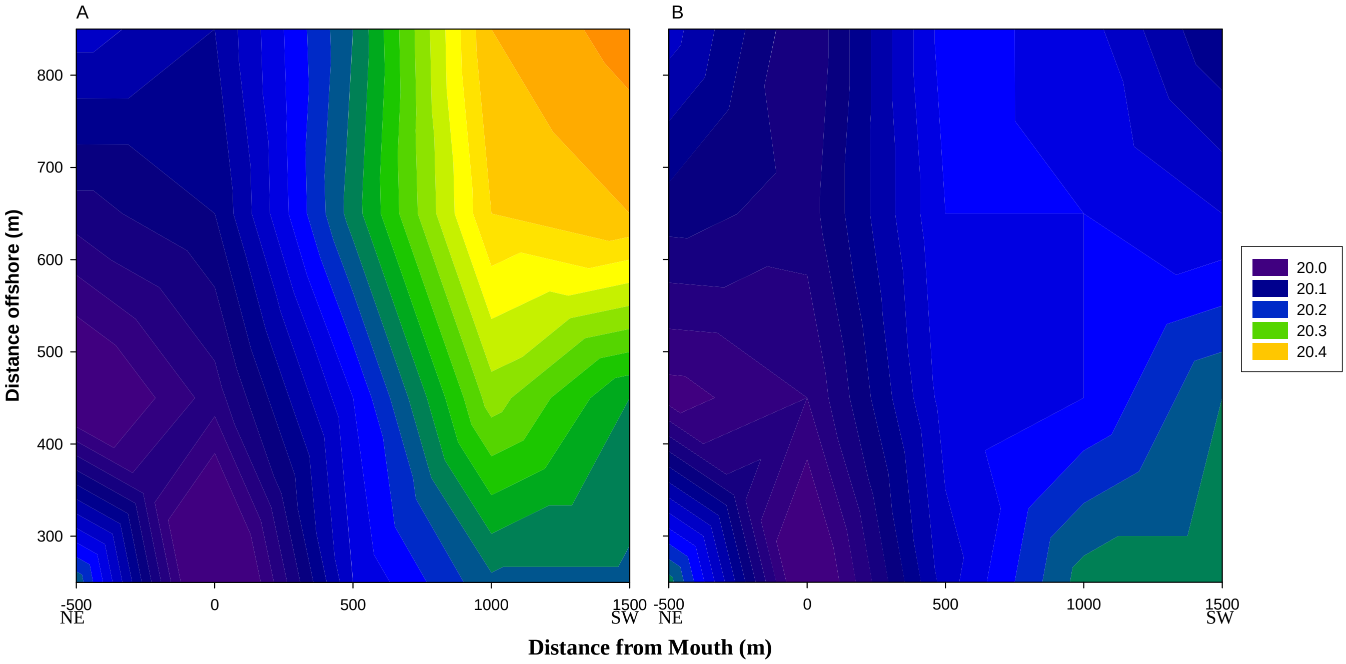
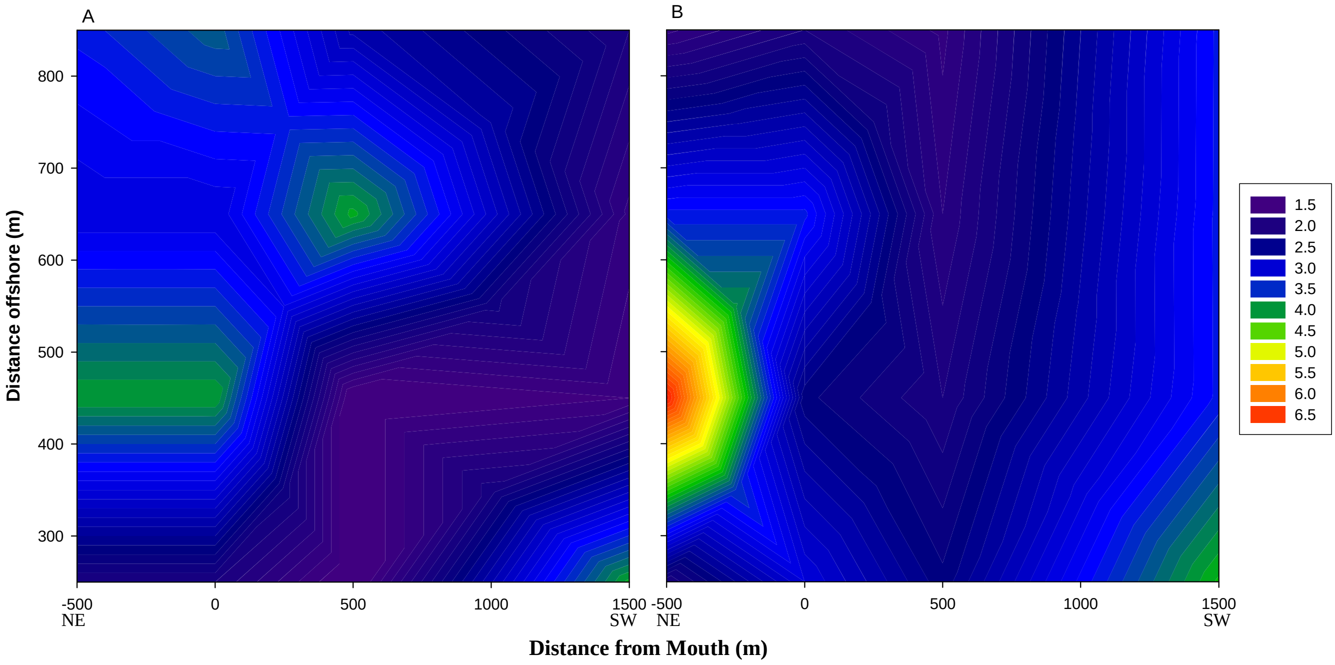
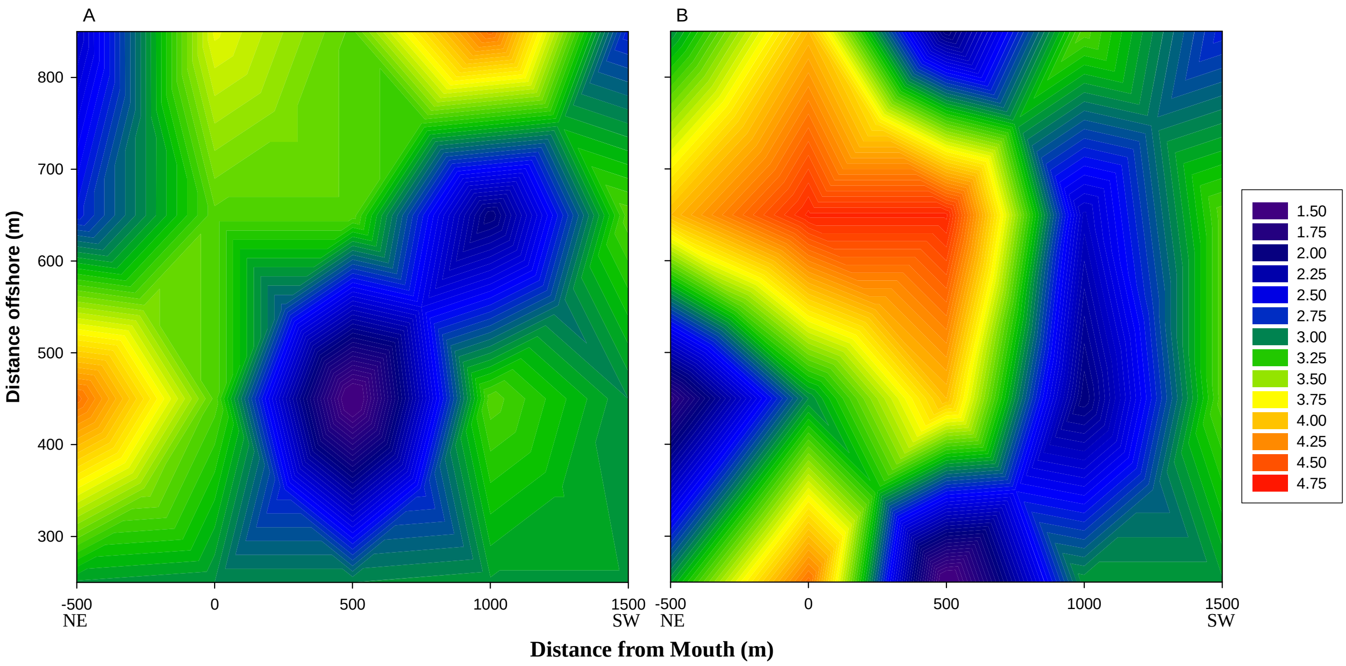


Figure A2.8: Water temperature (°C) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and at 5m (B) during March 2005. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.



Great Fish Estuary



Kariega Estuary

Figure A2.9: Particulate organic matter concentrations (mg.L^{-1}) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and 5m (B) during June 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

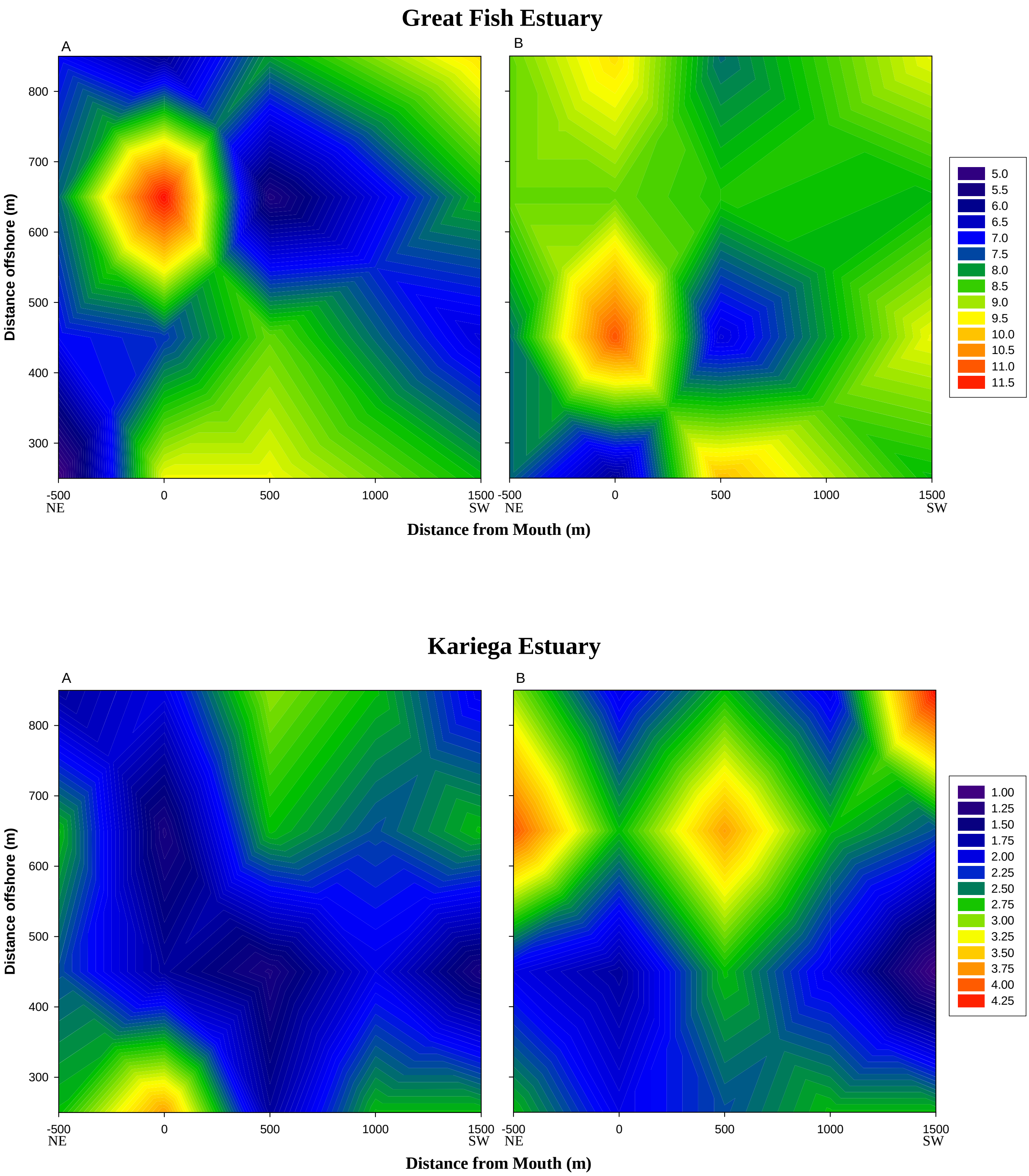
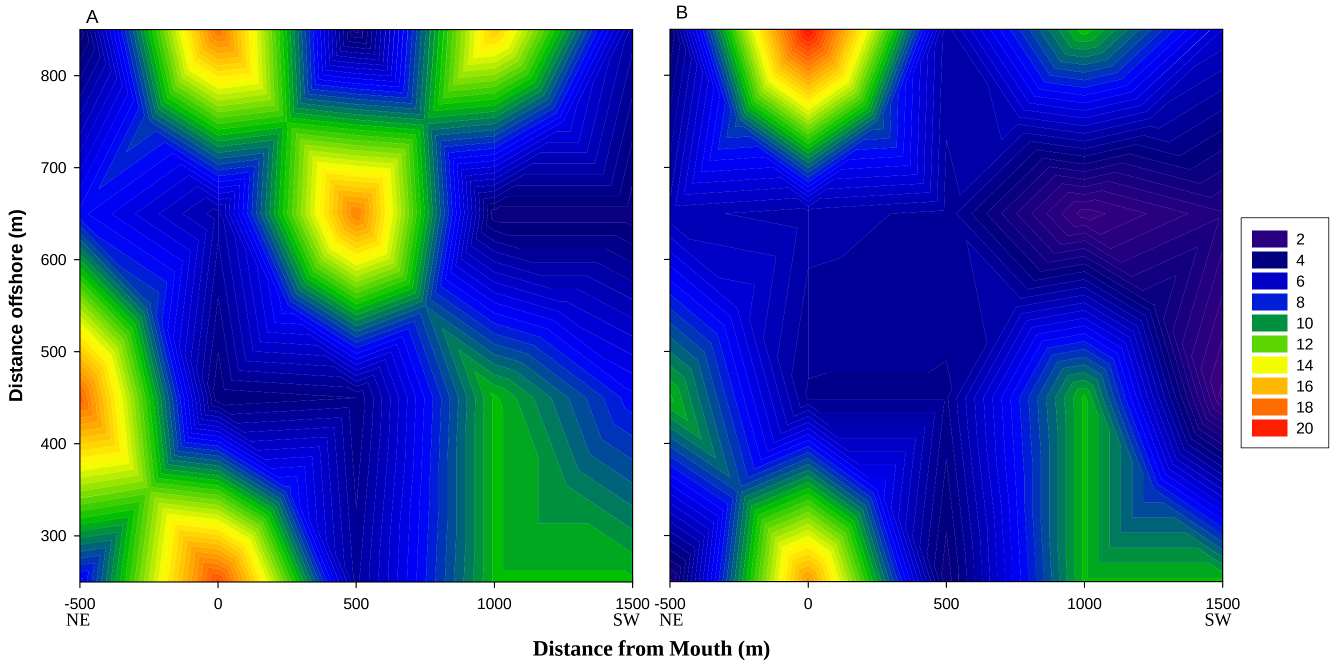


Figure A2.10: Particulate organic matter concentrations (mg.L^{-1}) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and 5m (B) during September 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

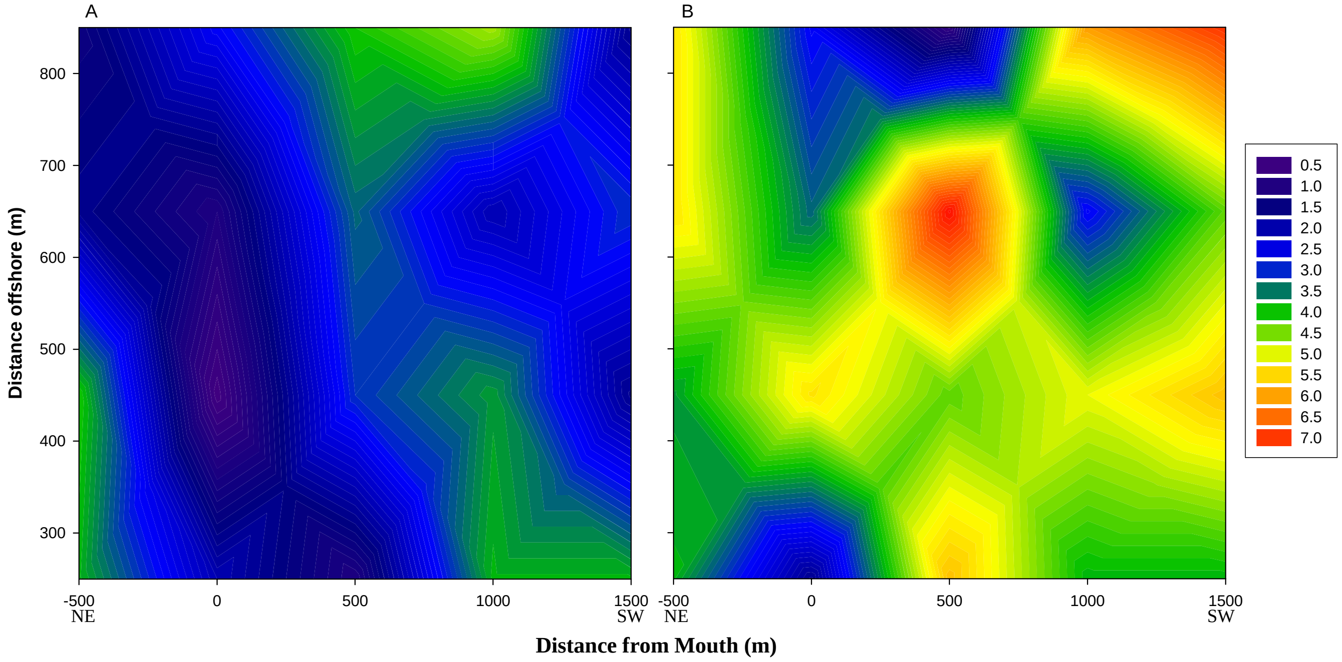
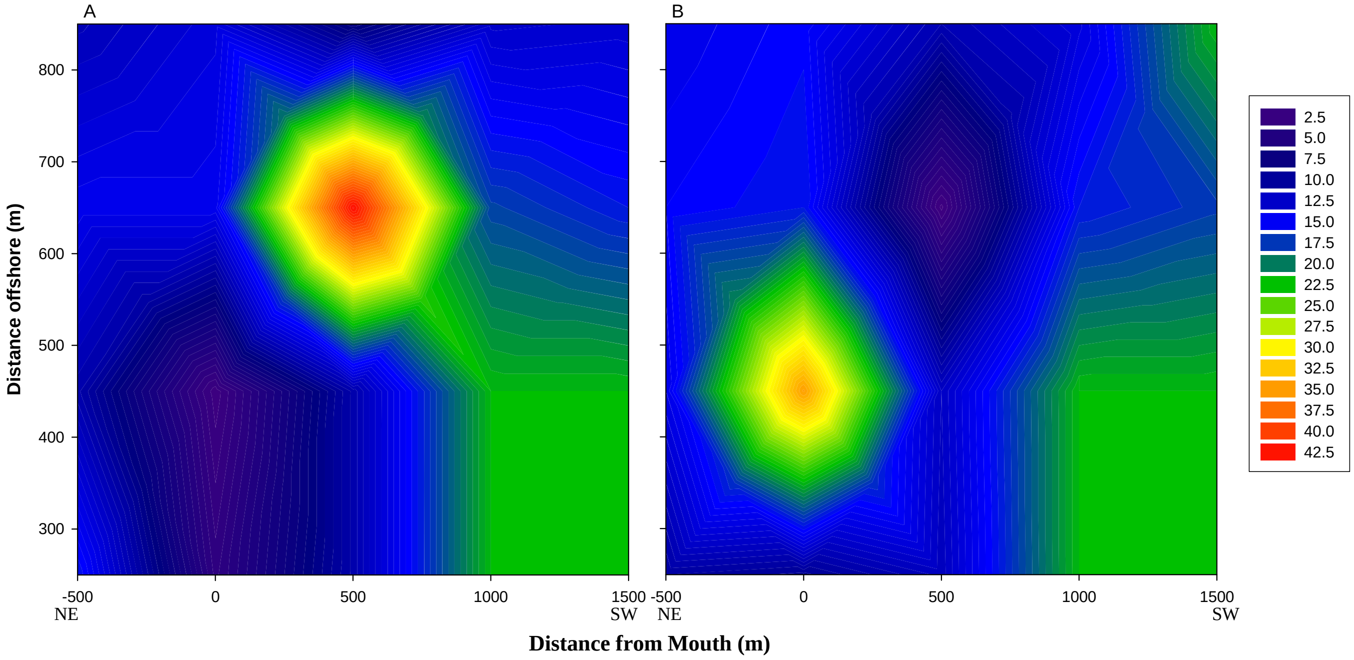


Figure A2.11: Particulate organic matter concentrations (mg.L^{-1}) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and 5m (B) during December 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

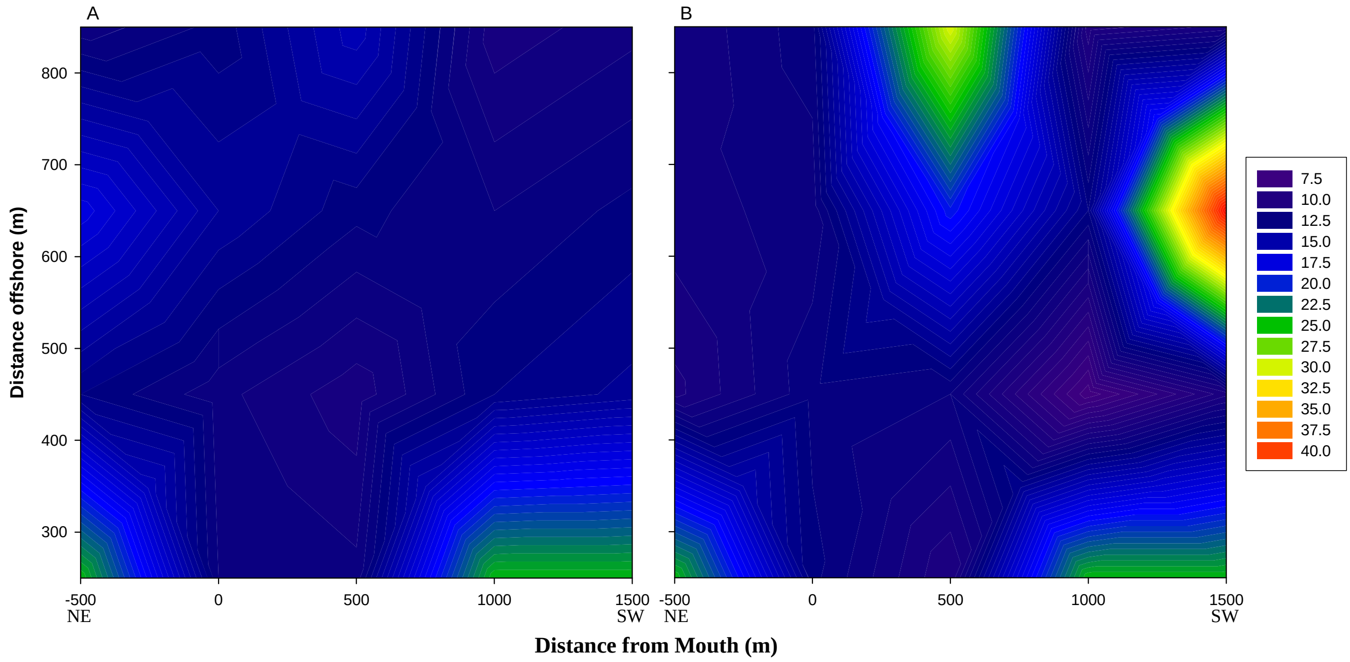
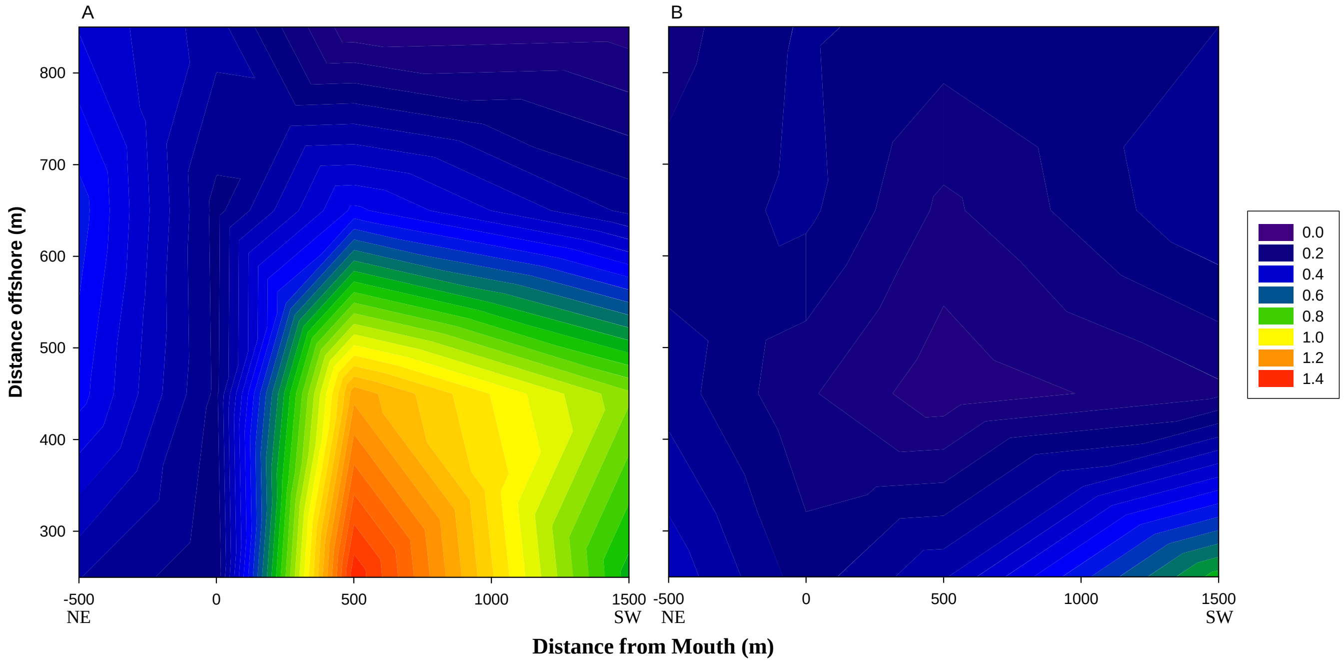
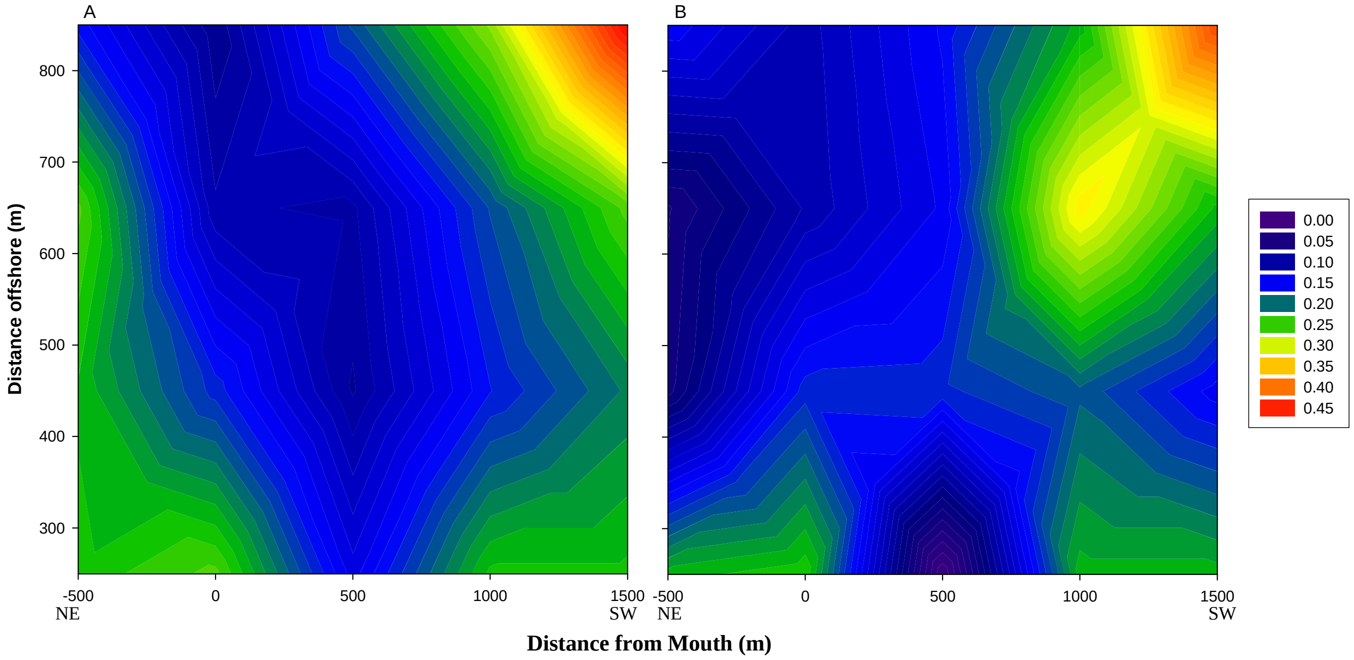


Figure A2.12: Particulate organic matter concentrations (mg.L^{-1}) adjacent to the Great Fish and Kariega Estuaries at the surface (A) and 5m (B) during March 2005. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

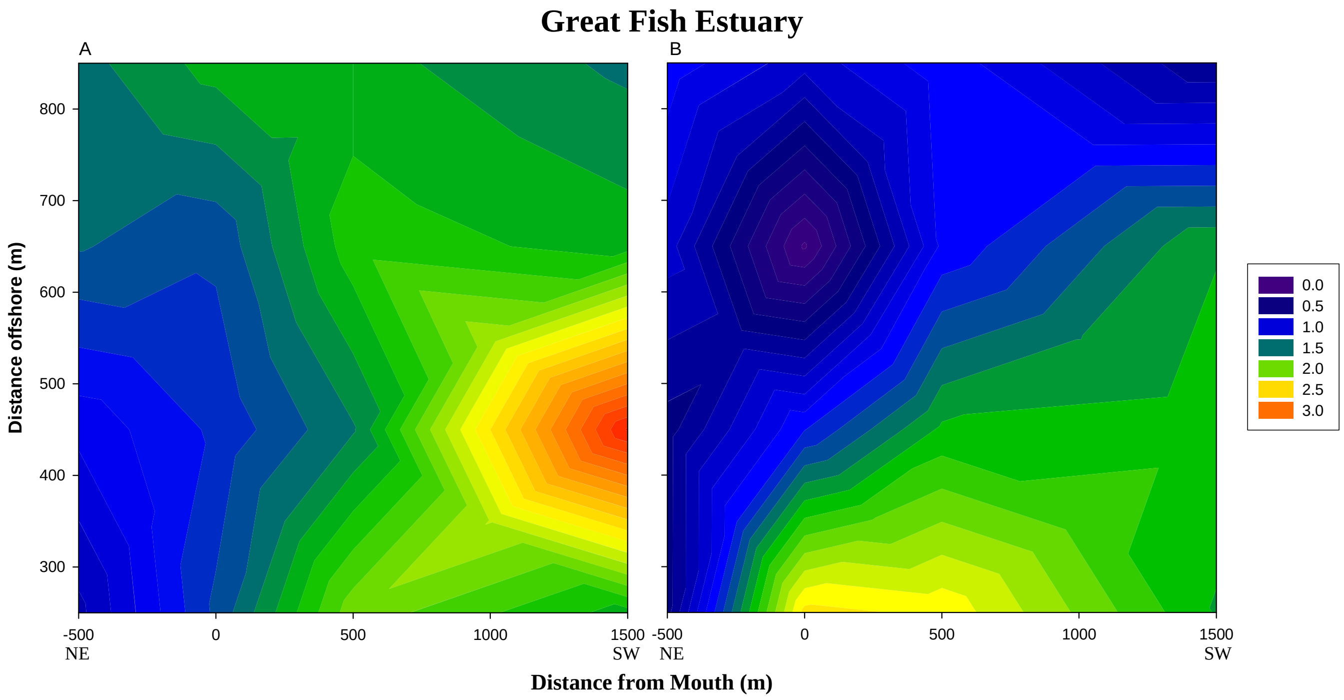


Great Fish Estuary

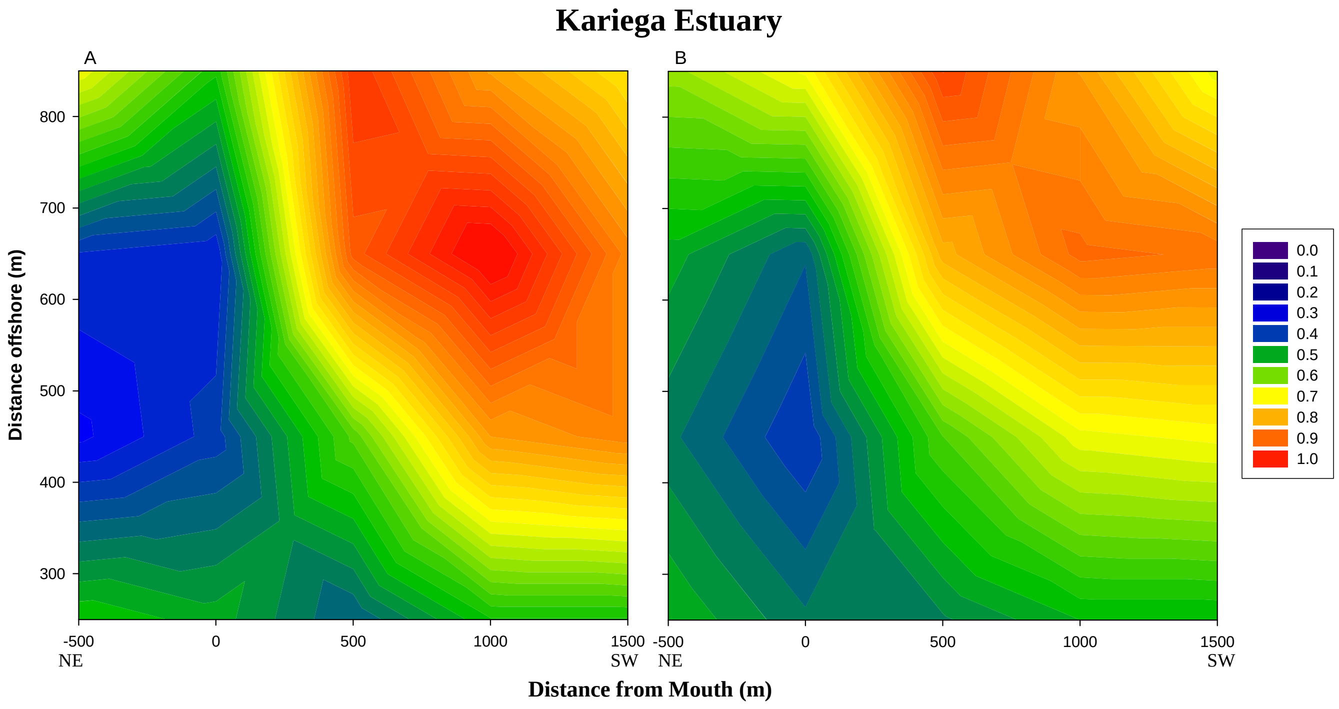


Kariega Estuary

Figure A2.13: Total chlorophyll-*a* concentration (µg.L^{-1}) recorded adjacent to the Great Fish and Kariega Estuaries at the surface (A) and 5m depth (B) during June 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.



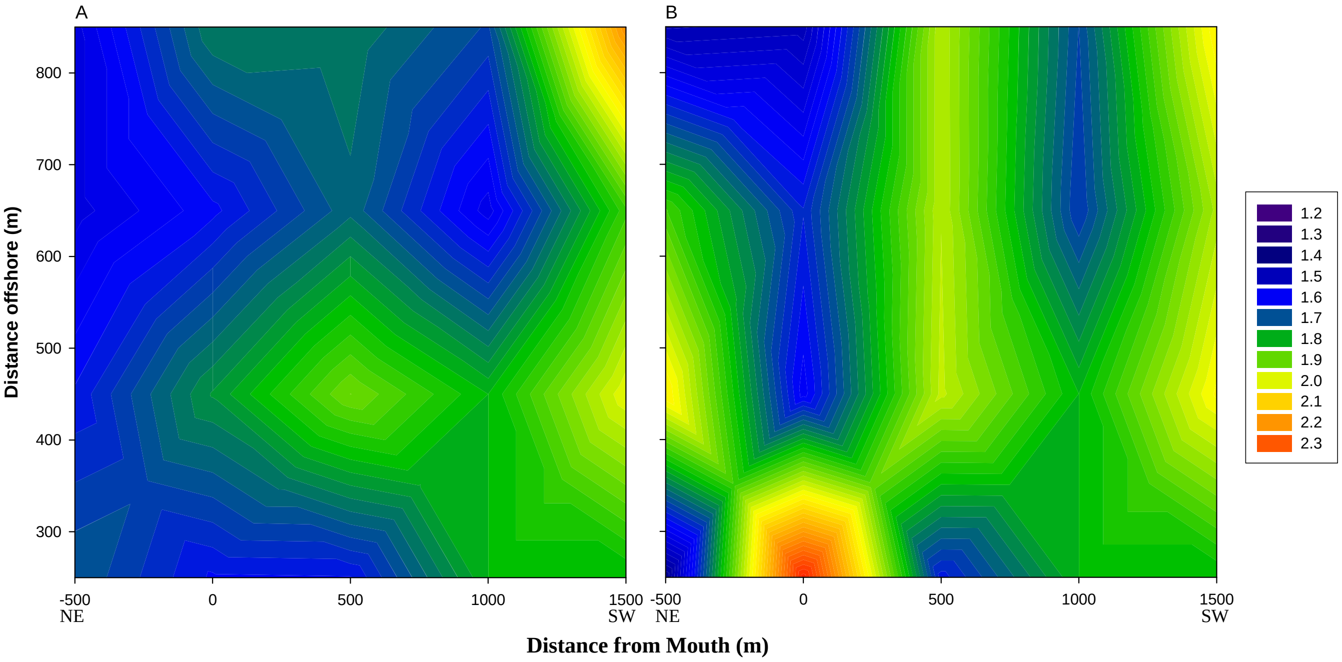
Great Fish Estuary



Kariega Estuary

Figure A2.14: Total chlorophyll-*a* concentration (µg.L^{-1}) recorded adjacent to the Great Fish and Kariega Estuaries at the surface (A) and 5m depth (B) during September 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Great Fish Estuary



Kariega Estuary

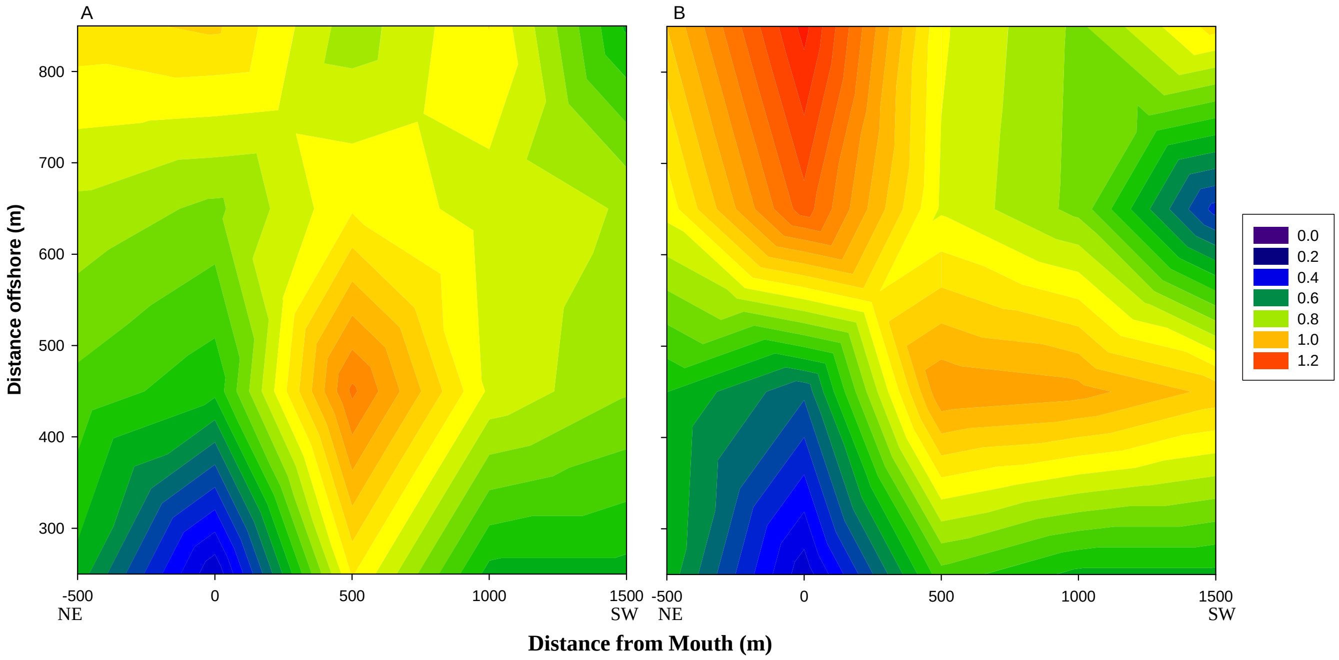
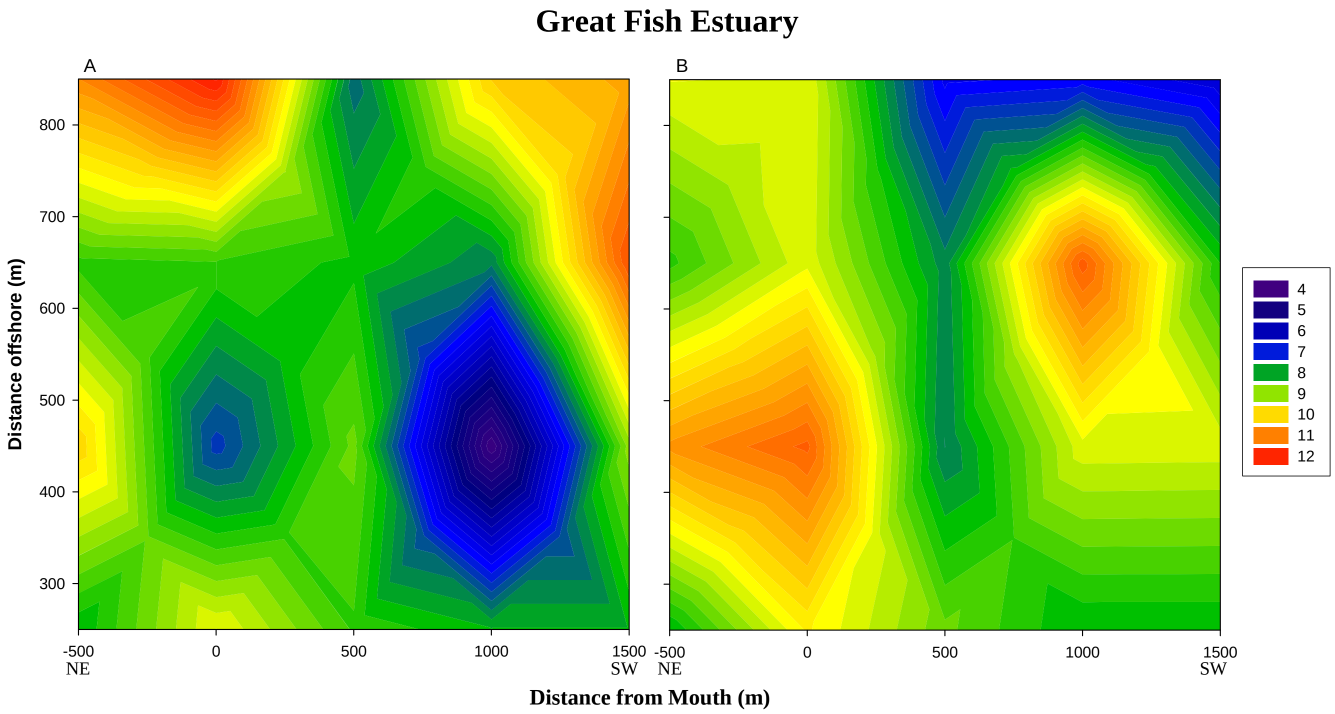


Figure A2.15: Total chlorophyll-*a* concentration (µg.L^{-1}) recorded adjacent to the Great Fish and Kariega Estuaries at the surface (A) and 5m depth (B) during December 2004. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.



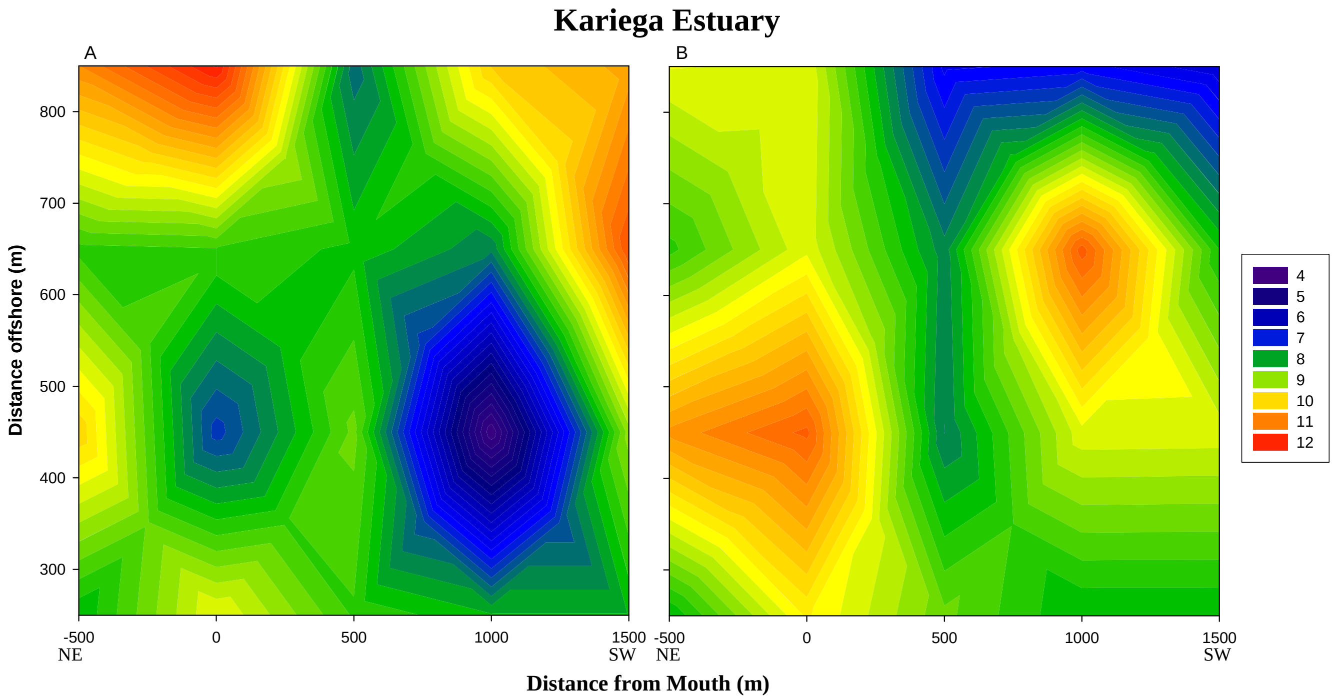


Figure A2.16: Total chlorophyll-*a* concentration (µg.L^{-1}) recorded adjacent to the Great Fish Estuary at the surface (A) and 5m depth (B) during March 2005. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

APPENDIX 3

THE LIST OF ZOOPLANKTON SPECIES RECORDED WITHIN AND ADJACENT TO THE GREAT FISH AND KARIEGA ESTUARIES

P indicates presence in the environment, while A indicates absence.

Taxonomic Group/Species	**Great Fish**		**Kariega**	
	Marine	**Estuarine**	**Marine**	**Estuarine**
Acartia africana	P	P	A	A
Acartia longipatella	P	P	P	P
Acartia sp1.	P	A	P	A
Acartia sp2.	P	A	P	P
Acartia natalensis	P	P	A	A
Aetideus sp.	A	A	P	A
Amphipods	A	A	P	A
Appendicularians	P	P	P	P
Barnacles	P	P	P	P
Calanoides acutus	P	A	A	A
Calanus agulhensis	P	P	P	P
Calanus simillimus	P	P	P	P
Calocalanus sp.	P	A	P	A
Candacia sp.	P	A	P	A
Chaetognaths	P	P	P	P
Clausocalanus breviceps	P	A	A	A
Clausocalanus laticeps	P	A	A	A
Clausocalanus spp.	P	P	P	P
Copilia sp1.	P	A	P	A
Copilia sp2.	P	A	A	A
Corycaeidae	P	P	P	P
Ctenocalanus sp.	P	A	A	A
Cumaceans	A	P	P	P

Taxonomic Group/Species	**Great Fish**		**Kariega**	
	Marine	**Estuarine**	**Marine**	**Estuarine**
Drepanopus forciputus	P	A	A	A
Eucalanus sp.	P	P	P	A
Gammarids	P	P	P	P
Gastrosaccus brevifissura	P	A	P	P
Genocalanus sp.	P	A	A	A
Harpacticoida sp.	P	P	P	P
Isopods	P	P	P	P
Labidocera acuta	P	A	A	A
Labidocera sp1.	P	A	P	P
Labidocera sp2.	P	P	P	P
Limacina sp.	P	P	P	P
Medusa sp.	P	P	P	P
Mesopodopsis wooldridgei	P	P	P	P
Microsetella norvegica	P	P	P	P
Microsetella rosea	P	A	P	A
Mussels	P	P	P	P
Nauplii	P	P	P	P
Noctiluca	P	P	P	P
Oithona sp.	P	P	P	P
Oncaea sp.	P	P	P	P
Ophiplutus sp.	P	A	A	A
Ostracods	P	P	P	P
Paraeuchaeta sp.	P	A	P	A
Pontella gaboonensis	P	P	P	P
Pontellina plumata	P	P	P	A
Pseudodiaptomus hessei	P	P	P	P
Pterapoda	P	A	P	A
Rhincalanus cornutus	A	A	P	A
Rhincalanus giga	A	A	P	A
Rhopalophthalmus terranatalis	P	P	P	P

Taxonomic Group/Species	**Great Fish**		**Kariega**	
	Marine	**Estuarine**	**Marine**	**Estuarine**
Salps	P	A	P	A
Sapphirina sp.	A	A	P	A
Schapocalanus sp.	P	A	A	A
Scolocithricela minor	P	A	A	A
Siphonaria	P	P	P	P
Unidentified sp1.	A	A	P	P
Unidentified sp2.	P	P	P	P
Unidentified sp3.	A	P	A	A
Subeucalanus pileatus	P	A	P	A
Temora stylifera	P	A	P	A
Temora turbinata	P	P	P	P
Zoea	P	P	P	P

APPENDIX 4

CONTOUR PLOTS OF THE PHYSICAL AND BIOLOGICAL DATA FROM THE EAST KLEINEMONDE AND KASOUGA ESTUARIESAND ADJACENT MARINE ENVIRONMENT

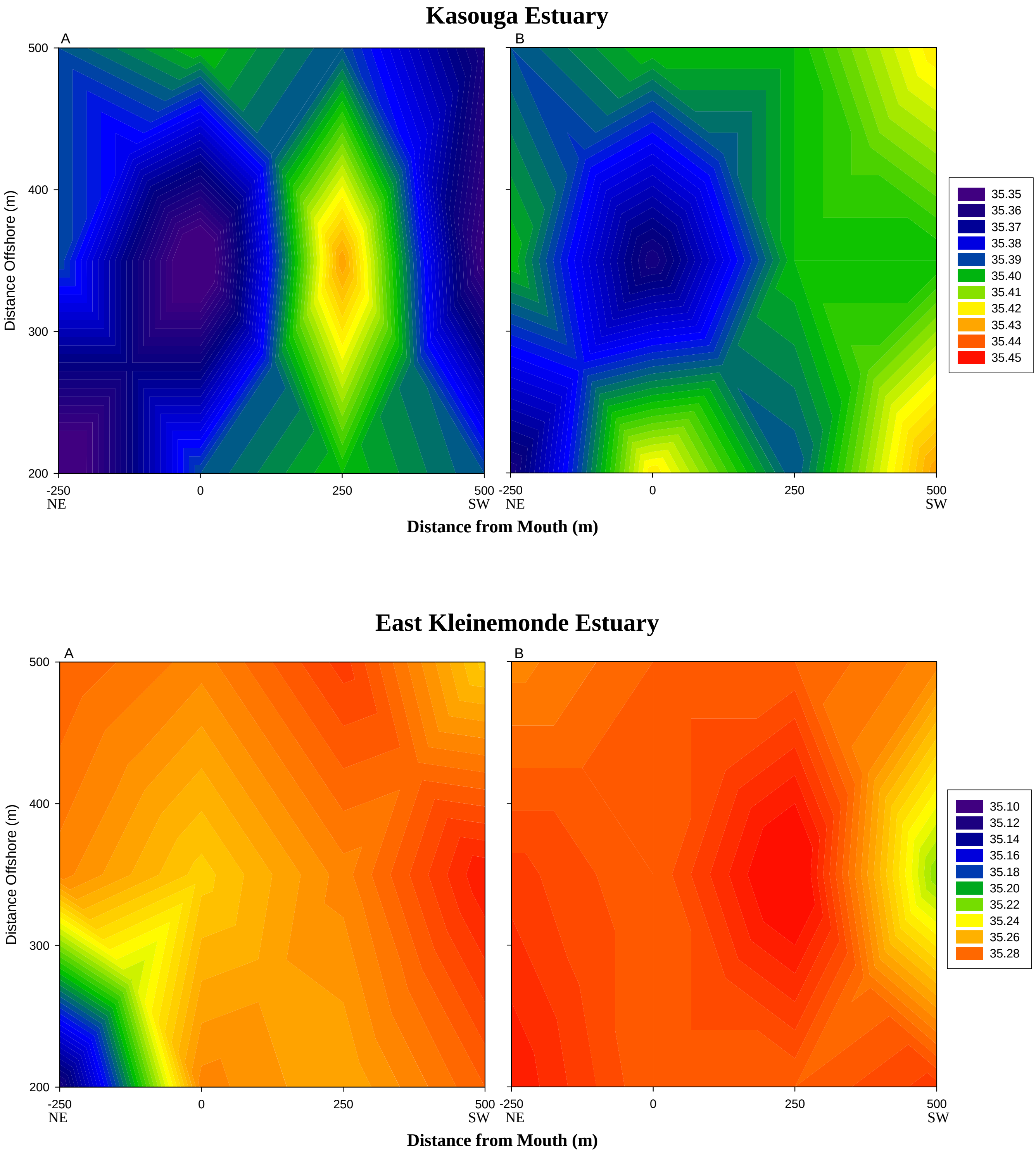
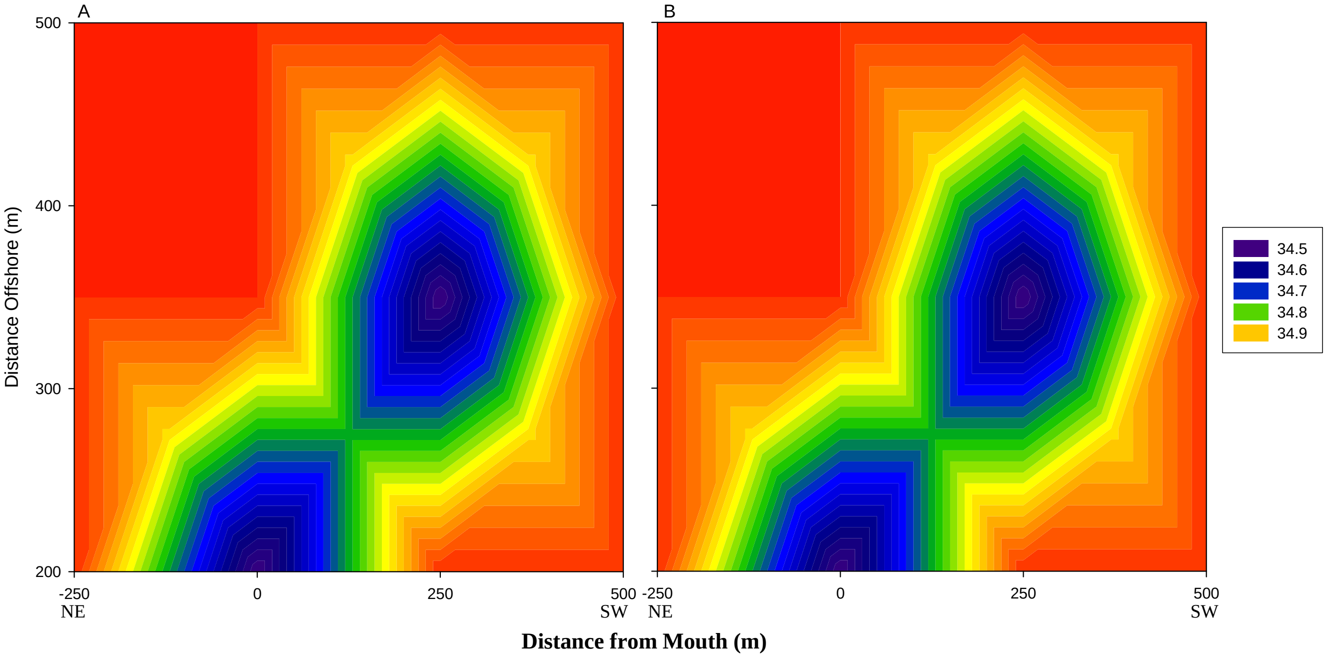


Figure A4.1: The surface (A) and 5m (B) salinity (practical salinity units) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the June 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.


Kasouga Estuary

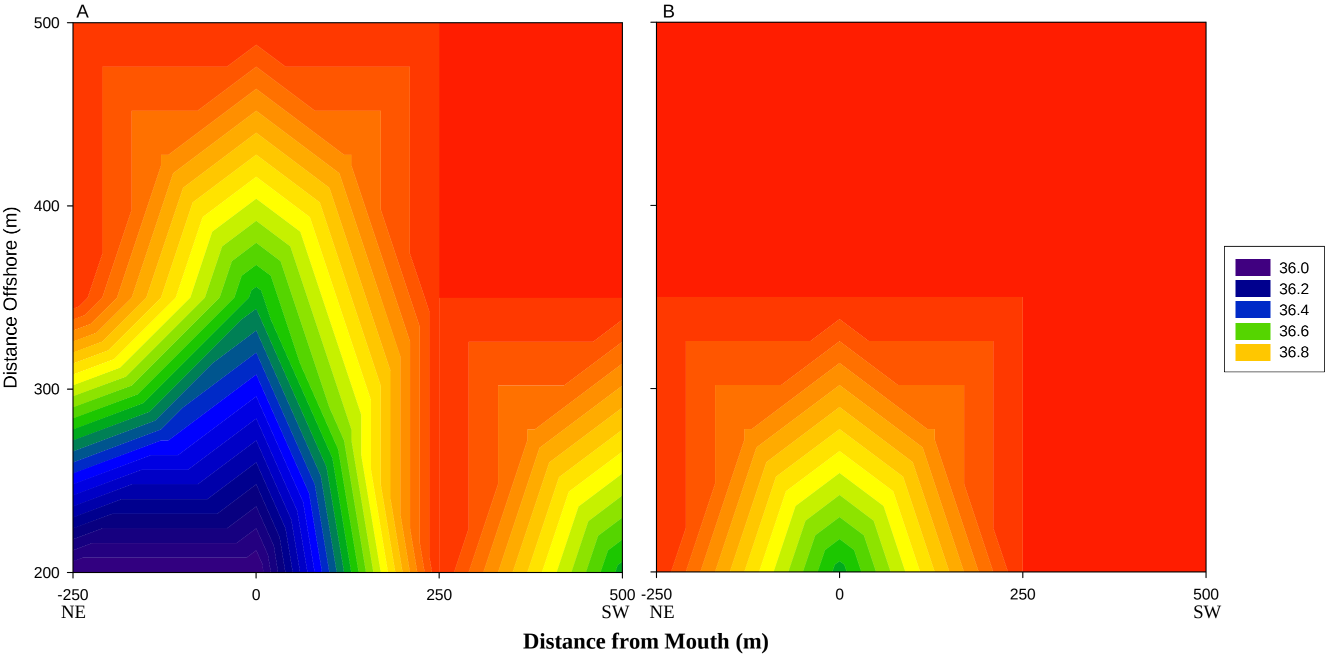
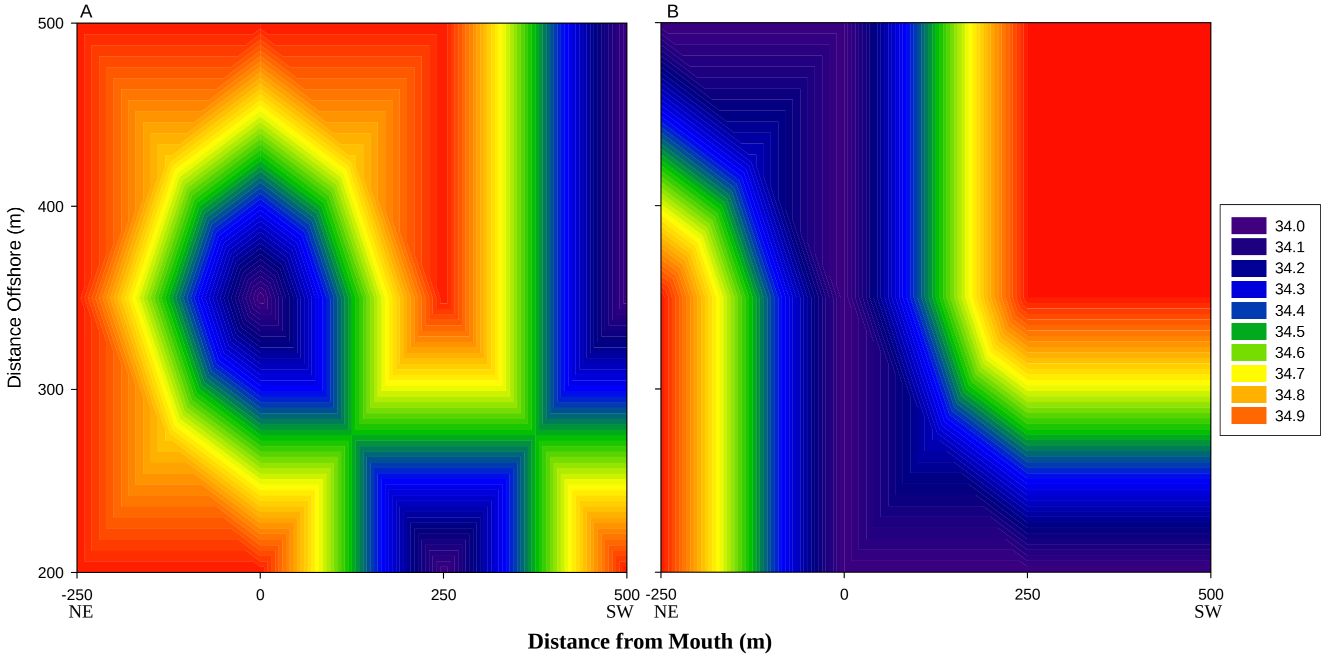
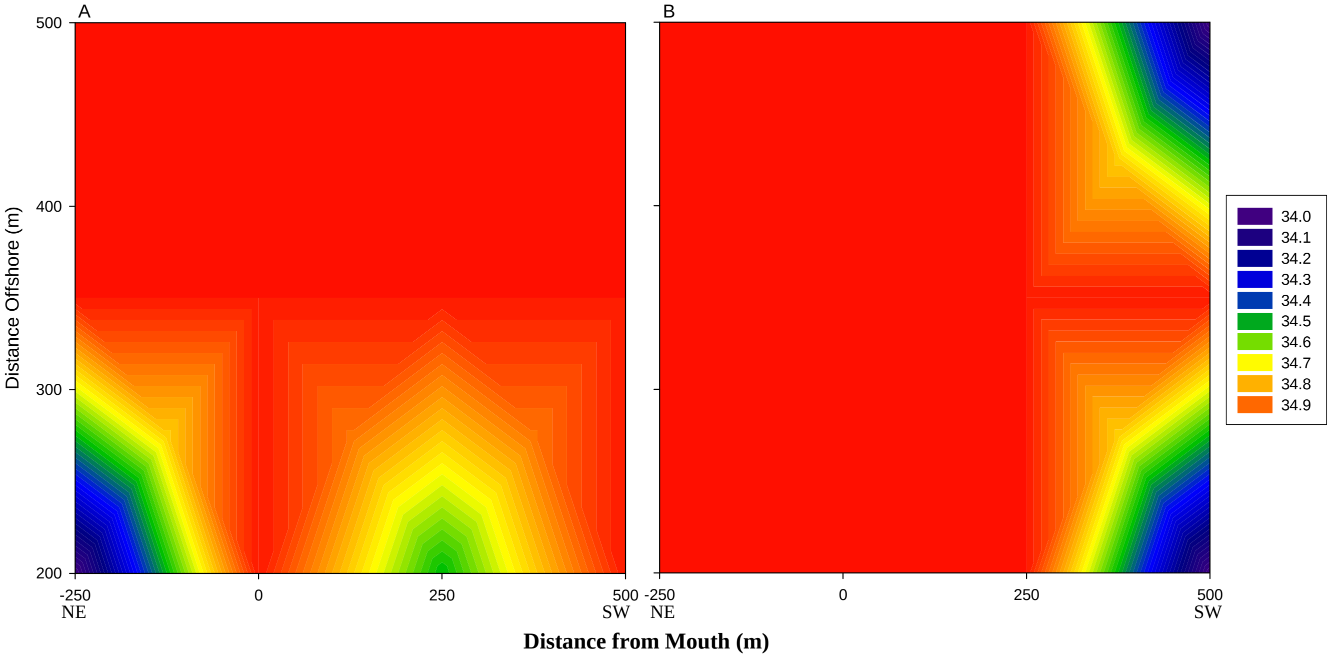

East Kleinemonde Estuary

Figure A4.2: The surface (A) and 5m (B) salinity (practical salinity units) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the September 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.



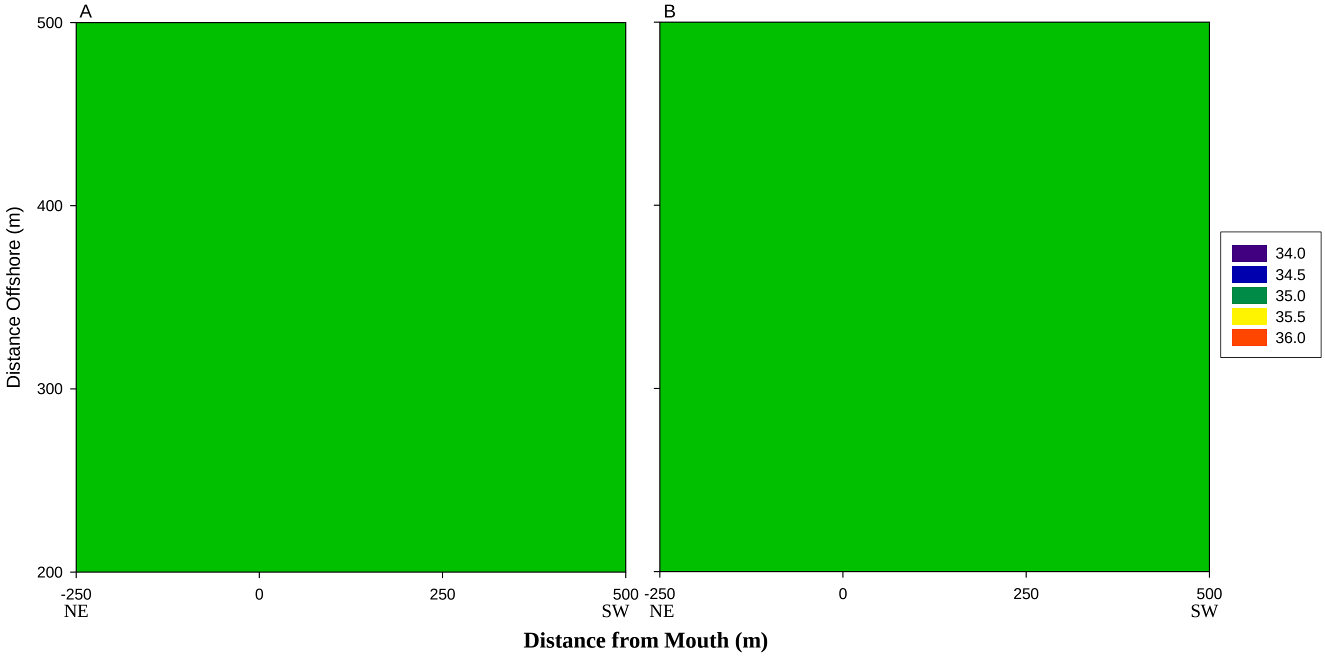
Kasouga Estuary



East Kleinemonde Estuary

Figure A4.3: The surface (A) and 5m (B) salinity (practical salinity units) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the November 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

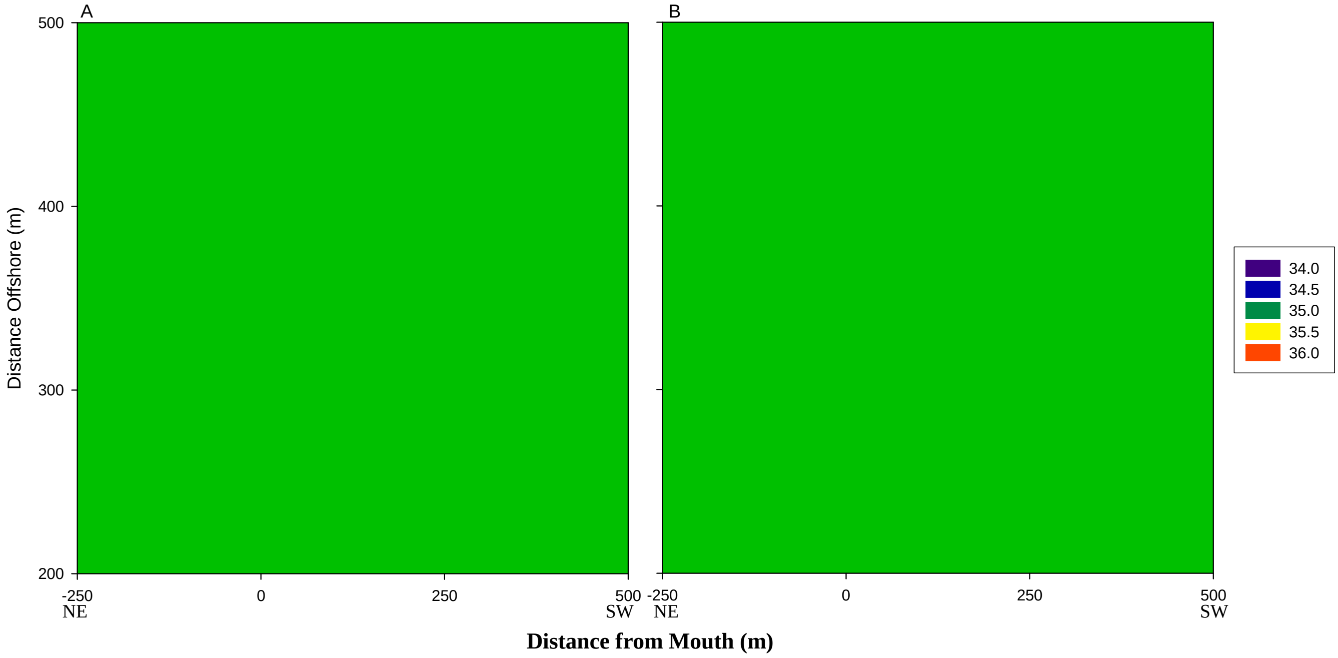
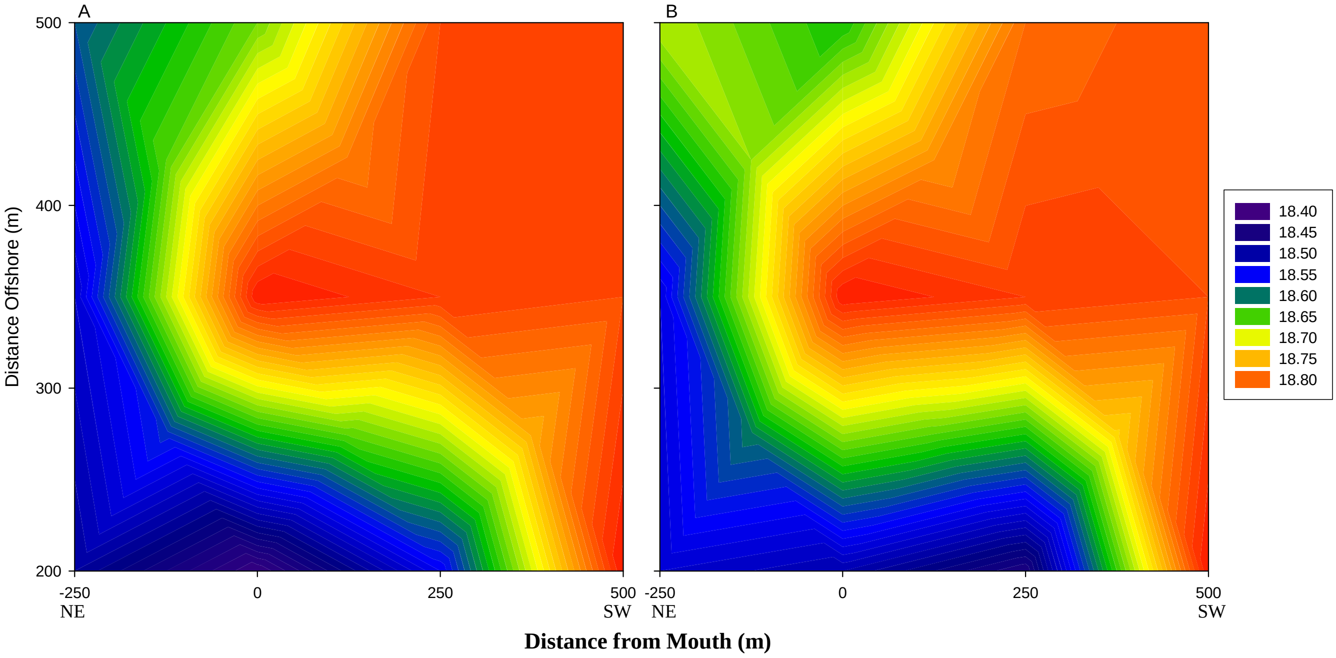


Figure A4.4: The surface (A) and 5m (B) salinity (practical salinity units) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the March 2006 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

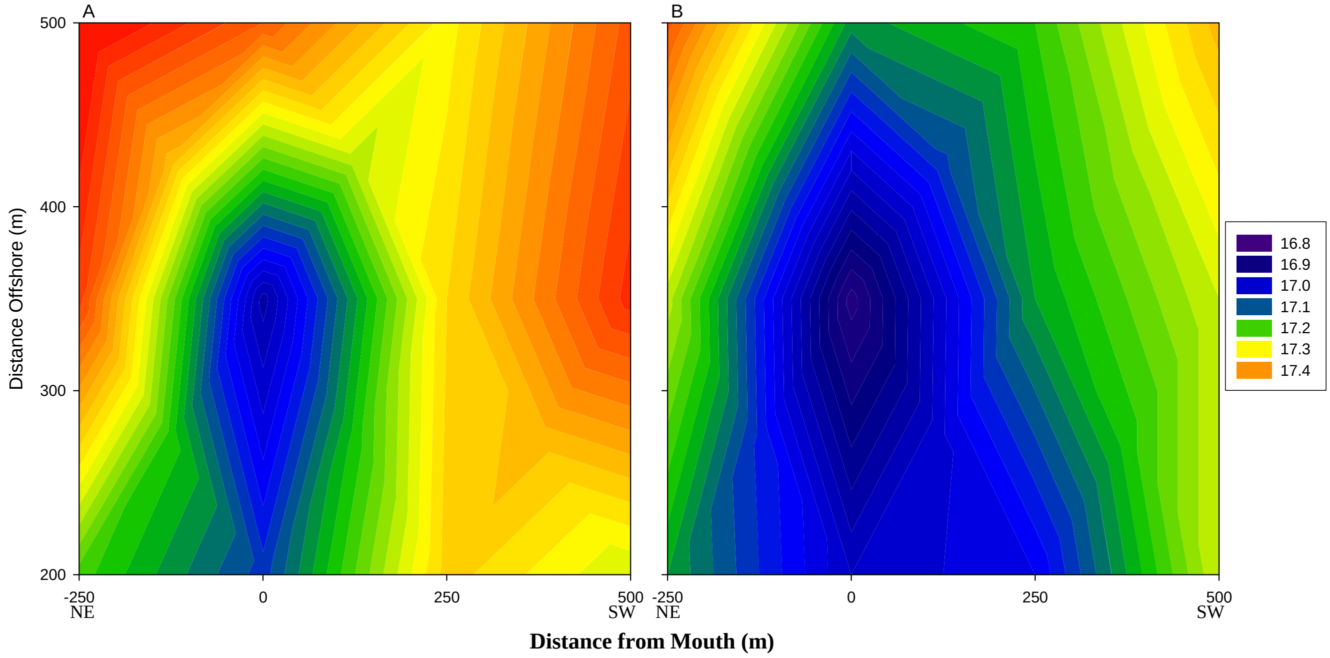
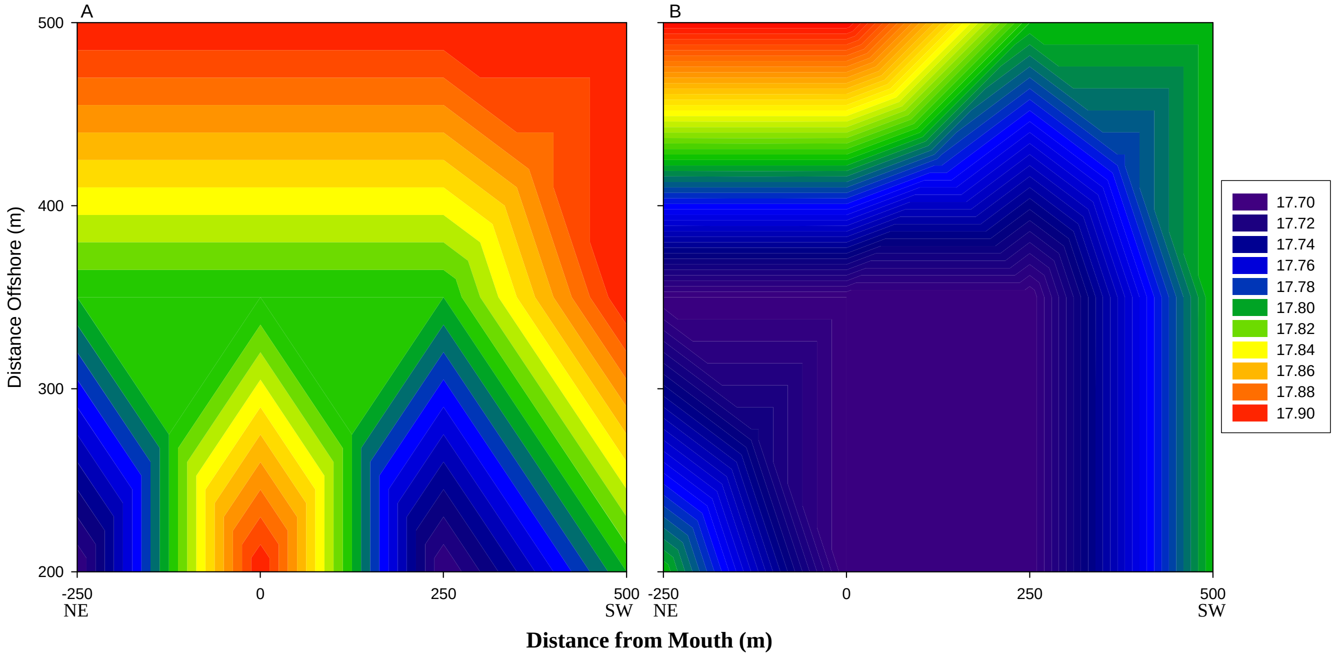


Figure A4.5: The surface (A) and 5m (B) temperatures (ºC) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the June 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

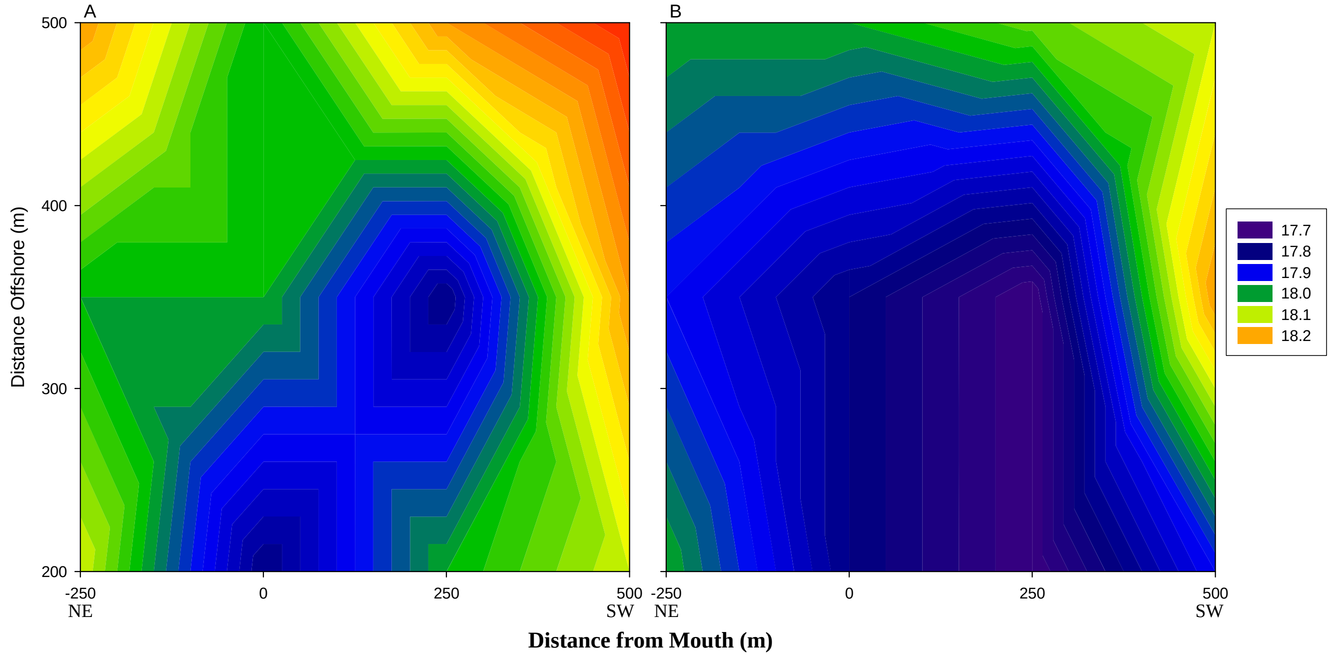
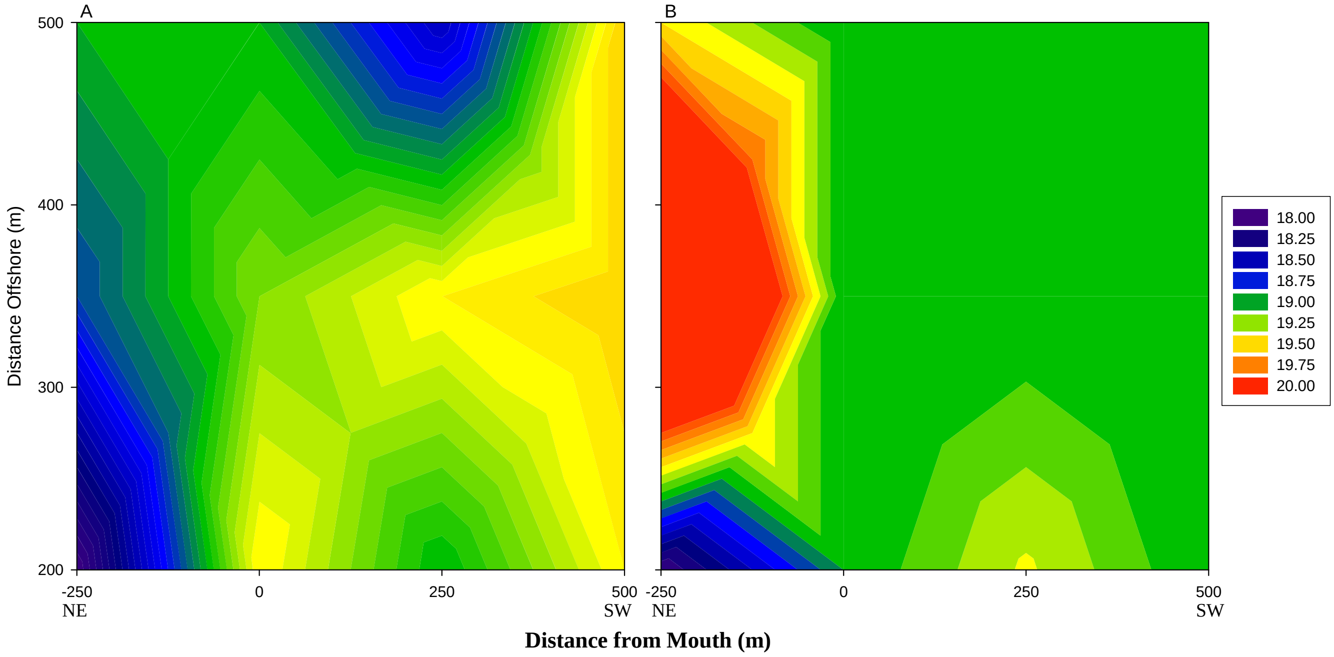


Figure A4.6: The surface (A) and 5m (B) temperatures (ºC) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the September 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

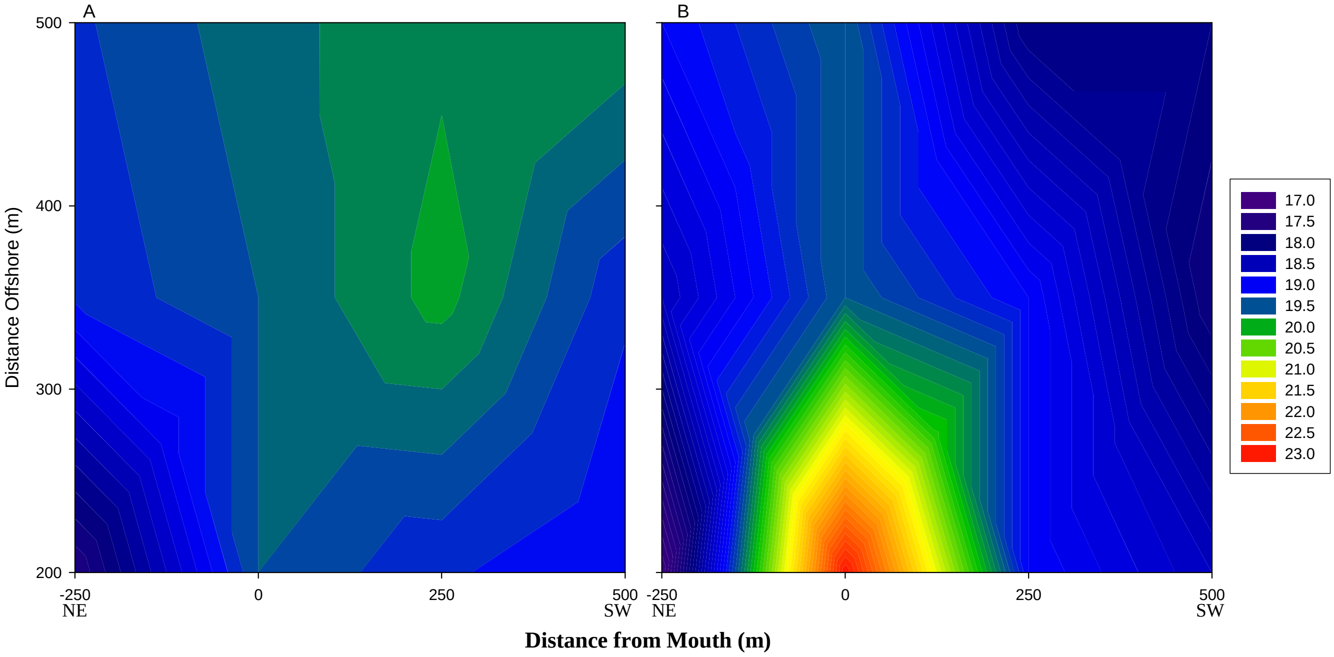
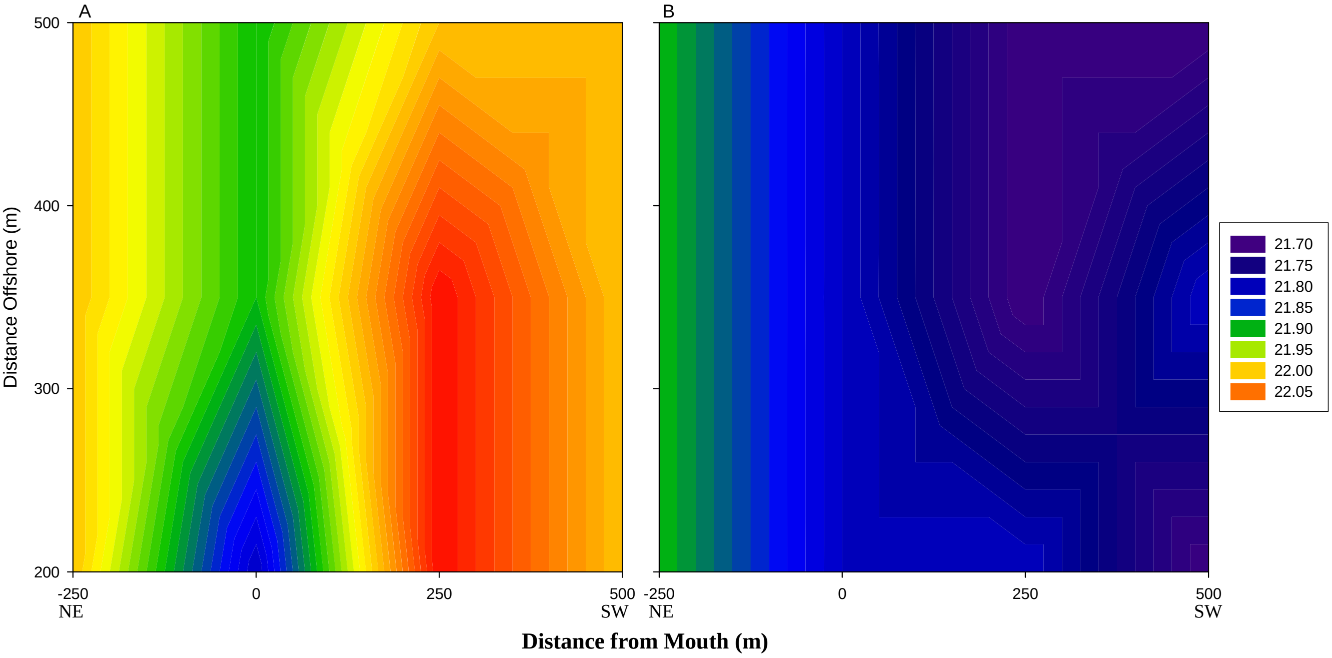


Figure A4.7: The surface (A) and 5m (B) temperatures (ºC) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the November 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

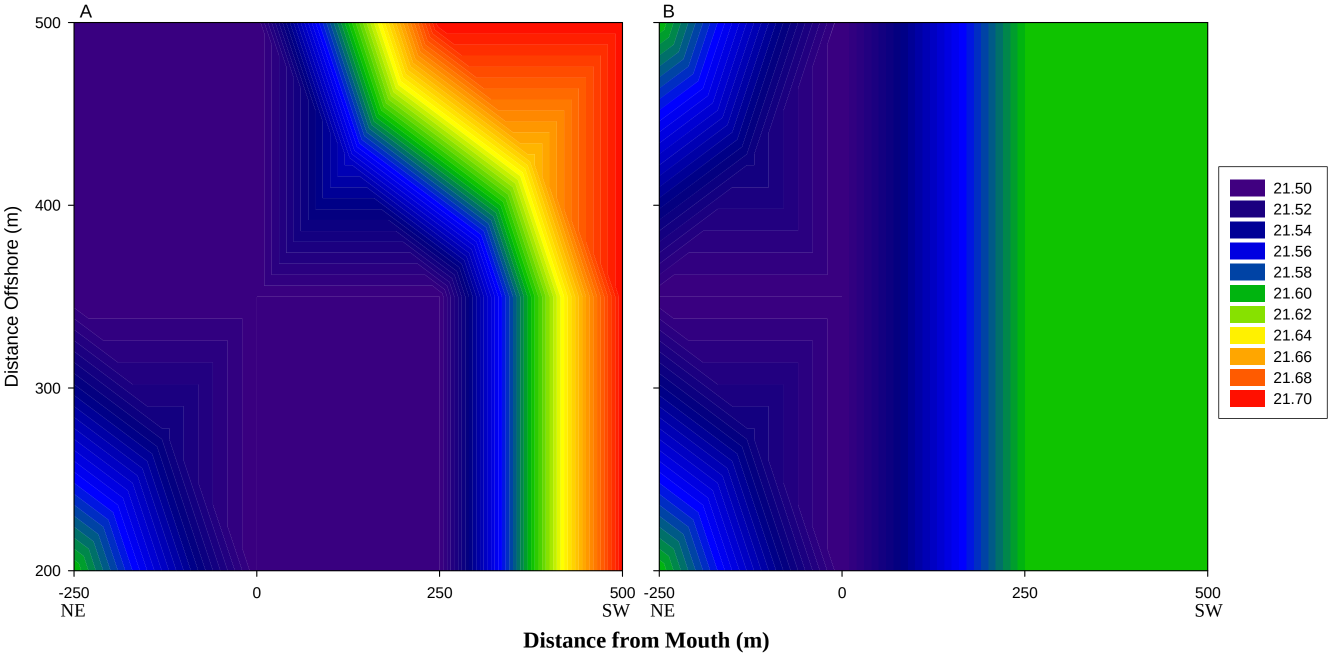


Figure A4.8: The surface (A) and 5m (B) temperatures (ºC) recorded in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the March 2006 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

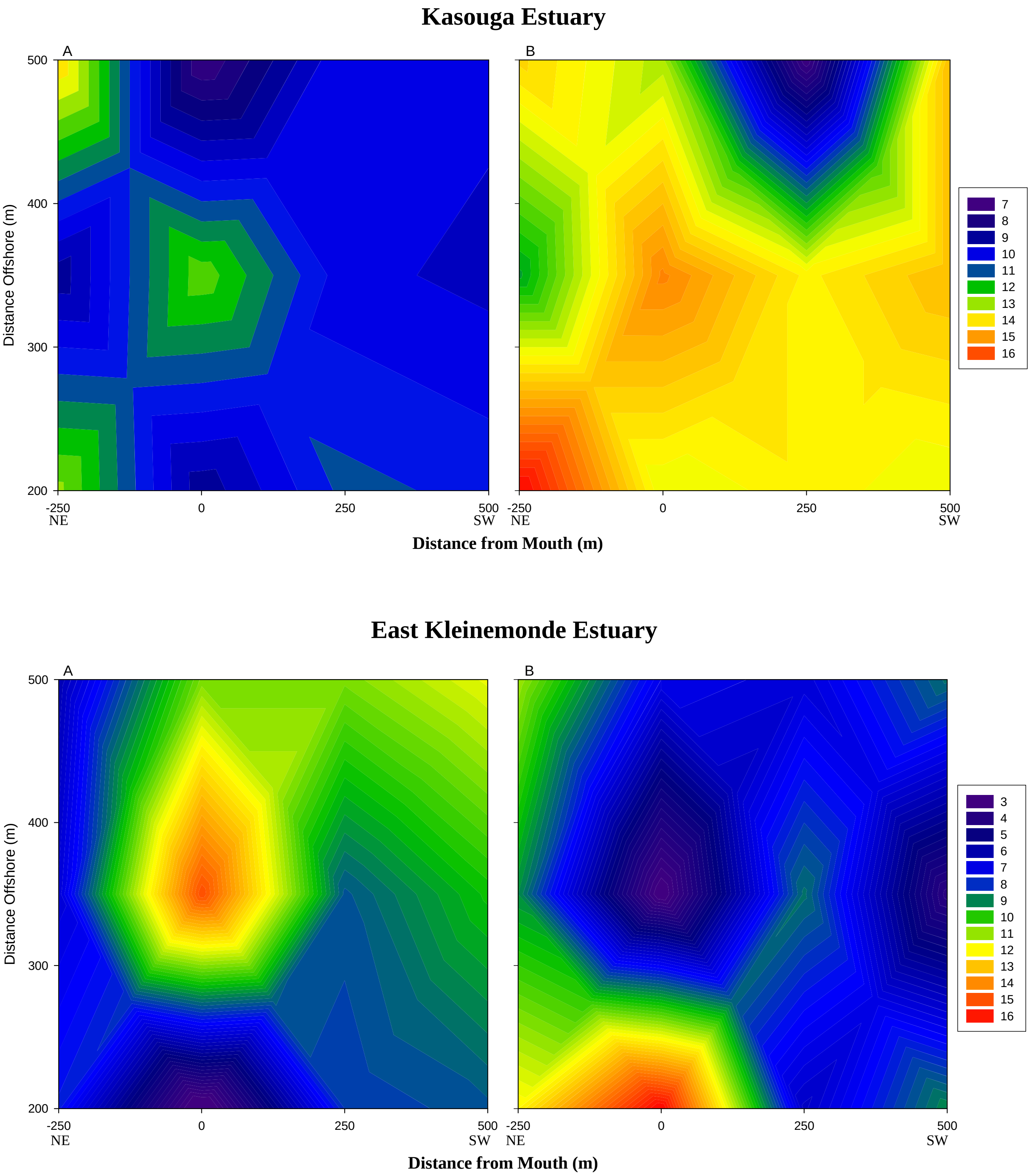
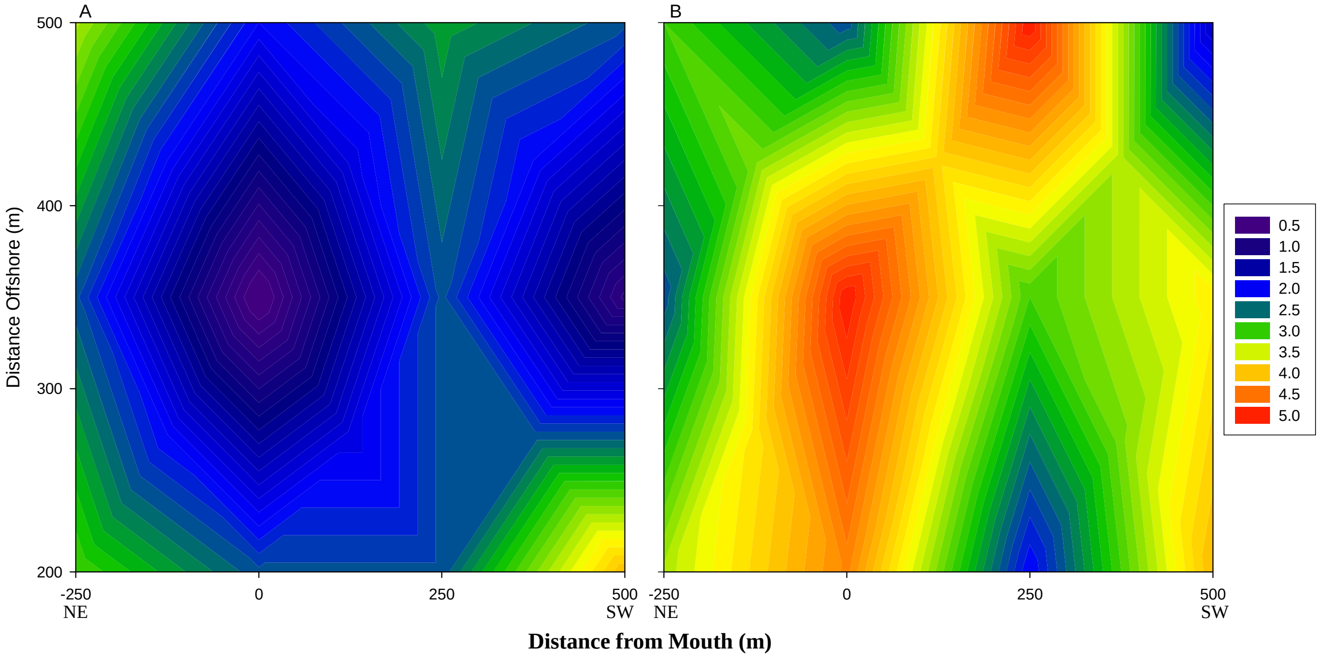


Figure A4.9: The surface (A) and 5m (B) particulate organic matter concentrations (mg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the June 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

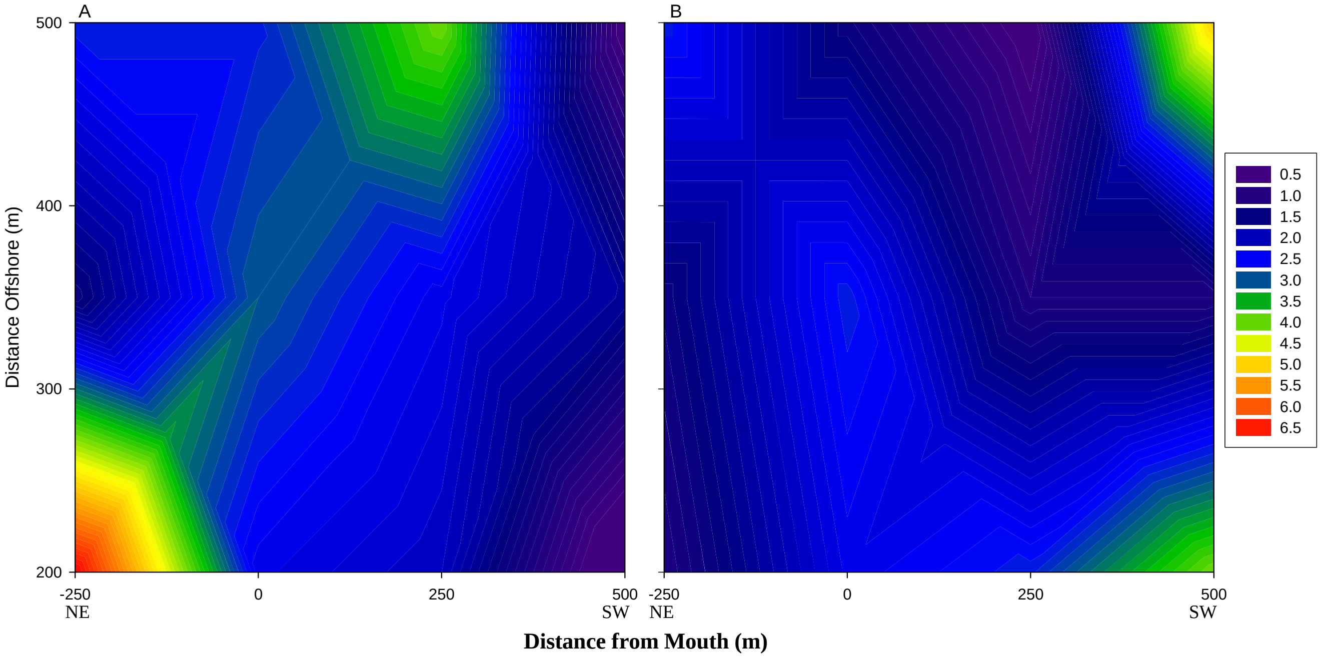
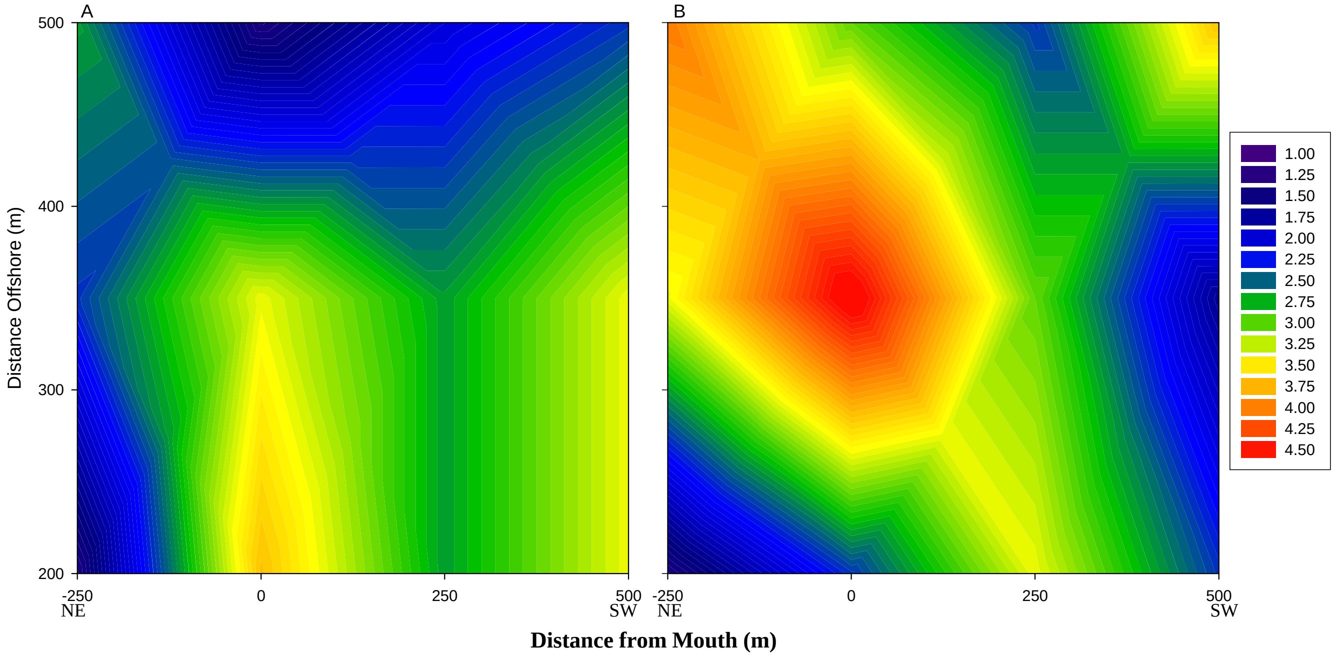


Figure A4.10: The surface (A) and 5m (B) particulate organic matter concentrations (mg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the September 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

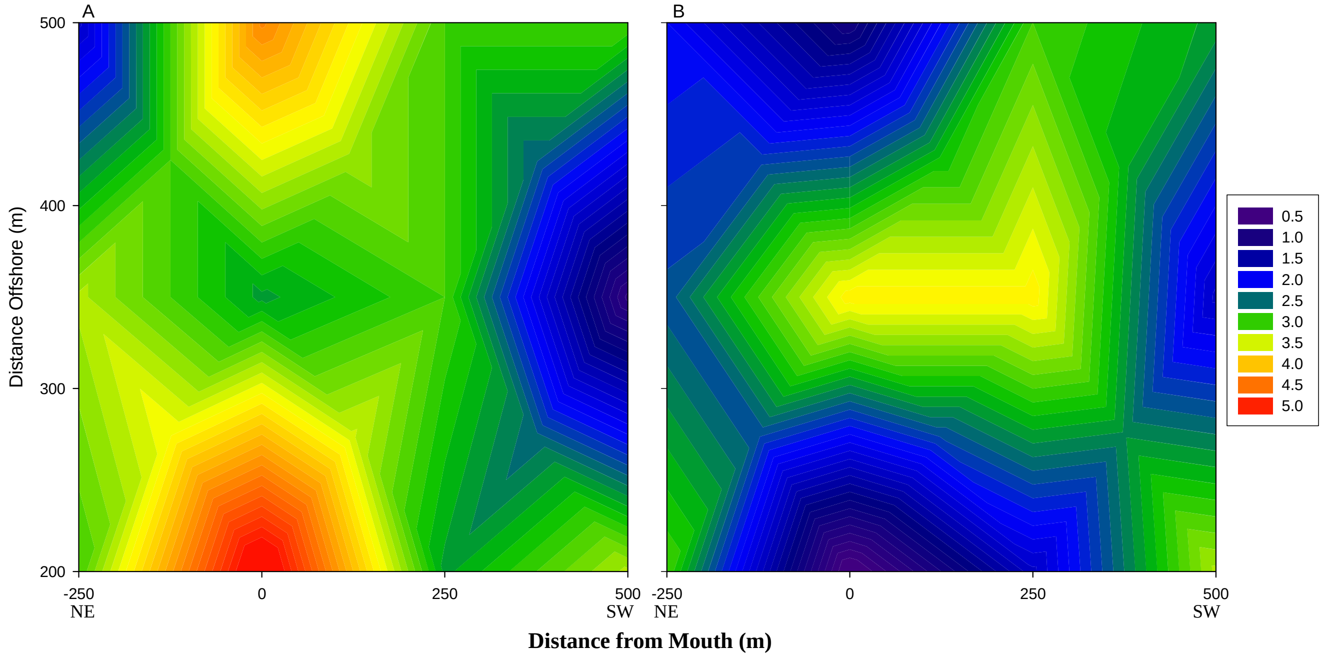
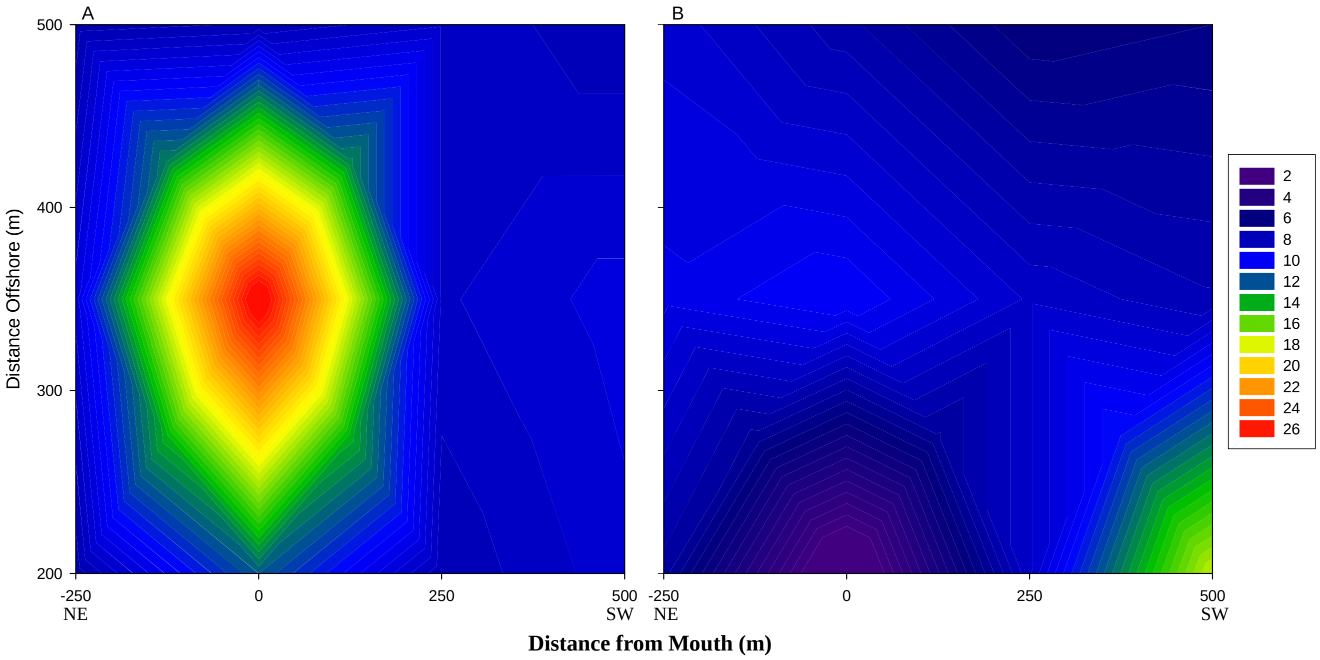


Figure A4.11: The surface (A) and 5m (B) particulate organic matter concentrations (mg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the November 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.


Kasouga Estuary

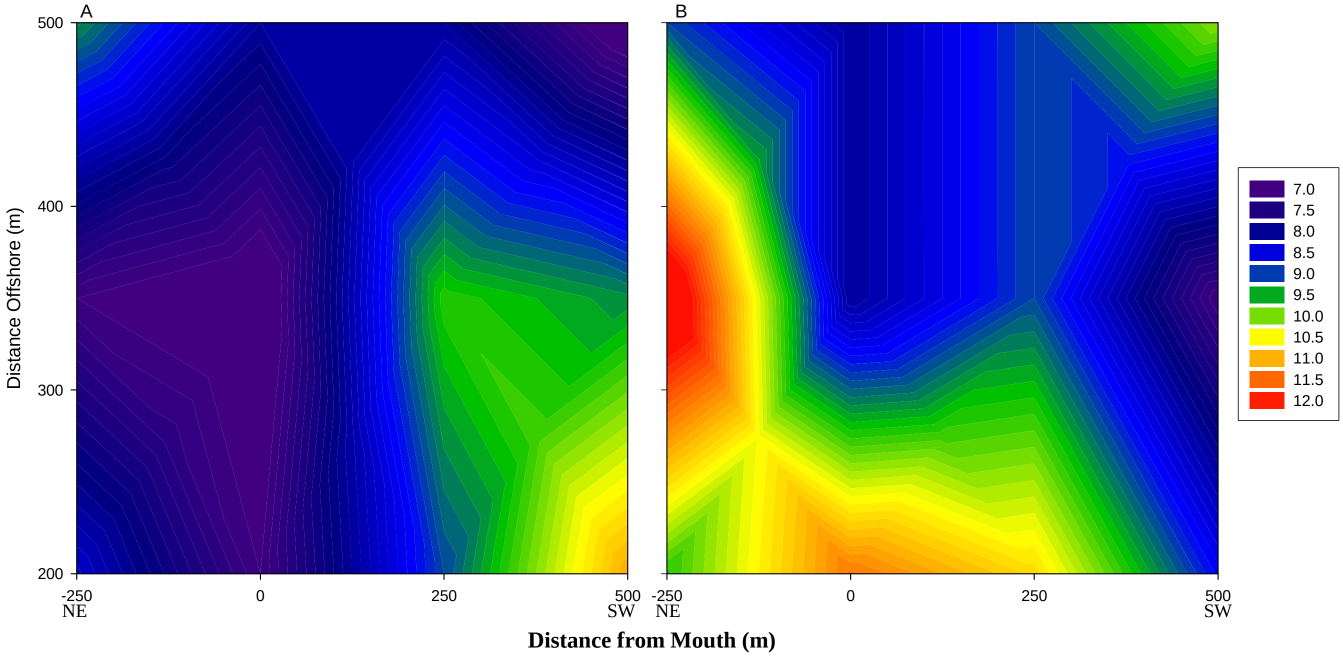
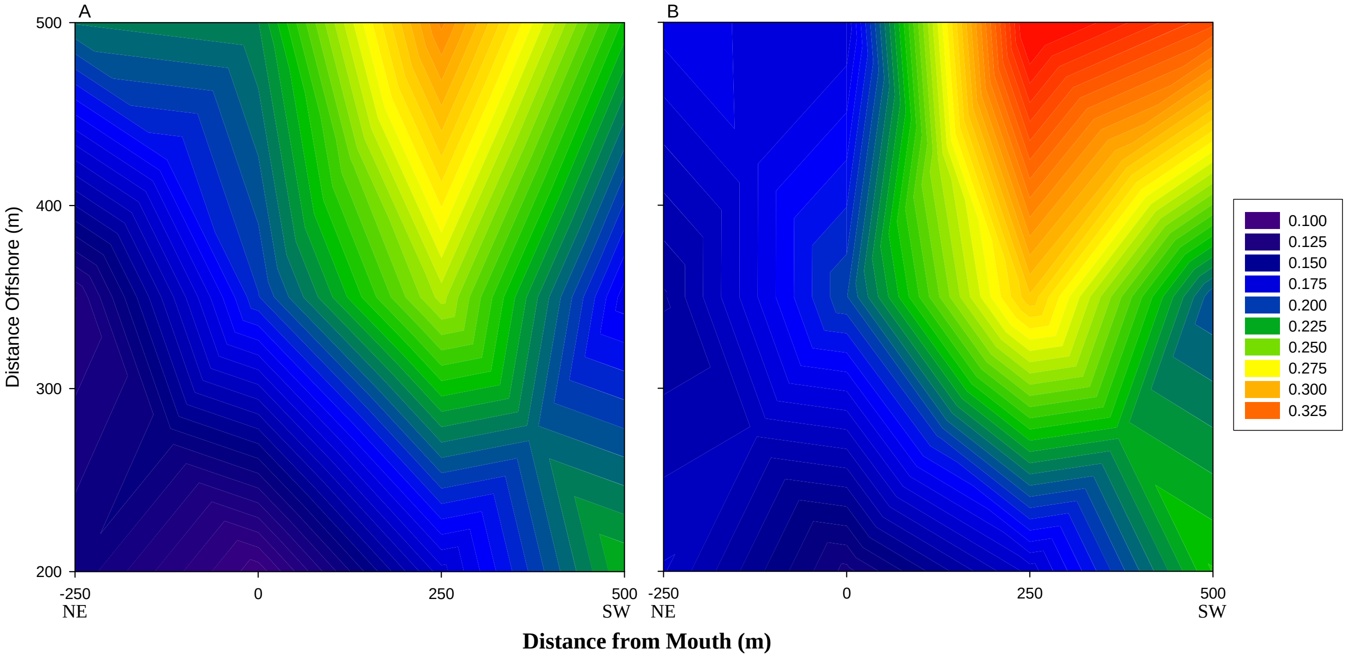

East Kleinemonde Estuary

Figure A4.12: The surface (A) and 5m (B) particulate organic matter concentrations (mg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the March 2006 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

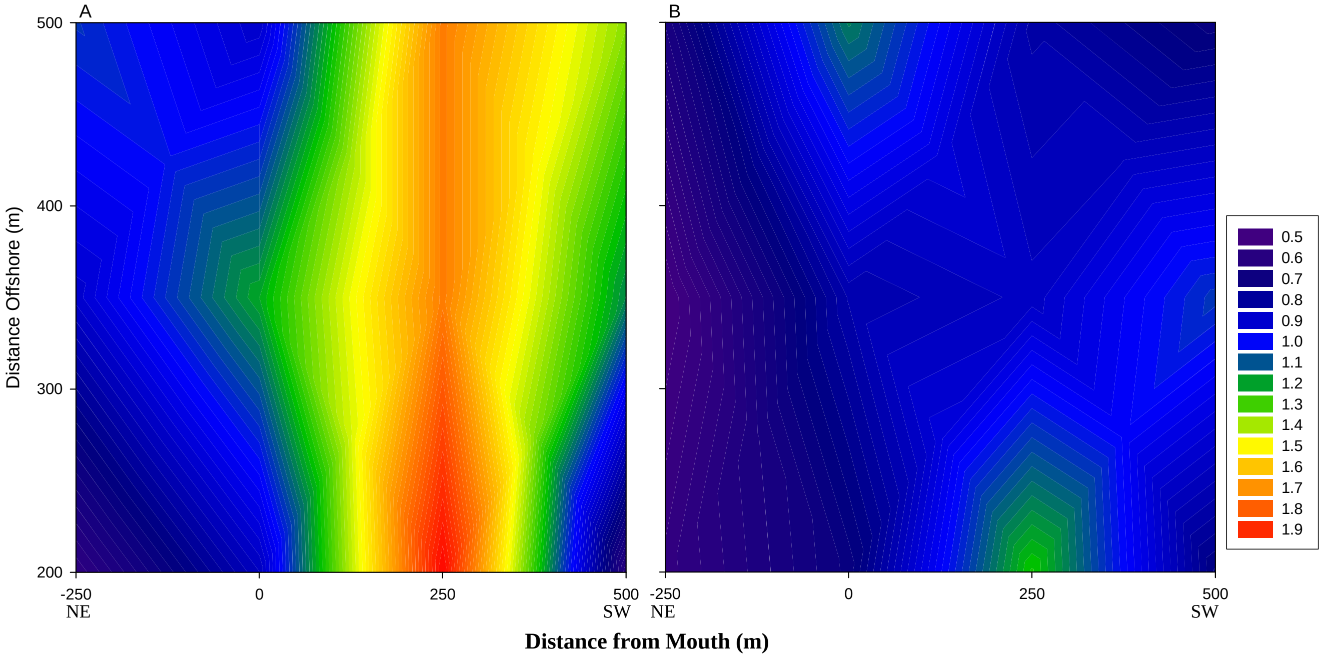
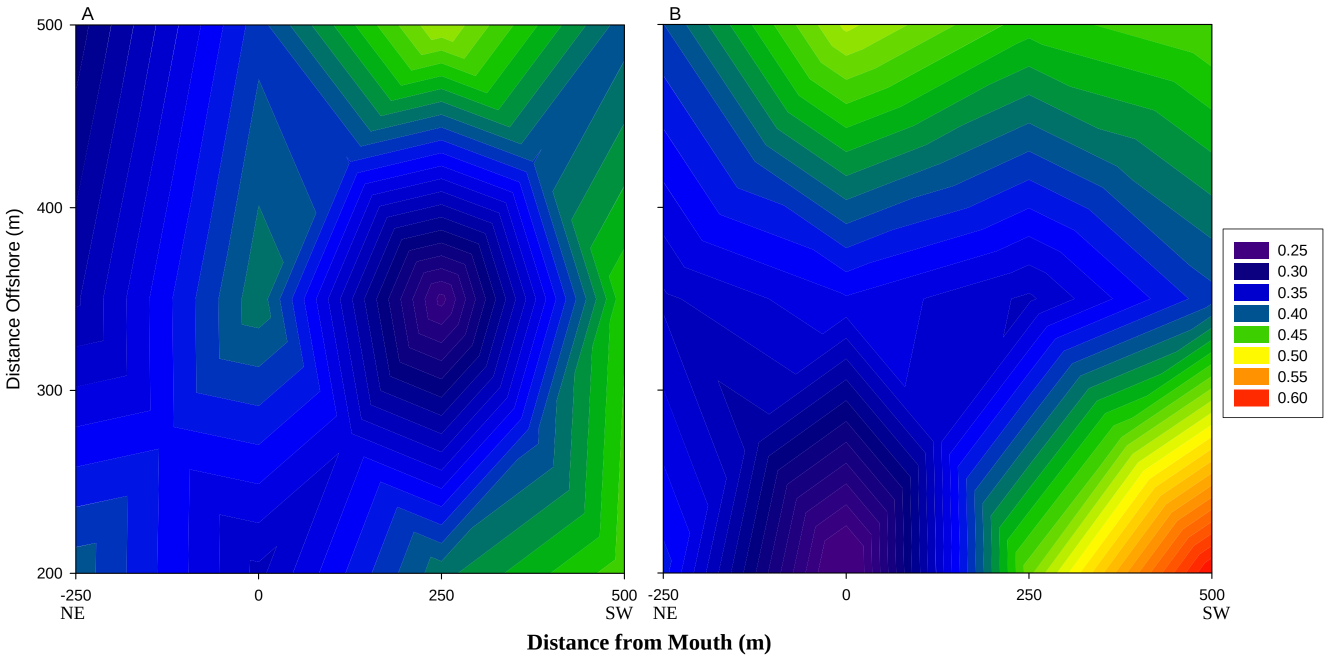


Figure A4.13: The surface (A) and 5m (B) total chlorophyll-*a* concentration (µg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the June 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

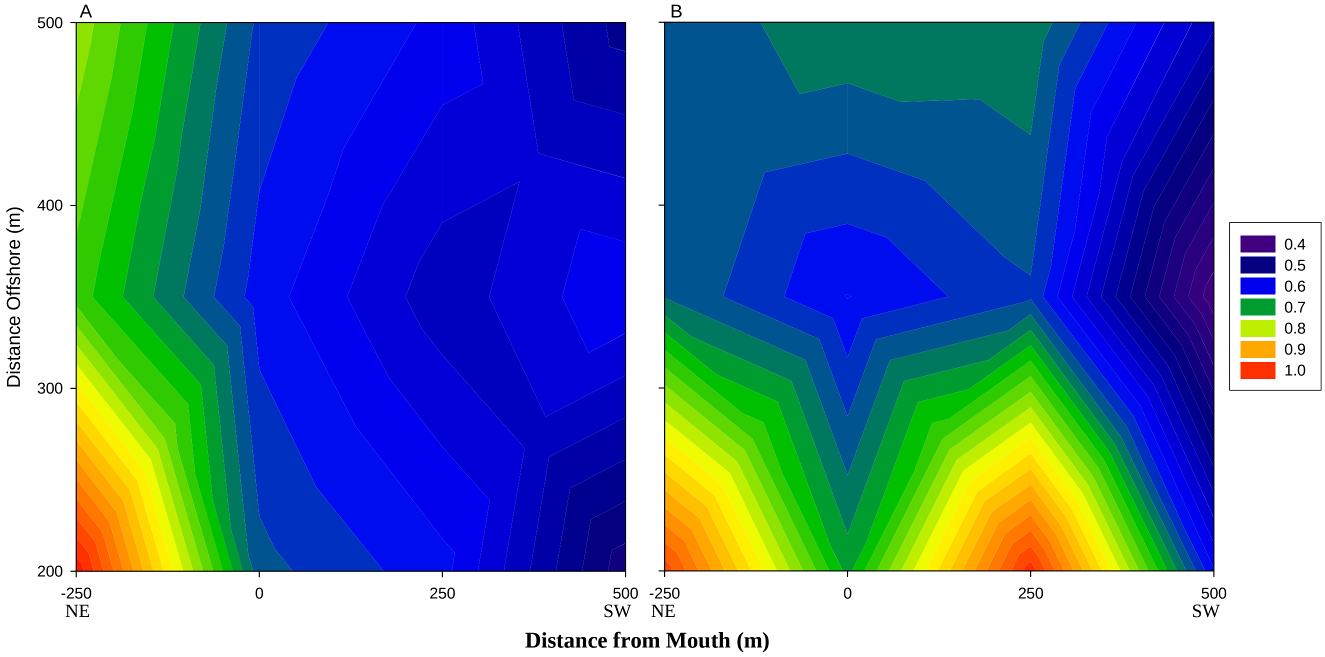
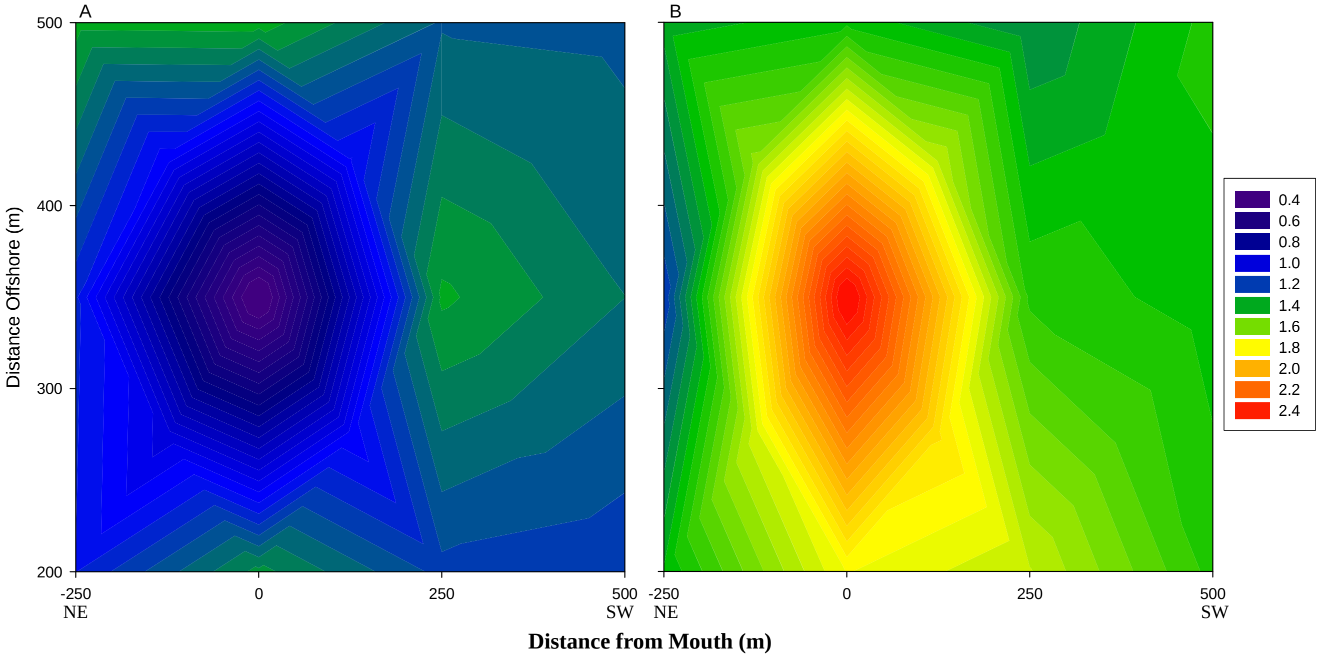


Figure A4.14: The surface (A) and 5m (B) total chlorophyll-*a* concentration (µg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the September 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

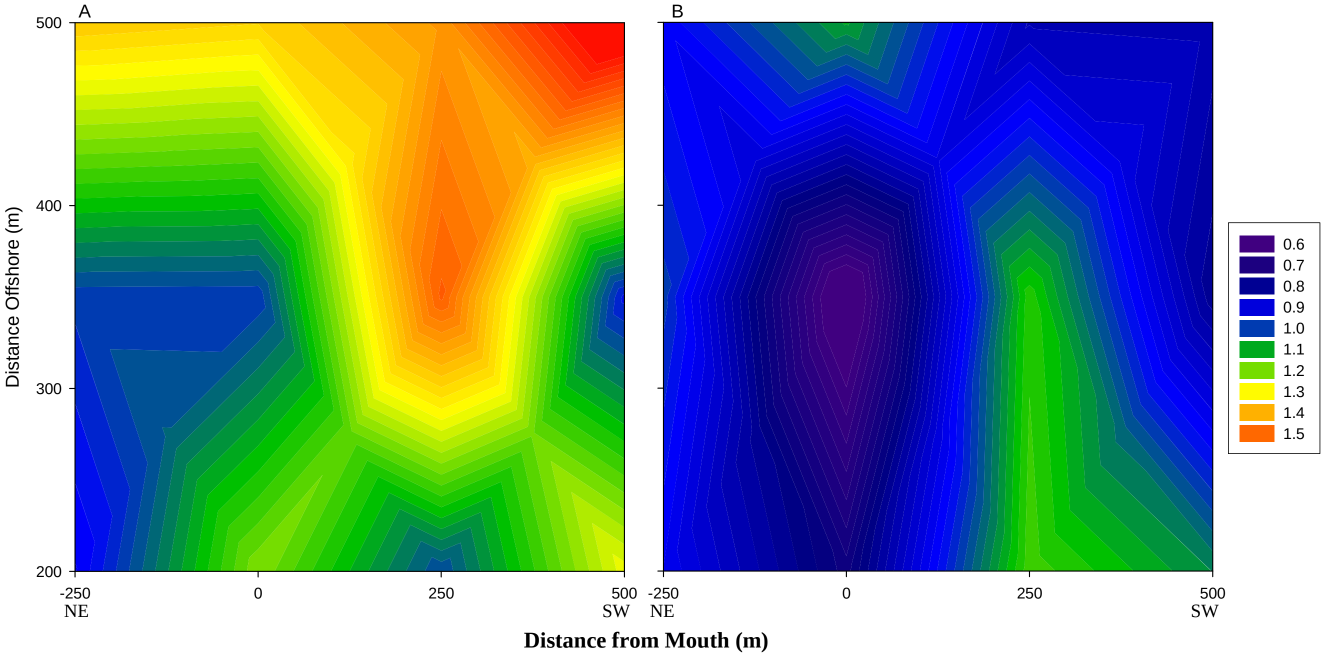
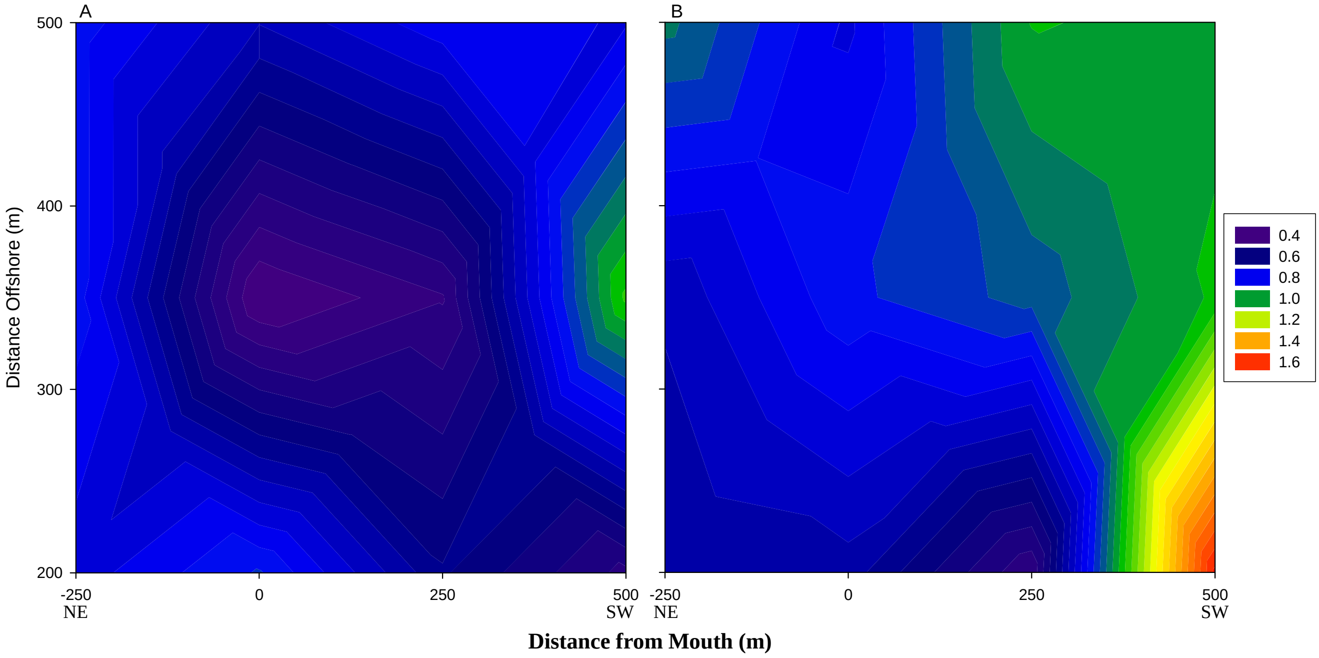


Figure A4.15: The surface (A) and 5m (B) total chlorophyll-*a* concentration (µg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the November 2005 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

Kasouga Estuary



East Kleinemonde Estuary

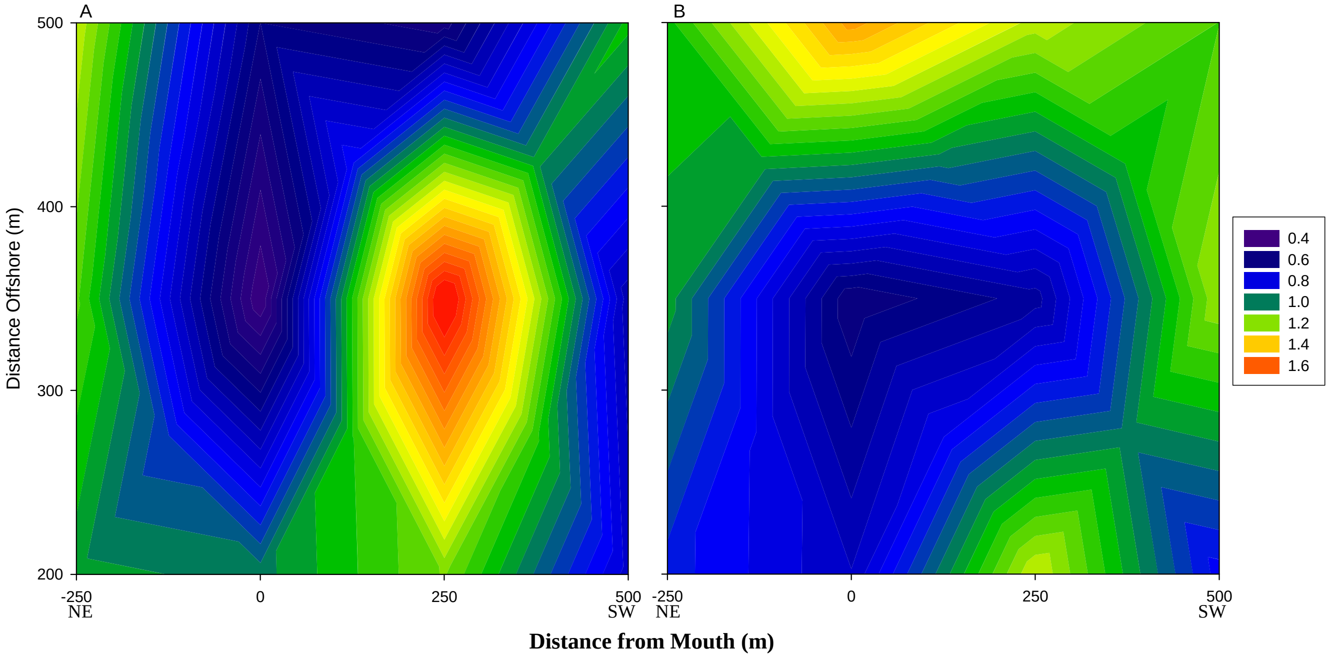


Figure A4.16: The surface (A) and 5m (B) total chlorophyll-*a* concentration (µg.L^{-1}) in the nearshore environment adjacent to the Kasouga and East Kleinemonde Estuaries during the March 2006 survey. NE (north-east) and SW (south-west) have been used to designate the compass points along the X-axis.

APPENDIX 5

THE LIST OF ZOOPLANKTON SPECIES RECORDED IN AND ADJACENT TO THE EAST KLEINEMONDE AND KASOUGA ESTUARIES

“P” indicates presence in that enironment, while “A” indicates absence.

Taxonomic Group/Species	**Kasouga**		**East Kleinemonde**	
	Marine	**Estuarine**	**Marine**	**Estuarine**
Acartia longipatella	P	P	P	P
Acartia sp1.	P	P	P	A
Appendicularians	P	P	P	A
Barnacles	P	P	P	P
Calanus agulhensis	P	P	P	A
Calanus simillimus	P	P	P	P
Calocalanus sp.	P	P	P	A
Candacia sp.	P	A	P	A
Chaetognaths	P	A	P	A
Clausocalanus sp.	P	P	P	P
Corycaeidae	P	P	P	P
Cumaceans	P	A	P	P
Eucalanus sp.	P	A	P	A
Gammarids	P	P	P	P
Gastrosaccus brevifissura	A	A	P	A
Harpacticoida	P	P	P	P
Isopods	P	P	P	P
Labidocera sp.	P	A	P	A
Limacina sp.	P	P	P	P
Medusa	P	P	P	P
Mesopodopsis wooldridgei	P	A	P	P
Microsetella norvegica	P	P	P	P
Microsetella rosea	P	P	P	P

Taxonomic Group/Species	**Kasouga**		**East Kleinemonde**	
	Marine	**Estuarine**	**Marine**	**Estuarine**
Mussels	P	P	P	P
Naupli	P	P	P	P
Noctiluca	P	P	P	A
Oithona sp.	P	P	P	P
Oncaea sp.	P	P	P	P
Ostracods	P	P	P	P
Paramacrochiron sewelli	P	A	A	A
Paraeuchaeta sp.	P	P	P	A
Pontella gaboonensis	P	A	P	A
Pontellina plumata	P	A	A	A
Pseudodiaptomus hessei	P	P	P	P
Rhincalanus cornutus	P	A	A	A
Rhopalophthalmus terranatalis	P	A	P	P
Salps	P	A	P	A
Sapphirina sp.	P	A	P	A
Schapocalanus sp.	P	A	P	A
Siphonaria	P	A	P	A
Unidentified sp1.	P	A	P	A
Subeucalanus pileatus	P	A	P	P
Temora stylifera	P	A	P	A
Temora turbinata	P	P	P	P
Zoea	P	P	P	P