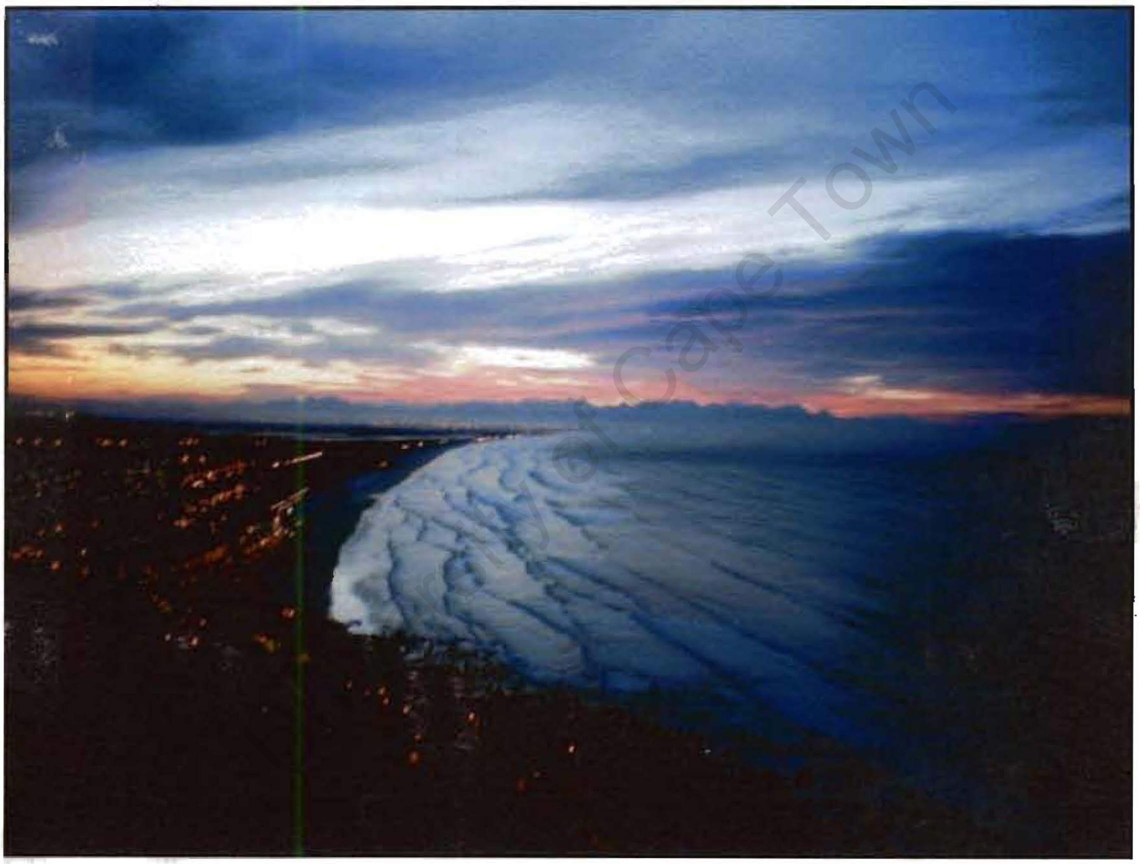
The Effect of the Cape Flats Aquifer on the Water Quality of False Bay



By Rhys Giljam

Supervisor: Dr Howard Waldron

Abstract

The aim of this project was to investigate the effect that the Cape Flats Aquifer, situated on the north shore of False Bay, is having on the water quality of the bay. Following increased development on the Cape Flats, the risk of the aquifer becoming contaminated has increased as it is situated below the informal settlement of Khayelitsha (where there is poor sanitation) and the Philippi agricultural area (where fertilisers are widely used).

Aquifer interaction with False Bay has been the subject of some conjecture yet is relatively understudied. Historically, very little is known about how the aquifer interacts with the sea. For this reason the first step was to undertake a review of previous studies on the study area which included physical characteristics such as geology, geohydrology, bathymetry, climatology and demographics to ascertain the extent of the current and future human impacts on the aquifer.

From past studies it became clear that the first step was to gain a fuller understanding of how the aquifer was discharging into the bay. A theoretical discharge from the aquifer into the bay was calculated using Darcy's Law and data from the literature. Secondly, using a CTD, a horizontal salinity transect of the north shore of False Bay was undertaken. The transect showed three areas of reduced salinity along the shore. These areas coincided with fluvial systems entering the bay. To establish whether discharge from the fluvial systems was sufficient to cause these areas of low salinity they were sampled further, with samples being taken from the berm of the beach, the surfzone and behind the surfzone. The concentration of nitrate, nitrite, phosphate and silicate in the samples was analysed. The results from the three approaches were interpreted in the context of data from the literature to determine if trends were evident.

It was found that the signal from the fluvial systems was not sufficient to explain the three low salinity sections. Taking into account an input of groundwater

justified the field results however, the methods used in the study did not provide a resolution sufficient to quantify the input in quantitative detail.

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1. Introduction

The aim of this project was to investigate the effect that the Cape Flats Aquifer, situated on the north shore of False Bay, is having on the water quality of the bay. Following increased development on the Cape Flats the risk of the aquifer becoming contaminated has increased as it is situated below the informal settlement of Khayelitsha (where there is poor sanitation) and the Philippi agricultural area (where fertilisers are widely used) and numerous nodal sources of pollution.

Several studies on the fluvial and stormwater systems entering False Bay have been undertaken as well as studies involving the physical and chemical oceanography but little is known about the effect or scope of the groundwater. The contribution of groundwater although not as easily recognised as oceanic exchange or subsurface flow could be important (Buddemeier, 1996). Around the world, although recognised for many years, submarine groundwater discharge has not yet received a great deal of attention. This is mainly due to the perception that the process is unimportant and the difficulty in quantifying it. Studies have now presented convincing arguments that the direct groundwater flow to the ocean can be significant to the overall nutrient balance in some areas (www.jhu.edu/~scor/wg112_article.htm).

Groundwater enters the ocean through a number of different processes. There are therefore many different methods used to measure the quantity of discharge and its effect on the environment (www.coastal-fluxes.slt.lk). Springs and seeps are responsible for funnelling fresh water and dissolved nutrients into specific areas, but the slow diffusive seepage of groundwater along the length of most shorelines is volumetrically more important. The quantity of nutrients being added in this way is uncertain due to the difficulties involved in trying to measure the flow, but the influence of groundwater discharge, the transport of nutrients and subsequently the effects on water quality has been demonstrated to be substantial. (Corbett, Burnett and Chanton, 2001). Swarzenski, Martin and Cable (2001) identified four main factors that affect submarine groundwater discharge. They state that discharge may occur where an aquifer is hydraulically connected to the sea through permeable bottom sediments. The discharge decreases with distance seaward away from the shore and is directly affected by groundwater withdrawals, for example evapotranspiration or extraction. They also recognise it as a potential source of coastal contaminants.

In the context of this global background False Bay is no exception, with very little being known as to how the aquifer interacts with the sea. The aquifer is vulnerable to many outside influences. In the time that the aquifer has been studied the problems affecting it have changed significantly and increased in severity. For this reason not only the aquifer and its interaction with False Bay was studied, but a review of previous studies done on the area was undertaken. The review included physical characteristics such as geology, geohydrology, bathymetry, climatology and changing demographics of the area to determine the extent of current and future human impacts on the aquifer.

Due to the sparse historical data on the subject varied methods were used to gain data. The first was a comprehensive literature review, which identified gaps in relevant information. Secondly, using data obtained in the literature the areas of highest discharge were calculated. Thirdly physical data was collected to determine whether physical evidence of the calculated discharge could be found.

1.2 Study Area

The study area extended from the Zeekoevlei outlet in the west to the Kuils River in the east. The northern boundary was the N2 highway and the southern boundary was False Bay *(Figure 1.1)*. This delineated an area encompassing the aquifer and its interaction with the coastal zone of False Bay.

1.3 Previous studies on the Cape Flats Aquifer

The Cape Flats Aquifer has been studied for the last three decades *(Table 1.3)*. The majority of the work especially in the 1970s and 1980s, focussed on the feasibility of abstraction from the aquifer and the subsequent impacts on water supply and quality. In the 1990s research shifted to determining the impact of nodal sources of pollution on the Cape Flats. This led to a number of impact assessments being done using the work done by Henzen (1973), Gerber (1981), Wessels and Greef (1980) and Vandoolaeghe (1989) as a base to the studies. Recently, due to the growing water demands for the Cape Town metropolitan area the work on abstraction is being revisited and even though no new fieldwork has been done the abstraction of groundwater is again being studied. Despite the interest in the aquifer over the past 30 years, the interaction between the southern boundary of the aquifer and False Bay has never been adequately studied. Three references relating to the interaction between the aquifer and False Bay could be found in the literature. Discharge from the aquifer into False Bay was mentioned by Engelbrecht & Tredoux (1989) in a report on the occurrence of brown water in False Bay. They stated that due to the differences in the depth of the bedrock and the permeability of the sand, water would discharge into the bay along well defined channels. Wright and Conrad (1995) had the opposite view that water loss was uniform along the whole coastline and not in well defined channels. This view was widely stated and accepted in the literature. Parsons (2000a) calculated the flux of nutrients from the Cape Flats Waste Water Treatment Works (WWTW) in relation to other areas along the coastline. With the exception of these three authors the interactions between the aquifer and False Bay have been left unstudied. The attitude towards the interaction between False Bay and aquifer can be summed up in a quote from Brown, Davies, Day & Gardiner (1991).

"Flow measurements from the aquifer into the sea through the intertidal beach are unavailable and, indeed, difficult or impossible to measure with any accuracy because of the diffuse and largely subterranean nature of the outfall"

1.4 Physical Characteristics of Study Area

1.4.1 Climate

The climatic conditions in False Bay are typified by harsh weather conditions and steep surrounding topography. The wind in False Bay blows along a north west-south east axis, with the south east predominating by blowing 35% of the time.

The weather in the bay is determined by both the South Atlantic High pressure situated over the Southern Atlantic, and eddies in the zonal westerlies. During the summer months the South Atlantic high pressure dominates causing strong south easterly winds, whilst during the winter the westerly wave perturbations dominate, bringing strong north westerly winds which are accompanied by heavy rainfall (Jury, 1991).

The climate is typically mediterranean with the rainy period occurring between May and September. The mean annual rainfall at the gauging station at Cape Town International Airport over the last 45 years is 554 mm with a range of 362 mm to 751 mm. During the year 2001 when the sampling for the project was done an above average rainfall of 595 mm was recorded (Cape Town Weather Bureau). Based on 31 years of rainfall data from the Zeekoevlei area a mean of 665 mm/a was calculated. The lowest mean rainfall occurs between November to January and the highest between June and July. Temperatures range from approximately 11° C in the winter to 20° C in the summer (Henzen, 1973).

1.4.2 The Bathymetry and Geology of Northern False Bay

False Bay, one of the largest natural embayments in South Africa, is an almost square body of water with sides approximately 30km in length which covers an area of approximately 1000 km^2 *(Figure 1.2)*. The east and west shores are rocky with precipitous slopes and vertical cliffs whilst the north shore is made up of a sweeping beach which runs from Muizenberg to Gordons bay, with the exception of the area around Swartklip (CSIR, 1982) and Standfontein where coastal aeolionites form cliffs (Mallory, 1970). The southern side of the bay is open to the sea between the rocky points of Cape Point and Cape Hangklip (CSIR, 1982).

The high relief and rugged topography of the western and eastern margins of False Bay is controlled by the structure and attitude of the hard Silurian quartzites of the Table Mountain Series, which are nearly horizontal in the Cape Peninsular and moderately folded about a north east – south west axis between Gordons bay and Cape Hangklip. Beneath the Table Mountain Series lies the late Precambrian slates and impure quartzites of the Malmesbury Formation, which are tightly folded about a north west – south east axis and are exposed with near vertical attitude in the northern part of the Cape Peninsular, around Belleville, Kuils River, Somerset West, Gordons Bay and along the east shore of False Bay at Kogel Bay (Simpson, du Plessis & Forder, 1970). In the west the rocky, steep coastline has many off lying rocks and reefs whilst the eastern coastline is clear of such features. A number of bays have formed within the eastern and western coastlines with Simons Bay and Gordon's Bay being the most sheltered (Mallory, 1970).

The bathymetry of False Bay reveals a number of important features. The seabed slopes due south towards the mouth of the bay with a gradient of 1:400 (Mallory, 1970). The bay reaches a maximum depth of 100m between the two Capes. The depth contours are smooth over a large part of the western and southern bay, whilst in the east the bottom is highly irregular with rock pinnacles and reefs interrupting the smoother part of the bay in the areas around Roman Rock, Seal Island, York Shoal, East Shoal and Whittle Rock (CSIR, 1982). A clear distinction can be made between the areas of rocky outcrop and those covered with unconsolidated sediments. Rocky bank, the Cape Point Massif and a large area of the southern part of Cape Hangklip exhibit convoluted contour characteristics reflecting rapid relief changes indicative of hard rock outcrops, which is in contrast to the north western and central part of the bay where near spacing of contours is suggestive of unconsolidated sediment cover (Glass, 1976).

The CSIR (1982) divided the bedrock geology of the bay into three main lithostratigraphic units, namely the Malmesbury Shale, Cape Granite and Table Mountain Sandstone. Whilst Glass (1976) further divided the geology into the following lithological units as hard rock outcrops in the bay: Upper Cainozoic Calcrete and Aeolianite, Bokkeveld Group, Table Mountain Sandstone Group, Cape Granite and Malmesbury Formation. Most of the western part of the bay is underlain by granite, with small sandstone inlays occurring between Muizenberg and Vishoek, Glencairn and Simonstown and Smitswinkel Bay and Cape Point. Other sandstone areas are Rocky Bank and the south east part of the bay including Hangklip Ridge. The entire north eastern section is underlain by Malmesbury shale with the exception of a small inlayer between Kogel Bay and Gordons Bay which is sandstone (Gentle, 1970). Glass (1976) suggests that Gentle (1970) overestimates the extent of the Table Mountain Sandstone Ridge and that the area is underlain by shale rather than sandstone. He restricts the occurrence of sandstone to the perimeter of the bay, and divides the bay diagonally into granite and shale (CSIR, 1982). Cape granite bedrock forms the western part of the bay except on Rocky Bank and terraces off Cape Point where the Table Mountain Group is present. The eastern half of the bay is covered by the Malmesbury Group, which forms the upper surface of the Palaeozoic and older rocks in False Bay (du Plessis & Glass, 1991). In many parts of the bay there are remnants of lithified coastal-marine sediments present, especially off the coast at Swartklip. Calcrete has also been found in many samples around the bay (CSIR, 1982).

Two major rock outcrops affect the topography at the entrance to the bay namely Rocky Bank and a ridge running south west from Cape Hangklip (CSIR, 1982). Rocky bank is a shoal positioned 20km South of Whittle rock at the entrance to False Bay which is connected to the Cape Point Massif by an accuate hard rock ridge that surrounds a sediment filled basin to the north east (Glass, 1976). It divides the entrance of the bay into two large submerged channels, with the eastern channel being further constricted by a ridge running south west from Cape Hangklip. These two channels emerge at 120m below mean sea level, proving that False Bay is a southward extension of a large valley that continues into the Cape Flats (CSIR, 1982). Rocky Bank plays a role in focussing wave energy on the east coast of the bay due to wave refraction. It is composed of Table Mountain sandstone and is a feature that underwent planation during a lower sea stand (Glass, 1976).

The sediments of False Bay fall into two major compositional groups, the Terrigenous and the Biogenous, each of which is further divided into a number of grain assemblages and associations. The relative distribution of each group is illustrated by the carbonate content of the coarse fraction of sediments. The terrigenous sediments dominate almost the entire northern part of the bay. There are a few exceptions to this along the eastern shore in the nearshore zone off Gordon's Bay and Strand, and on the western shore in Simons Bay. Most of the southern part of the bay is dominated by Bioclastic deposition, with the exception of the sediment fan in the lee of Rocky Bank, which forms a corridor linking the sediments in the northern part of the bay.

The Terrigenous sands contain an appreciable amount of rock fragments which originate from the local bedrock. For this reason in the north western part of the bay granite gravel is common whereas in the north east flakes of Malmesbury shale occur in the coarser sediments. Calcrete pebbles and fragments of eroded aeolianite occur locally. The bioclastic component consists of as least six different types, each being produced by different marine organisms. The grain type often changes with size (CSIR, 1982).

The coarse sands in False Bay are mainly restricted to the west and east margins of the bay, due to the high energy conditions which prevail and the low sediment supply. These areas are also characterised by a high calcium carbonate content of the sands which are made up of coarse robust shell debris.

The majority of the bay is floored by fine to medium grained sands with very fine sand occurring at deeper depths near the mouth south of Seal Island. There is a strip of well sorted sands along the north shore of False Bay and to the south of Seal Island. The rest of the sediments are moderately sorted except for those along the western margin. The modal sizes are displaced towards the finer grades; this asymmetry is typical of beach and shallow marine sediments.

The calcium carbonate content of the Bay can be divided into three zones. The first is two belts of high values along the eastern and western margins of the bay. The second is an area occupying the northern part of the bay, but extending into the south central region where values are less than 50%. Thirdly in the south where values of 50 –75% are common. The high value belts have been accounted for on a basis of high energy conditions, coupled with small inorganic Terrigenous supply, under which coarse robust shell fragments become the dominant sample. The low values in the north reflect the proximity to inorganic influx centres on the north coast coupled with a scarcity of pelagic organisms (Bowie, Fuller & Siesser, 1970).

1.4.3 Physical Oceanography of False Bay

False Bay has an average surface temperature of 19°C during the summer which drops to 15°C during the winter. Significant stratification develops during the summer with a bottom temperature of 1° - 3°C lower than during the winter.

A semi-diurnal tide is dominant with a tidal range varying between 0.3m at neap tide to 1.9m during spring tide. Clockwise currents have been recorded about 50% of the time during south east wind conditions, whilst during north west wind conditions anticlockwise currents have been recorded less than 10% of the time. Tidal currents are dominant during calm conditions, flowing in a northerly direction during flood tide and a southerly direction during ebb tide. A residence time of 4 – 6 days has been calculated using the rotational period of the bay.

Wave heights were recorded along the north shore in 1980. The waves were defracted and focussed by the topography into either the north west or north east comers of the bay. Plumes of coloured water have been observed extending south from the north shore of the bay to a distance 10km offshore. The plumes possible contained sediment, which was suspended by wave action along the shallow north coastline and then carried beyond the coastline by prevailing currents. Drogues tracked in the vicinity of the north shore have shown a mainly clockwise flow along the bay perimeter and an eastward drift along the north coast which turns south along the east coast (Grundlingh & Largier, 1991).

1.4.4 The Geology of the Cape Flats

The geology of the Cape Peninsular is a reflection of passed climate change showing the result of the pronounced glacioeustatic effects felt during the late Cenozoic period (Wright, Kloppers & Fricke, 1993). The oldest geological formation in Cape Town is the late Neoproterac Malmesbury group. This group is intruded into by plutons of Cape Granite, which extend south from Sea Point past Kirstenbosch to Cape Point and east into the centre of False Bay. Over a wide area in False Bay there are a large number of Dolerite dykes, which intrude up through the basal Table Mountain Group strata (Reid, Rogers, Hartnady & De Wit, 1993) and have been named the False Bay Dolerites. They are the same age as those found within the Karoo (Hartnady and Rogers, 1990).

Horizontal sandstones found in the Peninsular Mountain Formation in the west are linked to the same formation capping the Hottentots Holland Mountains to the east. In between the two mountain ranges post Palaeozoic erosion has removed the sandstones to form the Cape Flats (Reid, Rogers, Hartnady & De Wit, 1993; Hartnady & Rogers, 1990). The surface sands of the Cape Flats have been calculated to cover an area of between 630km^2 (Hartnady & Rogers, 1990) and 765 km^2 (Maclear, 1995), which stretches from False Bay to Table Bay, (Hartnady & Rogers, 1990) and extends in a northerly direction up the west coast *(Figure 1.3)* (Wright & Conrad, 1995). The thickness of the sand increases to the east (Meyer & De Beer, 1981). In addition to the current fluvial systems on the Cape Flats there is evidence of past systems which have carved valleys into the Cape Flats and False Bay. These river valleys become more incised the closer they are situated to the mountains (Reid, Rogers, Hartnady & De Wit, 1993).

The current stream systems on the Cape flats are:

1. *Keysers- Diep River*

   This system rises on the slopes of Table Mountain and the Constantiaberg and enters the sea via Sandvlei.

2. *Lotus River*

   Arises on the Cape Flats near Cape Town International Airport and enters the Zeekoevlei complex.

3. *Kuils- Eerste River System*

   Arises in the north east of the Cape Flats. The Kuils is barred from entering the sea by the Late Pleistocene aeolianites of the Langebaan formation and therefore flows east to join the Eerste River, which enters False Bay east of Swartklip (Hartnady & Rogers, 1990).

Surfzone erosion during sea level transgressions has caused the formation marine platforms between Gordon's Bay and Strand in the south east corner of the Cape Flats. This fluvial and marine erosion has been responsible for shaping the topography of the deeply weathered Malmesbury Group and Cape Granite bedrock (Reid, Rogers, Hartnady & De Wit, 1993).

The predominant argillaceous weathered Malmesbury Shale and minorly weathered granite bedrock is about 40m thick. The gradient of the bedrock varies substantially rising 80m above average mean sea level at Belville and dropping to 40m below sea level at Zeekoevlei. The bedrock topography shows a palaeo-valley reaching more than 40m below mean sea level to the east of Zeekoevlei, which runs north below the present day Lotus River (Wright & Conrad, 1995). If the course of the valley is extrapolated it would join with the present day Elsieskraal and Kuils Rivers. The southward extension runs south east of Seal Island, York Shoal and East Shoal to north central False Bay. The formation of this valley represents a period of Late Tertiary low sea level stand, perhaps even a major Oligocene regression, where the sea level dropped 400m below the present sea level (Hartnady & Rogers, 1990).

The sedimentation of the Cape Flats aquifer unit initially occurred in a shallow marine environment, progressing to intermediate beach and wind blown deposits and finally to aeolian and marsh (peat) conditions. This is the source of the large amount of shelly material present in the sand. The sand body is stratified horizontally and several lithostratigraphic units can be recognised. Calcareous sands and limestone deposits cover certain portions of the area, while silcrete, marine clays and bottom sediments of small inland water bodies also occur (Wright & Conrad, 1995).

Extensive investigation into the geology of the Cape Flats has been done. Hartnady and Rogers (1990) give an overview of the entire area, whilst Vandoolaeghe (1989) did extensive work in the Mitchell's Plain area situated 2 km north of False Bay and east of the Cape Flats WWTW. Jolly (1996) has studied the area to the west of the Cape Flats WWTW.

The Cape Flats Aquifer mainly consists of Cenozoic deposits underlain by essentially impervious Malmesbury shales or Cape Granite *(Figure 1.4)* (Wright & Conrad, 1995). The sediments of the Cenozoic Sandveld group over lie the bedrock and consist of: from the Middle Miocene the Elandsfontyn Formation, from the early Pliocene the Varswater Formation, from the Pleistocene the Springfontyn, Velddrif and Langebaan Formations and from the Holocene the Witzand Formation (Reid, Rogers, Hartnady & De Wit, 1993).

1. Varswater Formation

Has been found in boreholes underlying the coastal plain between Muizenberg and Swartklip. It is a marine formation of highly fossiliferous phosphate bearing, muddy very fine quartzose sand (Hartnady & Rogers, 1990). The sands, which range from very fine to medium are often silty and contain an abundance of small shells and shell fragments and coarse shelly gravel (Wright & Conrad, 1995). Vandoolaeghe (1989) identified three separate members in his study area namely the Calcareous Sand member, the Shelly Gravel Member and the Elandsfontyn Formation.

1.1 Calcareous Sand Member

The calcareous sand member is a marine deposit consisting of very fine to medium, often silty sand. It contains plenty of small shells and shell fragments. The thickest layers are found along the sea towards the east of the study area.

1.2 Shelly Gravel Member

In this member the shell content was found to be as high as 70%. The shells and fragments were heavily weathered, whilst the coarser sediments are interbedded with, or grade gradually into finer very shelly sands.

1.3 Elandsfontyn Formation

This formation consists of angular, fine to coarse clayey sands. Peat and peaty clay layers are characteristic. A patchy inland occurrence of sediments suggests that the bulk of the terrestrial deposit may have been removed by subsequent marine transgressions (Wright & Conrad, 1995) & (Vandoolaeghe, 1989).

2. *Springfontyn Formation*

The Springfontyn Formation is chiefly an aeolian formation of fine to medium quartzose sand (Hartnady & Rogers, 1990). The grain size increases with depth and thin calcareous clay and peat lenses may be present locally. It is relatively uniform and free of intrusions, (Wright & Conrad, 1995; Vandoolaeghe, 1989) and is exposed over most of the central part of the aquifer. In the Philippi area sands attain an unusually high degree of purity (99.5% SiO_2) and are mined for high quality glass (Wright & Conrad, 1995). These sands are present at Atlantis on the west coast and are used for groundwater abstraction (Hartnady & Rogers, 1990).

Vandoolaeghe (1989) suggests that the Springfontyn Formation is nothing more than a decalcified facies of the Witzand formation, because whenever the Springfontyn deposits are prominent the Witzand Member is insignificant and vice versa. Decalcification results where subsurface and surface permiabilities are high and thus conducive to recharge and quick subsurface through flow of groundwater (Vandoolaeghe, 1989).

3. *Langebaan Formation*

The Langebaan formation (locally called the Wolfgat formation) (Wright & Conrad, 1995) forms the original hairpin shapes of parabolic dunes that are situated along the coast and extend inland for 20km. The resistant upper calcretised surface of the Langebaan formation helps to form cliffs up to 50m high at Wolfgat (Hartnady & Rogers, 1990). The formation consists of calcrete and fine to very fine calcareous sands, which contain crossbedding along the coast (Wright & Conrad, 1995; Vandoolaeghe, 1989).

The eastern Cape Flats is covered by an irregular layer of sandy, surface limestone. Over this area the degree of sedimentation, lime content and thickness of the unit varies considerably. The calcareous unit consists mainly of several hard, well cemented layers which alternate with soft clayey or crumbly lime rich zones. The lime rich bed which covers the greater part of the area is only a few meters thick and consists of an upper, hard, densely cemented zone 250 - 350mm thick which rests on soft sand and yellow calcrete which grades into calcareous sand whose lime content generally decreases with depth. This represents the precipitation of secondary lime by groundwater action (Wright & Conrad, 1995).

4. Velddrif Formation

The Velddrif Formation is a patchy deposit of poorly consolidated intertidal and estuarine sediments. The formation is best exposed immediately east of Swartklip and at the foot of the cliffs west of Swartklip. It is overlain by the crossbedded, semi-consolidated aeolianites of the Langebaan formation (Hartnady & Rogers, 1990).

5. Witzand Formation

The Witzand formation consists of unconsolidated, often partially vegetated, calcareous dunes, which occur east of Swartklip between Wolfgat and Muizenberg (Hartnady & Rogers, 1990). The dunes consist of fine to very coarse calcareous sands and have an abundance of small shells and shell fragments (Wright & Conrad, 1995).

1.4.5 The Geohydrology of the Cape Flats

The Cape Flats Aquifer is constituted from sediments of the Bredasdorp formation and more specifically the Sandveld group (Vandoolaeghe, 1989). The aquifer area, which is best depicted by the saturated sand isopleth, covers an area of 630km^2 and has a maximum thickness of 45- 50m near the False Bay coast and wedges inland in a northerly direction *(Figure 1.5)* (Tredoux, 1984). It is regionally unconfined and internally it is essentially free of lateral hydraulic or geological boundaries, which may influence the regional behaviour (Wright & Conrad, 1995). The aquifer is interbedded with clay and peat layers which show no evidence of being continuous or effective in confining the aquifer (Gerber, 1981). The aquifer is not hydrologically linked to any other aquifer, except the talus/ scree material along the foot of the mountains to the west. To the north, west and east the aquifer pinches out against impermeable boundaries, whilst the coast of False Bay between Muizenberg and Macassar forms the southern boundary. The depth of the primary aquifer is marked by the presence of weathered Malmesbury bedrock, which forms an impervious basement (Wright & Conrad, 1995).

Groundwater flow on the Cape Flats is either west towards Table Bay or south towards False Bay. In the main part of the Cape Flats Aquifer (area south of the N2) the flow is either west towards Zeekoevlei or south towards Mnandi or Monwabisi. Water level contours show a lower hydraulic conductivity along the coast than inland (Wright & Conrad, 1995). Vandoolaeghe (1989) documented in his work on a well field around Mitchell's Plain that the water table gradient (piezometric) is relatively steep in a 1km strip joining the coast (0.015). This steep gradient flattens out rather sharply inland (0.003). This he attributed to a function of the topography or the hydraulic contrast between the low transmissive Varswater formation in the coastal zone and the more transmissive Bredasdorp formation further inland. ie. A hydraulic bottle neck situation exists.

Historically a number of different opinions on the method of discharge of water from the aquifer into False Bay have been stated. Wright & Conrad (1995) state that water loss should occur uniformly along the whole coastline, whilst Engelbrecht & Tredoux (1989) state that due to the differences in the depth of the bedrock and the permeability of the sand, water will discharge into the bay along well defined channels. Rogers, Jolly and Haye (pers. comm.) incorporate both points of view as they think that water will discharge along the entire coast but it should be more pronounced in areas with a high permeability. The water level of the aquifer fluctuates seasonally. Wright & Conrad (1995) found these water level fluctuations to range up to 2m in the north. Whilst to the west of Zeekoevlei, Jolly (1996) observed a maximum fluctuation of 1.085m and a minimum of 0.58m between December 1995 and November 1996. These figures are similar to monitoring done by DWAF in the Mitchell's Plain area between 1977 and 1983. Jolly (1996), Parsons (2000c) found groundwater levels to fluctuate on average 2 – 3m annually, being at the lowest level in May and the highest level in September/ October. This was confirmed by Gerber (1981) who after an inspection of the topographical maps and waterlevel variations in the Cape Flats concluded that natural water level fluctuations seldom exceed 3m with the higher values being observed in areas with uniform topography.

The Springfontyn and Witzand members of the Bredasdorp formation are by far the most important members from a production point of view. The sands range in size from fine to coarse and are generally well sorted and rounded. It is these characteristics which translate into an above average hydraulic conductivity giving 30 –40 m/d in the central area of the aquifer (Vandoolaeghe, 1989) and 15 – 50 m/d in the east (Wessels & Greef, 1980). Vandoolaeghe (1989) found that the Weltevreden Road high transmissivity zone coincides with the most prominent pocket of the Bredasdorp deposits. The calcareous Witzand sands have been shown to contain groundwater of above average hardness. Closer examination reveals that the Witzands and Springfontyn formations possess a degree of heterogeneity and anisotropy due to the occurrence of sandy clay and clayey sand lenses (Vandoolaeghe, 1989) and due to vertical and lateral grain size graduation (Wright & Conrad, 1995). This results in anisotropic groundwater flow conditions and/or a vertical flow component (leakage, delayed yield) to occur to a more or lesser extent when the formation is pumped. ie. When the aquifer is formed by Witzand and Springfontyn sediments it has unconfined to semi-confined characteristics (Vandoolaeghe, 1989) & (Wright & Conrad, 1995). The vertical permeability ranges from 1 –10% of the horizontal values (Gerber, 1981).

The calcareous clay and calcrete layers of the Langebaan (Wolfgat) formation act as a barrier to hinder free flow within the aquifer. The unit acts as an aquitard and results in a semi-confined aquifer (Wright & Conrad, 1995; Vandoolaeghe, 1989). The sediments from the Varswater formation form the major aquifer whenever the very transmissive Bredasdorp sands are relatively thin or altogether absent, however when the Bredasdorp formation is present they form the bottom aquitard. They have been noted to have a hydraulic conductivity of 1 – 10m/day (Vandoolaeghe, 1989). This is relatively low as even shell gravel has conductivities between 6 – 23 m/day (Wright & Conrad, 1995). The Elandsfontyn formation plays a minor role in the hydrology of the study area and can be lumped into the Varswater aquitard (Vandoolaeghe, 1989).

Due to its peltic and extensively weathered nature, the Malmesbury metasediments has always been regarded as the impervious basement of the primary aquifer system. Wessels & Greef (1980) allowed the possible occurrence of transmissive, brecciated zones associated with faults in the Malmesbury bedrock as a number of boreholes produced good yields. Vandoolaeghe (1989), Wright & Conrad (1995) and Bertram (1989) showed production boreholes in the Philippi agricultural area to produce yields of up to 15 l/s, whilst a number of boreholes in the east of the Cape Flats have also experienced high yields out of the Malmesbury group as well as boreholes on the west coast (Vandoolaeghe, 1989; Wright & Conrad, 1995).

Recharge in the aquifer is principally from precipitation falling within the catchment. The average annual rainfall is 500 – 800 mm increasing in a westerly direction and falls during the winter and spring (Wright & Conrad, 1995). Gerber (1981) calculated recharge from precipitation to be 154 x 10^6 m^3/year. To put this figure in perspective he then calculated the recharge from the Kuils River, which he thought to be the most significant fluvial system, to contribute 0.5 x 10^6 m^3/year. At this time recharge from water bodies in the west was considered insignificant. This has since been argued by Jolly (1996), Rosewarne (1999) and Parsons (2000abc) not to be true.

The high permeability of the sand cover over the Cape Flats suggests that surface runoff is unlikely to occur except where the water table is close to the surface, the rainfall intensity is very high or the land surface has been modified (e.g. by the building of roads). Gerber (1981) proposed recharge rates of 40% of the mean annual precipitation whilst Vandoolaeghe (1989) estimated the recharge to be 15 – 37% of the mean annual precipitation. Similar recharge rates have been estimated for other similar aquifers. Parsons (2000c) states that calculating recharge rates as a percentage of the mean annual precipitation is simplistic and naïve. The reason for this is that recharge is an event driven process governed by a host of factors which include the rainfall depth and intensity, the slope, the hydraulic conductivity of the soil and the aquifer and the antecedent moisture conditions. Parsons (2000c) states that a certain threshold has to be reached before the aquifer recharges. For an unconfined system such as the Cape Flats Aquifer recharge is unlikely to occur if the rainfall is less than 10mm over a 5 day period. If the rainfall exceeds 50mm over a 5 day period, 50 mm will recharge the aquifer and the rest will be lost through runoff. Given that the mean annual precipitation is 550mm/a he tentatively proposed that 300mm/a should fall for recharge to take place. This could however occur in a single significant storm event.

Aside from rainfall, recharge to the aquifer occurs by other means. Localised sources of recharge other than precipitation also include irrigation, septic tanks, leaking water mains and broken sewer pipes (Parsons, 2000c). The Cape Flats WWTW was originally investigated by Henzen (1973) who concluded that there was some evidence of sewage infiltration but the quantities involved in the long established ponds were so small compared to the daily flow it was negligible. Wright & Conrad (1995) has also identified the municipal sewage ponds at the Cape Flats WWTW as sources of recharge. This was then further investigated by Parsons (2000a) who found that the construction of the Cape Flats WWTW caused the direction of the ground water flow to be reversed. Under natural conditions the southern part of Zeekoevlei would discharge water into the groundwater system. The construction of the Cape Flats WWTW has however caused the water to flow northwards into Zeekoevlei, with a hydraulic gradient of 0.01. Increased hydraulic gradients were also measured to the west (0.04) and to the south (0.03) of the Cape Flats WWTW, the natural gradient of the aquifer in the area is 0.003. The groundwater movement in this area is therefore greater than that in the rest of the Cape Flats.

Gerber (1981) investigated Zeekoevlei and stated that at first glance it appeared to be a major source of recharge. Water table analysis however showed that the pond is partly maintained by groundwater seepage with the exception of short periods after heavy rains where the quasi- equilibrium system may be disturbed. He found the bottom of the vlei to appear sealed as a result of mud and clay deposition. Jolly (1996), Rosewame (1999) and Parsons (2000c) have since investigated the primary aquifer to the west of Zeekoevlei, showing Gerber (1981)' s work to be flawed. Parsons (2000c) showed the limitation on the water coming out of this section of the aquifer is the quality, not the transmissivity as Gerber (1981) stated. Groundwater in this area plays a crucial part in sustaining the vleis (Parsons, 2000abc). Data indicates hydraulic conductivity to be relatively constant between 15m/d and 20m/d with the fluctuation in transmissivity being a function of the saturated thickness (Parsons, 2000c. During the winter months the vleis are mainly recharged through direct rainfall, whereas during the summer months a large amount of recharge occurs through the groundwater (Parsons, 2000b). Grobicki (1999) presented data clearly showing discharge from a 5km unlined section of the Lotus River between Vygekraal Road and Ottery that may cause losses of up to 60% under dry summer conditions into the groundwater system.

Investigations have been done on specific parts of the aquifer. These mainly consist of areas which have been identified as possible pollution threats to the aquifer. Jolly (1996) investigated the aquifer in the region of Capricorn Park. Using data collected he formulated a conceptual model of the aquifer. The grain size variations indicate a permeability variation of less than 1m/day in the sand and clay horizons to 50m/day in the gravely sand lenses. The aquifer has a saturated thickness of approximately 25m and a transmissivity of 349 to 620m^2/day. The flow direction is towards the coast at a gradient of 1:1000.The depositional history of the various geological formations making up the aquifer has resulted in an upper and lower aquifer of different qualities being formed. The upper aquifer occurs at a depth of less than 11m and is separated from the lower aquifer consisting of poorly sorted muddy sands. Groundwater quality varies between 255 mS/m in the upper aquifer and 2400 mS/m in the lower aquifer. The lower aquifer is leaky and unconfined. The higher salinity of the lower aquifer has been ascribed to the marine origin of the Varswater Formation (Jolly, 1996).

Ransome & de Wit (1992) studied the Coastal Parks Waste Disposal Site, which is situated 4km east of Muizenberg and 400m north of the False Bay shoreline. The ground water was originally encountered between 1m and 3m meters below the natural ground level in the form of saturated sands, this water was then encountered again at 20m to 22m in the Varswater Formation. The main aquifer in this area is situated between 22 and 26m below natural ground level in the shelly gravel layers of the Upper Coastal Parks Member. There was no groundwater found in the Lower Coastal Parks Member.

Cave (2000) studied the Swartklip Waste Disposal site which is situated on the southern edge of the CFA. The closure of this site has been initiated as the type of waste disposal that occurs at the site is unsuitable for the aquifer system. The site was chosen to be situated on the south eastern Cape Flats, as the depth to the water table is over 20m. Tests by Gerber (1981) and Henzen (1973) have, however, shown the aquifer in the area to be low in salinity and to have a high transmissivity (>500m^2/day) which means the area is highly suitable for abstraction. This was also reported by Wright & Conrad (1995). The Langebaan formation which constitutes most of the unsaturated zone varies in thickness between 13m and 28m. The southern boundary of the site occurs on top of twin calcrete horizons in the Langebaan formation. The ground water flow is south to south east and there is approximately 20m of unsaturated zone between the surface and the watertable. The rate of horizontal movement was found to be 20-40 m/day and there was a 5 –10 day travel time for vertical water movement between the wastepile and the 20m unsaturated zone.

1.4.6 The Potential Impacts on the Cape Flats Aquifer and False Bay

1. Sources of Pollution on the Cape Flats

Many potential sources of pollution that have the ability to affect the water quality within the Cape Flats Aquifer and False Bay are situated on the Cape Flats *(Figure 1.6)*. Some of these sources occupy large parts of the Cape Flats and are capable of effecting the environment over a large area, whilst other point sources of pollution have the potential to cause great impacts in localised areas. It is important not only to understand the scope and subsequent effect of pollution entering the aquifer, but it is also important to identify sources of pollution entering False Bay directly. The source of polluted water in the bay can then accurately be determined.

The most important of the low to medium risk sources of pollution are the low income residential townships which often contain large informally housed communities, which have little to no sanitation (Wright & Conrad, 1995). Vandoolaeghe (1989) recognised that pollution sources are a concern due to the sandy, unconfined nature of the aquifer which makes it particularly vulnerable, which is exacerbated by the water table being extremely close to the surface. The aquifer is already showing signs of local contamination.

A number of types of high risk nodal pollution sources have been identified. These are as follows:

(i) Waste Water Treatment Works
(ii) Waste disposal Sites
(iii) Power Station
(iv) Commerce and intensive agriculture

Signs of local contamination have been identified in numerous areas of the aquifer. For example Tredoux (1984) provided evidence of groundwater pollution from Mitchell's Plain WWTW and Swartklip Waste Disposal site. Waterlevel testing during the Pilot Abstraction Test also proved that the Cape flats WWTW maturation ponds were causing pollution. Whilst Bertram (1989) showed that much of the Philippi area is contaminated as a result of agricultural practices.

2. Water Quality of the Cape Flats Aquifer

The salinity in the majority of the Cape Flats Aquifer is low but the water is characterised by a relatively high level of temporal hardness. The more saline areas are found on the periphery of the aquifer, with Philippi having the highest salt content due to irrigation. High potassium and nitrate concentrations found in this area are further evidence of the 400 tons of fertiliser used annually. The abundance of shelly material throughout the aquifer results in groundwater saturated in calcium carbonate, which has lead to the occurrence of calcrete horizons appearing near the water table (Wright & Conrad, 1995).

3. Land Use and Population Characteristics in the False Bay Coastal Frame

van der Merwe, Vlok & van der Merwe (1991) outlined the changes in land use and urban growth in the areas affecting the north shore of False Bay. The paper focussed on changes between 1960 and 1988 and gave some predictions for the future. This information is important and relative to the project since all problems pertaining to environmental quality, recreational facilities, economic development and urbanisation are directly or indirectly related to landuse. They outline this further whilst discussing the expansion on the north side of False Bay in the form of the southward sprawl of the Cape Town Metropolis.

"In future the greatest impact on False Bay will emanate from the vigorous expansion of the present coloured residential areas at Mitchell's Plain, Eerste River/Blue Downs, and Firgrove/ Macassar, as well as the black residential areas of Khayelitsha, Eerste River and Mfuleni. Recreational needs and pollution output from these areas will have a great impact on the False Bay Environment."

All of these areas are within close enough proximity to the Cape Flats Aquifer to have an effect on it. The reference to designated "coloured" and "black" areas was a function of the apartheid legislation at the time.

In the years between 1960 and 1988 there was an increase in the urban settlement of 12% which came at the expense of a decrease in agricultural and vacant land of 15%. There was an unexpectedly modest increase in the recreational areas along the coastline. There has been the establishment of extensive industrial and institutional activities with a high pollution potential such as sewage disposal, stormwater canals and a chemical factory along the coastline.

False Bay forms an integral part of the rural/ urban fringe of the larger Cape Town metropolis. van der Merwe, Vlok & van der Merwe (1991) identified a large housing shortage especially in the former coloured and black areas which justified residential development, although they questioned the choice of location for this development as False Bay would experience the impact of the development in the future. This fear has largely been realised with the fast growth of informal housing in Khayelitsha.

Not only did the landuse around False Bay change in the period between 1960 and 1985 but the population characteristics have also changed. In 1985 nearly 500 000 people occupied the 890km^2 in the False Bay frame. This gives a very high population concentration of 540 people/km^2 as opposed to 230 people/km^2 in 1960, with the 15 urban areas accommodating 95% of the population. The urban population increased 153% between 1960 and 1985 whilst the rural population decreased by 13%. They also warned about the pressures from the increase in population from Khayelitsha and surrounding areas, as the population of Khayelitsha increased by 100 000 between 1985 and 1989.

4. Direct inputs into False Bay

Brown *et al.* (1991) identified nine sites along the north shore of False Bay as potential sources of chemical pollution which directly input into False Bay. They are as follows:

(i) *The Outfall of the Zandvlei Estuary*

The Zandvlei Estuary drains a catchment of 80 km^2 which consists of housing, light industry, agricultural land, afforested areas and natural fynbos. From this area, pollutants in the form of sewage, industrial effluent, stormwater and garbage all enter the system. Sewage inputs are infrequent and only occur when there is an overflow at a nearby pumping station. The system largely cleans itself before entering False Bay as it enters a wetland containing beds of Typha and Phragmites before flowing into Zandvlei which contains a large amount of potomogetan.

(ii) *Zeekoevlei Outfall*

The system drains a catchment of 83 km^2 and receives effluent from the Cape Flats WWTW. The water from the Cape Flats WWTW dominates the flow for most of the year. The flow from the catchment which includes areas of housing industry and market gardening is negligible in summer but significant during the winter.

(iii) *Mitchell's Plain West (Mnandi) Stormwater Drain*

Drains part of the Mitchell's Plain area.

(iv) *Mitchell's Plain WWTW Outlet (Standfontein Sewer)*

Drains the effluent from the Mitchell's Plain Sewage works.

(v) *Mitchell's Plain East Stormwater Outfall*

The outfall consists of two pipes 1.2m in diameter which drain a large part of Mitchell's Plain (an area of low to middle income housing) and a small part of Khayelitsha (low income/ informal housing).

(vi) *The Monwabisi Stormwater Outfall*

The outfall drains most of Khayelitsha and has been found to contain raw sewage on occasion. It has an approximate aperture of 3 x 1.5m and opens near the Monwabisi tidal pool which is heavily used for recreation.

(vii) *The Eerste River Estuary*

The estuary is fed by the catchment of the Eerste and Kuils Rivers which have a combined area of approximately 600m^2. Land use in the Eerste River catchment includes vineyards and fruit and vegetable farms which leach nutrients into the river. The estuary has poor water quality due to over abstraction, a substantial input of effluent from the Stellenbosch sewage works and insufficient compensation water from its dammed upper reaches. The catchment of the Kuils River is highly urbanised with some industrialisation. The system receives treated sewage and industrial effluents. The lower reaches of the Kuils River pass through areas of intensive dairy farming and feedlots which are situated close to the river. The Zandvliet sewage works discharges into the common estuary (Brown *et al*, 1991).

The highest flow rates were recorded at the Zeekoevlei, Zandvlei and the Eerste and Kuils River outfalls. The flow rates at the other sites were significantly lower. The flows at all of the sites were distinctly seasonal and winter spates were, on occasion, recorded as being an order of magnitude greater than the baseline figures. The PO_4 – P was high at all of the sites but stayed below 16 umol/l except at the Zeekoevlei and Eerste River outlets where concentrations in excess of 100 umol/l were recorded. These high concentrations were probably due to treated effluent in the system. Calculated loading rates of PO_4 – P at the Zeekoevlei outlet varied from 100 to over 1500 kg/d with a yearly median in excess of 600 kg/d.

With the exception of the Zandvlei estuary, all of the outlets exceeded the Special Industrial Effluent (SIE) standard for NO_3 - N of 107 umol/l. The Mitchell's Plain outfall displayed a mean concentration of 2000 umol NO_3 – N/l and the Standfontein Sewer a concentration of 1350 umol/l. The loading rates at the Zeekoevlei outlet vary between approximately 100 to over 6000 kg/d with a yearly median in excess of 500 kg/d. It is thought that due to its similar flow rate the Eerste River should show similar results. These loading figures should only be regarded as an order of magnitude approximation.

A number of groundwater samples were taken from boreholes to try and estimate the impact of groundwater. The nutrient levels in the samples were high with NH_4 - N concentrations of over 28500 umol/l recorded. A single berm sample showed a concentration of 1500 umol/l and three berm samples showed PO_4 - P concentrations of 55, 1320 and 245 umol/l respectively. The other PO_4 - P concentrations were below 32 umol/l. There was considerable variation in the nutrient samples recorded in different parts of the aquifer. The calculation of loading rates was not attempted.

The report found the following to be a cause of concern. The high PO_4 – P concentrations at Zeekoevlei and the Eerste River, they were however not a recent development. The suspended solids at Mitchell's Plain East, Monwabisi and Mnandi. The NO_3 - N and NO_2 - N at Mitchell's Plain Storm Water East, Strandfontein and to some extent Zeekoevlei and Eerste River. All of the nutrient concentrations recorded from the Cape Flats Aquifer, especially the NH_4 - N.

It was concluded that the loading of nutrients along the north shore of False bay has increased as a result of the growth of Khayelitsha and adjacent developments as well as the establishment of a new WWTW.

The following point sources of pollution were identified and the subsequent effect on the aquifer has been recorded.

5. Cape Flats Waste Water Treatment Works

The Cape Flats Waste Water Treatment Works (WWTW) is situated 3km east of Muizenberg and discharges effluent into the runoff from Zeekoevlei. The effect that it has on False Bay is twofold, not only is it responsible for introducing a large amount of nutrients into the bay but the effluent it discharges is freshwater, which will cause the beaches to suffer from a freshwater effect (Skibbe, 1991). Zeekoevlei and Rondevlei are situated nearby in the western compartment of the Cape Flats Aquifer. The shallow watertable and transmissive nature of the aquifer system result in it being very vulnerable to anthropogenic impacts. The area around Zeekoevlei has been used to dispose sewage since the 1920's with the current WWTW being established in 1979 on a groundwater fed wetland system. The plant treats, on average, approximately 130megal/d (Parsons, 2000a) although the plant has a capacity of 200megal/d. Due to the heavy rains during and before the winter sampling was taking place it was treating a peak of 365 and average of 330megal/d (pers comm. Gow). The treated effluent is either discharged into the Zeekoevlei canal or is used for irrigation (e.g., Steenberg Golf Course). The southern most evaporation ponds are no longer used to treat sewage but are maintained as they attract a large variety of birdlife. Geohydrological investigation shows that groundwater in the area should flow south and discharge into the ponds, the construction of the WWTW however reversed the direction of the ground water flow to a northerly direction. i.e.

towards Zeekoevlei. It is thought that a total of 12400 kg or 34% of the total load of phosphorous is discharged into Zeekoevlei each year (Parsons, 2000a).

Impact on groundwater

Due to the shallow water table it is thought that groundwater plays a large part in filling the vleis, it is also very susceptible to any nutrient loading coming from the WWTW.

Electric Conductivity (EC)

The Cape Flats WWTW has a limited impact on groundwater salinity. Bertram (1989) recorded the area around Philippi (highest EC in aquifer) to have an EC of 180m/Sm whilst the ambient EC in the aquifer is 70 –120 mS/m. The EC of the Cape Flats WWTW falls within these ranges, except in the area to the north east and south east of the evaporation ponds, where there is a slight increase in salinity. Both of these areas were used to dispose of sewage sludge (Parsons, 2000a).

Nitrogen

NH_4 – N is the dominant form of nitrogen in the vicinity of the WWTW. NO_3 - N and NO_2 - N concentrations are low except in sludge disposal areas. A significant increase in ammonium concentrations were detected to the south and south east of the WWTW, with the highest concentrations being found in the vicinity of the sludge disposal area, where concentrations in excess of 14000 umol NH_4 – N/l are present. Excluding concentrations taken from boreholes in the old sludge disposal areas, the harmonic mean for NH_4 – N concentrations around the WWTW is 650 umol/l with a background concentration generally less than 7 umol/l and 36 umol/l seldom being obtained. The levels obtained clearly show an impact on groundwater from the WWTW. Attenuation is evident with distance from the source, but the current available data is insufficient to identify the extent of the plume. The historical data suggests a concentration of groundwater discharge into the sea and Zeekoevlei of 1430 umol/l and 1070 umol/l respectively (Parsons, 2000a).

Phosphate

The concentrations of PO_4 – P around the WWTW exceed 320 umol/l with the highest concentration of 1600 umol/l being found in an area of sludge disposal whilst the ambient concentrations in the aquifer are less than 1.5 umol/l. The high concentrations decrease to 225 umol/l obtained 160m north of the WWTW. It is however not possible to determine the concentrations to the south and therefore the discharge into the sea. The harmonic mean of samples taken from wellpoints closest to the sea is 270 umol/l which translates to two orders of magnitude greater than ambient concentrations (Parsons, 2000a).

Silica

The SiO_2 - Si concentrations range between 100 and 285 umol/l with a mean of 160 umol/l. Edwards (1989) reported typical concentrations in the central productive part of the aquifer to range between 120 and 190 umol/l with a median of 145 umol/l (n = 403). Concentrations of silica in groundwater south of the WWTW are similar to ambient concentrations (Parsons, 2000a).

Sampling shows high nitrate and phosphate concentrations. The extent of the plume is unknown but discharge into the sea is two orders of magnitude greater than ambient concentrations. Using data available it is impossible to indicate contamination load discharged into the sea, this therefore needs to be addressed.

These calculations clearly indicate the impact of the WWTW on the quality and quantity of groundwater discharge into the sea. The quantity of nitrate and phosphate is two orders of magnitude greater than elsewhere along the False Bay shoreline. Because of the increased rate of groundwater discharge at the

WWTW, the quantity of silica discharged is double that of anywhere along the coast (Parsons, 2000a).

Impact of outfall on False Bay

The impact of the outfall has been studied by Skibbe (1991), CSIR (1991) and Ollis (1997). The outfall water comprises of water from Rondevlei (via a weir), Zeekoevlei (via sluice gates), the final effluent from the Cape Flats WWTW and seepage from the Cape Flats Aquifer (Bickerton, 1982). Skibbe (1991) found that the salinity returned to 35 psu within a distance of 400m to 500m from the effluent discharge point. He also measured concentrations of NO_3 - N, NO_2 - N, NH_4 – N, PO_4 - P and SiO_2 - Si, all of which gradually decreased to a stable concentration as the salinity returned to 35 psu. The NO_3 - N concentrations were higher than the NH_4 – N concentrations in the interstitial waters whereas the NH_4 – N concentrations were higher than the NO_3 - N in the surfzone. The phosphate concentration in the interstitial water was higher than in the surfzone. From this he concluded that the beach adjacent to Zeekoevlei is well oxidised, and the nutrient loads increase during winter (Skibbe, 1991).

A further investigation by CSIR (1991) and Ollis (1997), found that freshwater was still evident 1000m from the outlet and even when the longshore current was flowing in the opposite direction, the flow was still evident 600m. The latter study found signs of outlet water up to 2000m away from the mouth. The influence was tested under all flow conditions and although lower flow rates resulted in lower dilutions the differences were not extensive. The area of influence changed by less than 100m. The results showed no obvious differences due to different wind conditions, but conditions mostly had moderate wind conditions which are not as important to nearshore dilution. It was predicted that strong offshore winds would help to transport surface effluents offshore whilst strong onshore winds would have the opposite effect (CSIR, 1991).

CSIR (1991) conducted a series of dye bomb tests to identify several features of the nearshore circulation. Dye was released in the outlet, the breaker zone and behind the breakers. The dye bombs which were dropped behind the breaker zone were often transported in an along shore direction for more than a kilometre, without showing any offshore tendencies. The dye bombs which were dropped in the breaker zone stayed trapped and found it difficult to break through by means of rip currents. A clear difference in the dispersion characteristics of the dye bombs dropped in and beyond the breaker zone was noticed. Due to the breaking waves the growth rate and therefore dilution were a factor of three higher than those beyond the breakers. During all three tests the dye was visible for 750m along the coastline and in two cases it was transported 1.5km along the coast before breaking the surfzone. Low dilutions were also found relatively far away.

6. The Mitchell's Plain Waste Water Treatment Works

The sewage purification plant has an inflow of 30 mega l/d and outflow of 29 mega l/d, losing 1/d through evaporation. The sludge used to be dumped on site, but is now removed as leachate because it was considered to be harmful to the environment. After treatment the plant water flows through settling ponds where scum and sludge is skimmed off (pers. comm. Kloppers). The outlet discharges in to the sea between Mnandi and Standfontein and the extent of freshwater flow has been monitored for about 100 – 150m on either side of the outlet (CSIR, 1991).

7. The Zandvliet Waste Water Treatment Works

The Zandvliet WWTW services mainly Khayelitsha and Bluedowns. The effluent flows straight into Kuils/Eerste River. Presently there are no maturation ponds, but they have been planned (pers. comm. Newman).

8. Swartklip Waste Disposal Site

The Swartklip Waste Disposal site is situated on the southern edge of the Cape Flats aquifer. The site is classified as highly unsuitable for location on a major aquifer system. The CMC has therefore initiated a process to close the waste disposal facility due to the perceived negative impact of the waste on the water quality of the aquifer.

In 1974 a ground water monitoring network was established around the old Divisional Council Waste disposal site situated on the opposite side of Swartklip Road. This site was sampled until the early 1980s, by Tredoux (1984). The groundwater to the south east of the old site was found to be polluted but this was mainly due to the co-disposal of sewage sludge along with waste during the winter months. The pollution subsequently started to abate when the co- disposal stopped in 1981. The site was then closed and developed into the Spine Road Sportsfields. The Swartklip site was established in 1979 before the current regulations and minimum requirements for Waste Management (DWAF, 1998ab) were implemented, therefore no detailed environmental investigation or risk assessment took place. There was no groundwater monitoring system in place for the first 12 years of operation at the site, and monitoring only began in the early 1990's to comply with legislative changes.

Water Quality

The background water quality shows an electric conductivity of 70- 150 m/Sm which means the water can be used for irrigation on tolerant crops. Up gradient from the site there are signs of localised pollution in the shallow groundwater, but the deeper ground water has not been affected. Downgradient, the water quality at some of the boreholes has shown increased levels of pollution since monitoring began. The groundwater directly south of the waste pile is polluted and no longer fit for use. The other boreholes to the south and east of the site show elevated ammonium concentrations, but no other signs of pollution.

A number of other sources in the area have been identified as potential contaminant sources. They are as follows.

- (i) Swartklip products to the north which operates a site for waste generated by metal plating.
- (ii) The old divisional council waste site (now under the Spine Rd sportfields)
- (iii) Polluted stormwater and wastewater from Khayelitsha urban area to the east and Tafelsig informal settlement to the south.
- (iv) The cemetery to the south.

(Cave, 2000)

9. Coastal Parks Waste Disposal Site

The Coastal Park Landfill Site was established in 1985 by the Cape Town City Council (CCC) to take predominantly municipal solid waste from the Southern Suburbs. The CCC was concerned about the site polluting the Cape Flats Aquifer but due to its close proximity to the Cape Flats WWTW the site was established (Traut & Stow, 2001). Monitoring of the site commenced in October 1986 soon after its establishment. The design of the site comprises 2m of natural soil unsaturated zone and no liner, this was thought to be adequate considering that the groundwater regime was thought to be neither pristine nor sensitive and any pollution would be attenuated or migrate towards the sea. The site was situated in a seasonally water surplus climate, therefore leachate generation and migration was expected. Monitoring has shown clear evidence of a leachate plume which is migrating away from the landfill at various rates (Ball & Stow, 2000). The ground water flow at the site is in a SE direction towards the Zeekoevlei outlet (Traut & Stow, 2001).

During the first 8 years of sampling high NH_4 - N concentrations developed to the south. These concentrations migrated down gradient to the Zeekoevlei outlet at a rate of approximately 6m/year. Using Darcy's Law and background data, an average groundwater flow rate of 8.7m towards the Zeekoevlei Outlet was calculated. The groundwater in this area, as well as in the area between the sea and the site, is polluted (Ball & Stow, 2000).

Monitoring has shown the movement of the leachate plume at between 0.5 and 1 m/month. There are high levels of naturally occurring sodium chloride found at depths greater than 20m with lenses of high salinity present at higher levels. By 1996 the pollution plume extended to beyond the furthermost sampling point, a distance 30m beyond the level recorded in 1991. The plume movement is thought to be slower closer to the surface. There is still no evidence at present of the plume moving beyond its 1996 level. Recently there has been a decrease in contamination along the sample lines on the east side of the site heading towards the river, but an increase in pollution in the south heading towards the sea. The amounts of leachate in the ground increased from 4% in 1991 to 8% in 1996. Later calculations done have given erratic results but indications give a peak around 10% at the end of 1999 which has now attenuated to a level equivalent to 6%. From these figures it appears that the release of landfill is remaining constant or may even be declining.

In summary 15 years of data collection has shown that the site has a low level of impact on the groundwater system. The contamination has been restricted to two areas, a stretch 500m wide and 60m long stretching towards the Zeekoevlei outlet running in a south east direction, and an area of unknown width stretching in a south east direction. Within this band the contamination is not uniform and monitoring suggests at least 5 'fingers' of polluted groundwater moving away from the site. Even though the amount of leachate has shown that it is not increasing seasonal fluctuations are evident. There is no conclusive evidence of signs of contamination in the Zeekoe River from the landfill site, even though it is the first surface water body which would be affected. The Varswater aquifer situated beneath the landfill site has been shown to be highly saline (salinity higher than 50% of seawater) so it is unlikely to be put to any use. Cognisance has been taken of the fact that it should not be further contaminated. The effects of leachate have been restricted to a depth of 12m and the aquifer is situated at a depth of 20m – 24m (Traut & Stow, 2001).

10. Philippi Agricultural Area

From historical data it is clear that nutrients, especially PO_4 - P and NO_3 - N are major contaminants in the area. PO_4 - P is the major contaminant, with higher concentrations being found in the surface water bodies (i.e. irrigation ponds and drainage channels) than the groundwater. The nitrate loading is high, but the natural systems (e.g. Zeekoevlei Wetland) assimilate most of the NO_3 - N. The water volumes and concentrations are higher in the winter, whilst the summer baseflow has a higher salinity. There is a naturally poorer water quality in the northern part of the area, where geological controls and evaporation cause higher salinity and water logging leads to anaerobic condition (Cave, Weaver & Batchelor, 2000).

Lotus River

The Lotus River receives inflow from the Philippi Horticultural Area. The river runs through the north west portion of the area where it receives baseflow from shallow groundwater along an unlined portion of the channel (Grobicki, 1999).

There is already a high concentration of nutrients and organic matter present in the Lotus River, before it reaches the Philippi area. The total nutrient contribution from the Philippi area is comparable to areas upstream despite having a lower concentration (Cave, Weaver & Batchelor, 2000).

The farming area has positive and negative impacts on the river in the form of nutrient contribution and assimilation and dilution and contamination.

Grobicki (1999) identified the following impacts of the Philippi agricultural area on the Lotus River.

(i) Flow Conditions

It contributes 40% of the flow through groundwater seepage and direct surface through flow during high flow conditions. The flow contribution is frequent in terms of groundwater seepage when the water table levels are high during winter. Groundwater recharge from the unlined sections of the canal between Vygekraal Road and Ottery Road may cause flow losses of up to 60% under dry summer conditions.

(ii) Water Quality

Nutrients and micro organisms are the principle pollutants, with the lower reaches being rich in phosphate and nitrate concentrations which are in the hypertrophic range.

The NO_3 - N concentrations vary seasonably with the peak concentrations and loads occurring during the high rainfall period, with the highest fluxes occurring during peak flows and storm events. NO_3 - N and NO_2 - N constitute the dominant total nitrogen in the water. The concentrations of NH_4 - N, NO_3 - N and NO_2 - N increase during the winter, whilst total nitrogen remains constant. Diffuse source and direct tributary inflows from Philippi contribute approximately 23% of the total nitrogen load in the Lotus River under winter high flow conditions. Approximately 65% of the total nitrogen load in the Lotus River is removed by infiltration to groundwater or assimilation in the Philippi Horticultural Area section under summer flow conditions. The principle sources of nitrogen in the Lotus River during winter and summer are the formal and informal urbanised areas of the catchment.

The PO_4 - P concentrations vary seasonally with peak concentrations and fluxes occurring during winter and high rainfall. The highest fluxes coincide with peak flows and stormevents. Diffuse sources and direct tributary inflows contribute approximately 50% of the PO_4 - P load under winter high flow conditions. The principle sources of PO_4 - P in the Lotus River are nutrient rich subsurface flows from the agricultural area during the winter and urban surface water flows in the summer, which include possible sewer overflows and diffuse contributions from inadequate sanitation (Cave, Weaver & Batchelor, 2000).

Groundwater

The quality of the shallow groundwater situated underneath Philippi is strongly influenced by the surface landuse. The NO_3 - N concentrations are greater in the southern area with elevated concentrations (> 5000 umol/l) to the west of Weltevreden Road east of Oliebloom Road, the sources of which still need to be established. PO_4 - P occurs in higher concentrations in the northern part of the study area, where light grey to red sandy soils occur. This could be caused by the calcareous sands in the southern part of the area immobilising the phosphate. Samples containing over 160 umol/l are sporadically distributed over the northern area with a maximum of 800 umol/l recorded in the northern Springfield vlei area. High PO_4 - P has also been recorded between Zeekoevlei and the Cape Flats WWTW. The deeper groundwater is of a better quality than the shallow groundwater, and although the lower Cape Flats Aquifer is not confined, some measure of water quality protection is offered by calcrete and clay lenses in sediment.

It is suggested that unlined sections of the Lotus River Canal have considerable capacity to absorb pollution, much of which ends up in the groundwater (Cave, Weaver & Batchelor, 2000). Grobicki (1999) has shown considerable infiltration losses along unlined sections of the river especially during summer, which in turn could distort the groundwater quality. This has since been proven by Cave &

Weaver (2000) who show that shallow groundwater and some deeper sections have already been affected.

1.5 Objectives

The objective of this project was to study the effect that the continued pollution of the Cape Flats Aquifer was having on False Bay. To accomplish this the working hypothesis, "Discharge from the Cape Flats Aquifer is having a negative effect on the water quality of False Bay." was formulated. Varied methods were then used to determine whether it was valid. The first was to gain a good understanding of the discharge characteristics from the aquifer along the north shore of False Bay. This was accomplished through studying historical data contained in the literature and calculating the potential discharge along the coast. The second was to determine whether there was physical evidence of freshwater entering the bay, which could confirm the historical data from the literature or the calculated discharge. The third was to use nutrient concentrations to determine whether the inputs were having an effect on the water quality of the bay.

2. Method

The three objectives were addressed applying the previously stated methods. The literature review yielded very little information about the location and the quantity that the aquifer was thought to discharge into the bay. This was mainly due to only a few studies whose results mainly comprised of speculation and differed considerably between authors, having been done on the aquifer.

Three schools of thought emerged from the literature. Discharge from the aquifer into False Bay was mentioned by Engelbrecht & Tredoux (1989) in a report titled 'The occurrence of brown water in False Bay.' They stated that due to the differences in the depth of the bedrock and the permeability of the sand, water would discharge into the bay along well defined channels. Wright and Conrad (1995) had the opposite view that water loss was uniform along the whole coastline and not in well defined channels. Rogers, Jolly and Haye incorporated both views stating that water would discharge along the entire coast but should be more pronounced in areas with a high permeability (Pers. comm.). The flux and location of discharge into False Bay from the southern border of the aquifer was calculated.

Values for transmissivity, hydraulic gradient and aquifer width were described by Henzen (1973) in his study of the western sector of the aquifer and Gerber (1981) who developed a simulation model to describe the subsurface flow of the southern parts of the Cape Flats Aquifer. Using this data and Darcy's Law a potential discharge along the coast could be calculated.

Darcy's Law states:

$$Q = T\ I\ W$$

where Q = Discharge (m^3/d)

T = Transmissivity (m^2/d)

I = Hydraulic Gradient

W = Width of Aquifer (m)

(Watson & Burnett, 1993)

Darcy's Law and the data from Henzen (1973) and Gerber (1981) was used to determine the potential discharge of the aquifer along the north shore of False Bay, from the Zeekoevlei outlet (18° 30' 30" E) to Macassar Beach (18° 44' 45" E). This area was divided into 22 bins of 1 kilometer width *(Figure 2.1)*. The potential discharge was calculated for each bin using data obtained from the two authors.

2.2 Data Collection

The calculated quantity of discharge was only sufficient to draw broad conclusions about groundwater discharge into False Bay. A horizontal salinity transect at constant depth parallel to the north shore of False Bay was obtained to determine if there was physical evidence that supported the calculated discharge. A clear description of changes in salinity along the shore was needed as these changes in salinity would indicate the occurrence of different sectors in the nearshore region of the bay, with areas of reduced salinity indicating the addition of fresh water to the bay. This would occur through either groundwater inputs or fluvial run off. The salinity transect could however only be used to trace the fresh water component of the groundwater discharge, which may only be a minor part of the discharge. In some systems re-circulated seawater is a very important component of discharge and often a channel for nutrients. Three sections of low salinity were identified, each one coinciding with inputs from a fluvial system.

The source of the decreased salinity sections was further investigated by collecting water samples from the berm, the surfzone and behind the surfzone *(Figure 2.2)*. A close interval sampling grid was set up over the areas of decreased salinity, whilst samples were obtained between the low salinity zones for purposes of comparison. The sampling was divided between land based and sea based stations.

Sampling took place on the following dates:

06/08/01	Horizontal transect along north shore of False Bay obtained.
19/08/01	Land based sampling
20/08/01	Land based sampling
21/08/01	Land based sampling
24/08/01	Sea based samples. Vertical CTD profiles and surface and bottom samples taken.

2.2.1 Horizontal Salinity Transect

The horizontal salinity transect was obtained in the following manner. The transect was obtained by towing a CTD behind the surfzone at a constant depth, as close to the ocean floor as possible, within operational constraints. The CTD was on average at a depth of 3m *(Figure 2.3)*.

The CTD provided measurement of pressure, temperature and conductivity twice per second. The following hydrographic variables were measured or computed from the CTD and the related software.

1.	Pressure	(decibars)	
2.	Temperature	(° C)	
3.	Conductivity	(S/m)	
4.	Salinity	(psu)	derived
5.	Density, sigma-t	(kg/m^3)	derived
6.	Depth	(m)	derived

The CTD used was a Sea–Bird electronics SBE – 19 portable CTD.

2.2.2 Land- Based Sampling

The land based sampling took place from the 19 – 21 August 2001. Groundwater was collected from the berm of the beach, and corresponding samples were taken from the surfzone *(Figure 2.4 and Figure 2.5)*. The samples were taken at spring low tide so that the effect of salt water intrusion into the berm would be at a minimum, and the amount of fresh groundwater flowing towards the sea would be at a maximum. A large spring tide occurred on the 19th of August and the samples were taken in the period two hours before and after low tide. Nutrient samples from the fluvial inputs entering the bay were also taken. The samples were kept chilled before being frozen at the end of each sampling session. The nutrient concentrations were used to gain an understanding of the water quality of the water entering and already present in the bay. Nutrients are however, not conservative and therefore could not be used as reliable tracers of groundwater discharge.

Groundwater sampling from the berm

Groundwater samples were taken along the beach by auguring through the berm to the watertable. The water was then extracted from the hole using one of the following two methods:

1. A piece of PVC pipe was sealed at one end and then had grooves cut in one side for about 15cm, starting 10cm from the sealed end. The pipe was placed in the augured hole and was hammered into the sand below the water table. The grooves in the pipe acted as a filter allowing water to enter the pipe from the sand. The pipe was then withdrawn from the hole and the water decanted into a sample bottle.

2. A plastic bailer was lowered down the hole and used to bail water from the hole. This method was used when the water table was situated in a calcareous or shelly layer which would not allow the PVC pipe to be hammered below the water table.

Surfzone Samples

The surfzone samples were taken at the same time as the berm samples.

2.2.3 Sea Based Sampling

The behind surfzone sampling took place on the 24 August 2001. The sample positions were taken as close as possible to the same longitudes as the land based samples and as near to the surfzone as possible *(Figure 2.6)*. At each of the sample sites a vertical profile was obtained using a CTD and surface and bottom water samples were taken. The CTD measured the same hydrographic variables as in the horizontal transect. The bottom water samples were obtained by using a messenger triggered General Oceanics bottle.

A General Oceanics bottle consists of a PVC tube with a spring loaded cap on either end. A thin line was attached to the bottle, which ran past the release mechanism for the spring loaded caps. The bottle was then lowered to approximately half a meter from the sea floor. A brass weight or 'messenger' was then dropped down the line triggering the release mechanism, causing the caps on either end of the bottle to close. The water sample was collected once the bottle had been returned to the surface, by being drained through a tap at the base of the bottle.

2.2.4 Analysis of Water Samples.

The water samples were chilled immediately after collection and frozen at the end of the sampling period. Once all the samples had been collected they were defrosted completely and filtered to remove any solids. The concentration of nitrate, nitrite, phosphate, ammonia and silicate in the samples was then measured colourmetrically using a Lachat Instruments QuickChem® continuous flow autoanalyzer. Subsequent work will incorporate the operational improvement of immediate filtration.

Nitrate/ Nitrite

The method used for nitrate determination was accurate from 0.36 to 28.57 umol $NO_{3/2}$ – N/l. The method was calibrated, using 6 known standards made up from sodium nitrate and deionized water. The filtered samples were then passed through a column containing granulated copper –cadmium to reduce the nitrate to nitrite. The nitrite was determined by diazotizing nitrite with sulfanilamide and coupling it with N-(1-napthyl)- ethylenediamine hydrochloride to form a highly coloured azo dye. This was measured colourmetrically at a wavelength of 540nm. The process was then repeated without using the cadmium column to determine the original amount of nitrite in the sea water. The concentration of nitrate in the sample was then determined by using the following equation:

NO_3 = NO_2 (after reduction) – NO_2 (before reduction)
(Smith & Bogren, 2001)

Silicate

The method used for silicate determination was accurate from 1 to 215 umol SiO_2 – Si/l. The method was calibrated using 4 standards made of silicofluoride prepared in deionized water. The soluble silica reacted with a molybdate reagent at 37° C and a pH of 1.2 to form a yellow siliciamolybate complex. The complex was subsequently reduced with stannous chloride to form a heteropoly blue complex which has an absorbance maximum at 820nm. The absorbance was proportional to the concentration of "molybdate reactive" silica (Diamond, 1998).

Phosphate

The method for phosphate determination was accurate from 0.5 to 2 umol PO_4 – P/l. The method was calibrated using 4 standards made of anhydrous potassium dihydrogen phosphate prepared in dionized water. The orthophosphate ions in the samples reacted with ammonium molybdate and antimony potassium tartrate under acidic conditions and formed a yellow complex. This complex was reduced with abscorbic acid and molybdate reagents were merged on the chemistry manifold and the reagent stream was then merged with the carrier stream. The absorbance was measured at 880nm and was proportional to the concentration of orthophosphate in the sample (Huberty & Diamond, 2000).

Ammonia

The method for ammonia determination was accurate between 0.36 to 42.86 umol NH_3- N/l. The method was calibrated using standards made from ammonium chloride and deionized water. The method was based on the Berthelot reaction where ammonia reacts in alkaline solution with hypochlorite to form monochloramine which in the presence of phenol, catalytic amounts of nitroprusside, and excess hypochlorite gives indophenol blue. The formation of monochloramine requires a pH of between 8 and 11.5, as at a higher pH the ammonia may begin to oxidise to nitrate. To prevent this from occurring EDTA was added as a buffer. The amount of indophenal blue measured at 630nm is proportional to the original ammonia concentration (Liao, 2000).

3 Results

The quantity of discharge calculated using Darcy's Law and the data from Henzen (1973) and Gerber (1981), differed significantly between the two authors. This can be attributed to a difference in the transmissivity stated by the authors (*Table 3.1*). Distinct peaks were however, present in each profile *(Figure 3.1)*. The discharge profile from Henzen (1973) shows a small peak at Bin D and a much larger peak from Bins G to K with a maximum value at Bin I, whilst Gerber (1981) shows a much more gradual peak starting at Bin G and slowly increasing to Bin M before dropping rapidly to end at Bin P.

The horizontal salinity transect indicated variation in the salinity along the coast. Taljaard (1991) recorded an average salinity of 35 psu in False Bay. Sections of the salinity transect which recorded a salinity below 34.9 psu were designated as areas of low salinity *(Figure 3.2: Areas of low salinity are red)*. Three sections of the transect showed such a reduction. The co – ordinates of the sections are in *Table 3.2* and the positions of the low salinity sections are depicted in *Figure 3.3*.

The three sections of reduced salinity were studied further and divided into segments containing similar salinities or uniform changes in salinity. The details of the segments are shown in *Tables 3.3, 3.4 and 3.5*.

The cause of the three low salinity sections was unclear as they coincided with fluvial inputs into the bay *(Figure 3.4)*. Low Salinity Section One coincided with the Zeekoevlei outlet. It was therefore important to determine whether the effect of the outlet water was sufficient to cause the observed decrease in the salinity. This was achieved by comparing the salinity data with studies done by the CSIR (1991) and Ollis (1997) to determine whether the low salinity section was within the area of influence of the outlet. The nutrient concentrations recorded from the berm, surfzone and behind the surfzone were used to trace the movement and mixing of the outlet water *(Tables 3.6 to 3.9 and Figures 3.5 to 3.8)*. The nutrient types all recorded high concentrations directly to the east of the outlet. The concentrations peaked directly to the east of the outlet in the berm and surfzone whilst behind the surfzone they peaked slightly further east. The concentrations gradually decreased in an easterly direction. A consistent increase in concentration was however recorded in the berm and surfzone samples between samples SZ04 and SZ05. The concentration of nitrate found in the berm exceeded that in the settling pond and the water from the outlet. This indicates that any increases in concentration recorded in the surfzone away from the outlet were probably caused by groundwater seepage. The concentrations in the berm were very variable between sample sites this indicates significant changes in the inputs of nutrients from groundwater.

An attempt was made to calculate the amount of fresh water from the Zeekoevlei outlet that would be needed to drop the salinity from the average for False Bay of 35 psu to the average of low Salinity Transect One (34.72 psu). The volume of water between the low salinity transect and the shore was calculated using an average depth of 5m. The amount of fresh water needed to be added to this volume to drop the salinity the required amount was then calculated. This was then divided by the daily flow rate of the Zeekoevlei outlet. An estimated 5 days of flow from the outlet was needed to cause the reduction in salinity.

Salinity Section two was 5555m long and was situated roughly equidistant on either side of the Mitchell's Plain WWTW. The Mitchell's Plain West storm water drain was situated on the eastern side of the salinity section. The low salinity section was compared to a report by the CSIR (1991) which studied the dilution and movement of outlet water, to determine the effect of the outflow of the Mitchell's Plain WWTW. The nutrient concentrations were used to trace the movement and dilution of the water and determine the source of any other likely inputs of low salinity water *(Tables 3.6 to 3.9 and Figures 3.10 to 3.14)*. The nutrient concentrations showed that the Mitchell's Plain WWTW did not have a significant effect on the surrounding water quality. The sample sites situated

400m on either side of the outlet did not record high concentrations for any of the nutrient types even though the outlet water recorded exceptionally high concentrations. The Mitchell's Plain West and East stormwater drains also had very little effect on the nutrient concentrations in the bay. This was mainly due to the nutrient concentrations in the stormwater being low. The cluster of berm samples BM09, BM10 and BM11 emphasized the difference in concentrations which could be recorded in berm samples within a close proximity of each other. The three samples were situated within 500m of each other and often recorded significantly different nutrient concentrations. These well defined differences in the berm often became less evident in the surfzone as it is a more dynamic environment where mixing would therefore occur more easily. The sample site situated in front of the Wolfgat Cliffs recorded very low nutrient concentration with the exception of NH_4 -N.

The low Salinity Section Three coincided with the Monwabisi outlet. This movement of the water leaving the outlet has not been studied in detail. The nutrient concentrations did however indicate that the probable cause of the low salinity section was outlet water *(Tables 3.6 to 3.9 and Figures 3.15 to 3.19).*

The recorded nutrient concentrations were compared to nutrient concentrations recorded from areas of the Cape Flats Aquifer, which historically in the literature had been identified to be contaminated. High nutrient concentrations down gradient of these sites would confirm the occurrence of groundwater input into the bay and give some insight into the impact that the aquifer is having on the water quality. The location of previous study areas is depicted in *Figure 3.20.*

Parsons (2000a) studied the area between the evaporation ponds and the sea at the Cape Flats WWTW. The study consisted of water samples taken from a number of boreholes situated in two east/ west orientated lines; the first close to the evaporation ponds and the second on the WWTW side of Baden Powell Drive. The NO_3 - N recorded from the Parsons boreholes was significantly lower than the values recorded in the berm samples. Parsons recorded a maximum concentration of 112 umol NO_3 – N/l to the west of BM04 and the second highest concentration between BM04 and BM05. The berm samples infront of the Cape Flats WWTW had a maximum at BM04.The PO_4 - P and NH_4 - N concentrations recorded in the berm were all an order of magnitude lower than those recorded by Parsons. The maximum concentration of both nutrients was recorded by Parsons at a borehole situated between BM04 and BM05. The concentrations from the berm samples recorded a peak at BM04 for both nutrients. The SiO_2 - Si concentrations recorded by Parsons were higher than those of the berm samples but not by the same amount as the PO_4 - P and NH_4 - N samples. The Parsons samples show a local maximum between BM04 and BM05 whilst the concentrations from the berm samples peak at BM04.

Taljaard (1991) studied the effects of the sewage effluent being discharged from the Zeekoevlei outlet on the surrounding area. NO_3 - N, NO_3 - N, NH_4 - N, SiO_2 - Si and PO_4 - P were measured. The data from Taljaard (1991) was compared to the nutrient concentrations collected from the surfzone and behind the surfzone. The results of the thesis data and Taljaard data are shown in *Table 3.10*.

Hartnady and Rogers (1990) recorded high silicate concentrations in the Philippi area. The SiO_2 – Si concentrations recorded in the berm were generally higher over the western half of the study area with concentrations well above median being recorded at BM08 (63.41 umol/l), BM10 (43.35 umol/l) and BM11 (74.72 umol/l) and near to the mouth of the Zeekoevlei outlet. To the east of these samples Edwards (1989) recorded a median groundwater SiO_2 – Si concentration of 146 umol/l which significantly exceeded the concentrations recorded at these samples. In comparison to the other samples the surfzone samples in this area were low, they were also below the average surfzone concentration of 6.4 umol/l recorded by Taljaard (1991) *(Table 3.10)*. High concentrations were however evident behind the surfzone at samples BS09 (3.04 umol/l), BS10 (3.43 umol/l), BS11 (2.37 umol/l), BS12 (3.51 umol/l) to BS13 (3.82

umol/l) and samples BB11 (4.27 umol/l), BB12 (4.95 umol/l) and BB14 (4.52 umol/l), BB15 (4.3 umol/l), BB16 (4.43 umol/l) and BB17 (3.68 umol/l) to the east of the Mitchell's Plain WWTW. These concentrations were also lower than concentrations recorded by Taljaard (1991) on two separate cruises which recorded average concentrations of 6.92 umol/l and 10.03 umol/l.

The berm samples south of the Philippi area recorded high $NO_3 - N$ concentrations at BM08 (133.56 umol/l), BM10 (274.40 umol/l) and BM11 (85.88 umol/l), which corresponded with high offshore concentrations recorded at BS09 (6.92 umol/l), BS10 (5.74 umol/l) and BB09 (4.83 umol/l). The surfzone did not show high concentrations compared to the other surfzone samples recorded. Ambient $NO_3 - N$ concentrations in the aquifer to the east of Philippi were quoted to be 110 umol/l by Edwards (1989) and in the Philippi area to range from 135 to 2700 umol /l by Grobicki (1999). The ambient concentration quoted by Edwards (1989) was exceeded at BM08 and BM10 showing that the samples were high not only in respect to the other areas within the study area but also historically. The samples fell within the lower part of the range quoted by Grobicki. Taljaard (1991) recorded an average $NO_3 - N$ concentration of 4.7 umol/l in the surfzone and concentrations between 4.00 and 7 umol/l offshore. The majority of samples fell within this range of concentrations.

The $PO_4 - P$ concentrations were above median at BM08 (2.37 umol/l), BM09 (2.02 umol/l) and BM12 (2.22 umol/l) whilst to the west of BM08 the concentrations were below median until the border of the Cape Flats WWTW. These samples were also above the ambient concentration of 0.35 umol/l quoted by Edwards (1989), they were however significantly lower than the concentrations quoted by Grobicki which ranged from 32.25 to 80.65 umol/l. Behind the surfzone high concentrations in relation to those recorded at the other sample sites were recorded at BS09 (1.15 umol/l), BS10 (0.95 umol/l) and BS12 (1.04 umol/l). They were however lower than the average surfzone concentration of 1.70 umol/l and were within the range of the average offshore concentrations which range from 0.60 to 1.50 umol/l. There was no sign of increased concentrations in the behind surfzone bottom samples.

Traut & Stow (2001) recorded elevated concentrations of NH_4 - N at the Swartklip Waste Disposal site. BM18 situated directly to the south of the site recorded a high ammonia concentration in the berm and a very high concentration at the surface behind the surfzone in comparison to the other samples sites. The surfzone and behind surfzone bottom concentrations were however, low.

The sea surrounding Seal Island often experiences an increase of nutrients which is present due to biological activity on and around the island. No sign of these increased nutrients was seen in the behind surfzone samples near the island.

Using the transmissivity and hydraulic gradient data from Henzen (1973) and Gerber (1981) the flux or discharge per unit length was calculated for each of the Bins described in Method One. The average concentration for the nutrients in the bin was then multiplied by the flux to obtain the flux load per unit length of coastline. The resultant flux and flux loads for each Bin are in *Tables 3.11 and 3.12.* Due to the different transmissivity values recorded by Henzen and Gerber the results differed in quantity but trends were still evident.

Total Nitrogen

The data from Henzen (1973) calculated the highest flux load at Bin H and the second highest at Bin B, whilst the Gerber (1981) recorded the highest load at Bin A and second highest at Bin H. Both sets of data showed elevated flux loads between Bins Hand K.

Ammonia

The Henzen (1973) and Gerber (1981) data both showed a peak between Bins H and K. The bins in front of the Cape Flats WWTW calculated relatively low flux loads.

Phosphate

The Henzen (1973) data calculated the highest flux load at Bin B and the second highest at Bin C, whilst the Gerber (1981) data calculated the highest flux load at Bin A. The Henzen data calculated a peak between Bin J and Bin K whilst the Gerber (1980) data showed a similar peak between Bin I and K.

Silicate

The Henzen (1973) data calculated the highest flux load at Bin F with high loads at Bin B, H, J and K whilst Gerber (1981) highest three values at Bin H, J and K all recorded very similar fluxes. High values were also calculated at Bin F and Bin B.

4 Discussion

The resultant quantity of discharge calculated, differed significantly between Henzen (1973) and Gerber (1981). This can be attributed to differing values of transmissivity quoted by the two authors. Both sets of data did, however, show that the discharge varies significantly between the bins. This suggests that the Wright & Conrad (1995) view of a uniform discharge along the coast is simplistic, whilst the view of Rogers, Jolly and Haye is more likely. The peaks in the two profiles were used to gain an understanding of the area along the coast where discharge from the aquifer is most likely to occur. It was concluded that the area, which has the highest potential discharge into the bay, occurs between Bin G and Bin O. The potential discharge calculated from Darcy's Law does not necessarily reflect the actual discharge however, as it does not take into account factors such as the availability of water in the area. The area around the Cape Flats WWTW and other large water bodies might experience high actual discharge rates, despite the low calculated potential discharge due to the interaction between surface and groundwater. The paleovalley identified by Hartnady and Rogers (1990), is situated in the area designated by Bin E to Bin I, which corresponds with the peak from the discharge using Henzen's data.

The three low salinity sections corresponded with fluvial inputs into False Bay. It was, therefore, important to determine whether the fresh water input from the fluvial system was sufficient to cause the reduction in salinity or whether there were additional inputs of groundwater in the form of offshore springs.

A vertical CTD profile was taken at each of the behind surfzone sample sites. The salinity recorded from the vertical profiles was compared to the salinity recorded in the horizontal transect. The surface salinities from the vertical profiles were on average lower than those recorded in the horizontal profile, whilst the bottom salinities were higher. This was probably caused by a storm event which occurred in the time between the horizontal transect and the vertical transects being recorded. The high rainfall associated with this event would have diluted the surface layer reducing the salinity.

Changes in salinity values recorded in the vertical CTD profiles corresponded to the changes recorded in Salinity Section One. The vertical CTD profiles recorded a decrease in salinity to the east and west of the Zeekoevlei outlet. To the east the salinity decreased until BS05 and then increased to BS08. This represents a local salinity minimum present between 1500m and 2000m from the outlet which was also evident in the horizontal salinity section. The increase between BS05 and BS08 was typical of outlet water mixing out as it was transported east and was also evident in the horizontal salinity transect. The bottom samples recorded an increased salinity from BB03 to BB06 this reflects the horizontal salinity transect and indicates outlet water mixing out as it travels further away from the source. The salinity decreases again at BS07 and BS08.

The CSIR (1991) and Ollis (1997) studied the movement and dilution of fresh water from the Zeekoevlei outlet in the surfzone. A good understanding of the fate of this water is important when determining the source of the freshwater signal visible in the salinity transect. The CSIR studied the dilution of the water in the surfzone east and west of the inlet using the equation:

$$A = S_{BG} - S_M / S_{BG}$$

Where: A = Dilution
S_M = Measured Salinity
S_{BG} = Background Salinity

Dilutions could accurately be measured to $A = 0.01$ or 1%, beyond which relatively small changes in the background salinity had an excessive influence on the calculated dilutions. The median dilutions were determined to the east and the west of the outlet disregarding influencing factors and conditions such as flow rate and wind direction. The resultant dilutions were below 0.01, 1200m to the east and 660m to the west *(Figure 4.1)*. The results were asymmetrical because of a higher occurrence of easterly surfzone currents which resulted in lower dilution to the east. The results were then broken down further to determine the influence of longshore currents on the easterly dilution of the water. When the longshore current flowed in an easterly direction the dilutions were below 0.01, 660m and 1200m to the west and east of the outlet respectively, when the longshore current flowed in a westerly direction the dilutions were greater than 100, 800m and 1200m to the west and east respectively. From this it can be seen that no matter the direction of the longshore current the influence of freshwater discharge was still noticeable 600m away on the side of the outlet opposite to the direction of flow.

The influence of a changing flow rate from the outlet on dilutions was determined, with the results from CSIR (1991) showing that lower dilutions occurred with lower flow rates and vice versa. The difference was, however, not extensive (the area of influence was less than 100m) because the average difference in flow rates were not extensive. The wind direction showed no obvious effect in dilutions (CSIR, 1991). Ollis (1997) however concluded that the tide state and river outflow had a major effect on the dilutions in the surfzone. He concluded this because at a spring high tide, the incoming water would block the Zeekoevlei channel causing a significantly lower flow rate. These conditions do not apply to the present study which was undertaken at spring low tide.

A dilution factor for each of the data points in the salinity transect using a background salinity of 35 psu was calculated. The points were also expressed as a percentage of the background salinity. A dilution factor of 0.01 or 1% (maximum accurate dilution according to CSIR (1991)) was calculated to be 34.65 psu.

The dye tests done by the CSIR (1991) gave a good indication of the movement of water and nearshore currents around the outlet, but did not give much insight into the dilution of nutrients leaving the outlet *(Figure 4.1)*. The concentration of the dye added to the outlet is not known therefore the transport and mixing of the outlet water in the surfzone can be observed, but no accurate conclusions can be drawn to determine the mixing of nutrients.

The first occurrence of salinity below 34.9 psu was recorded 700m to the east of the Zeekoevlei outlet and 1131m offshore. This marks the start of the horizontal salinity transect. The CSIR (1991) showed the dye moving a maximum of 1692m offshore and 738m east of the outlet. The CSIR (1991) dilution tests in the surfzone showed a dilution factor of 0.01, 1200m from the outlet, whilst the dilution calculated for this area was in the range of 78% – 85%. This means the drop in salinity is within the area influenced by the outlet water and was therefore caused by the fresh water input from the outlet.

After the initial drop the salinity stayed constant for 994m before it rose gradually for 162m in an easterly direction until it reached a 370m long plateau with a salinity of 34.8 – 34.9 psu. The plateau was 2020m away from the inlet and 1225m offshore. This area could not be accurately compared to the tests done by the CSIR as the dilution tests were only accurate up to 1200m from the outlet where the dilution exceeded 100 and the extent of the dye test was 1296m east of the outlet.

After the plateau, 2557m from the inlet and 1376m offshore, the salinity dropped to between 34.6 – 34.7 psu for a distance of 444m. This drop in salinity cannot definitely be attributed to the effects of freshwater outlet water. Ollis (1997) recorded traces of freshwater trapped in the surfzone 2000m from the outlet in September 1997 (a similar time in the year to when the transect was done) and the CSIR (1991) showed that dye bombs dropped in the surfzone were often transported for 1500m before they broke the surfzone. This low salinity section could indicate evidence of a freshwater plume moving along the coast and breaking the surfzone a significant distance from the outlet. It could however, have been the result of an injection of fresh water from another source. This low salinity section was also apparent in the vertical CTD profiles showing that it is a semi- permanent or permanent feature.

The nutrient concentrations from the offshore surface and bottom samples were used to trace the source of the low Salinity Section One. The offshore surface samples tended to have high nutrient concentrations when the salinity was low. This indicates that Salinity Section One was probably caused by the freshwater discharge from the Zeekoevlei outlet, as the nutrient rich fresh water would be less dense than the surrounding water and would therefore stay on the surface causing high surface concentrations. The recorded nutrient concentrations, with the exception of PO_4 - P, increased between BS03 and BS04. A drop in salinity was recorded over the same area. This can be attributed to water leaving the Zeekoevlei outlet. The nutrient concentrations then decreased as the salinity rose towards BS06. This shows a typical situation of fresh nutrient rich outlet water entering the sea and then mixing out as it is transported along the coast away form the source.

The eastern border of the Cape Flats WWTW marked a significant rise in the salinity and a drop in the behind surfzone nutrient concentrations compared to those recorded to the west. It is unlikely that the mixing out of nutrients to median occurred exactly at the eastern border of the Cape Flats WWTW. It is more likely that there was seepage of high nutrient fresh water from the evaporation ponds in the Cape Flats WWTW through the dunes into the sea. The nutrient concentrations were also high in the surfzone samples. During periods of heavy rainfall water could be seen seeping through the dunes from the evaporation ponds and flowing along the beach into the sea. Similar seepage was shown by Parsons (2000a).

The nutrient concentrations recorded near the Cape Flats WWTW were compared to data from Parsons (2000a) *(Figure 3.20).* Parsons measured the nutrient concentrations from a number of boreholes situated between the sludge ponds and Baden Powell Drive.

The NO_3 – N recorded from the Parsons boreholes was significantly lower than the values recorded in the berm samples. Parsons recorded a maximum concentration of 112.14 umol/l to the west of BM04 and the second highest concentration between BM04 and BM05. The berm samples infront of the Cape Flats WWTW had a maximum at BM04. The concentrations recorded from the Parsons boreholes and the berm samples indicated variation even though they were in close proximity to each other. The PO_4 - P and NH_4 - N concentrations recorded in the berm were an order of magnitude lower than those recorded by Parsons, whilst the SiO_2 - Si concentrations were lower but by a smaller amount. Parsons recorded a maximum concentration for the three nutrients at a borehole situated between BM04 and BM05. The three nutrients were at a maximum in the berm at BM04. This indicates that even though the magnitude of the concentrations recorded were not the same as those quoted by Parsons similar trends can be identified in the nutrient distribution. The area identified by Parsons and this project to contain maximum nutrient concentrations corresponds with the segment of lowest salinity in the Salinity Transect One. This indicates a strong likelihood that the drop in salinity is aided by groundwater flow. Parsons found ammonia to be the dominant form of nitrogen in front of the Cape Flats WWTW whereas in this study NO_3 - N was found to be dominant in the berm. NH_4 - N was however more dominant than NO_3 - N in the surfzone. This was probably due to the nitrate being taken up through biological activity. A decrease in nutrient concentration was noted from the ponds to the samples taken closer to the road, indicating that the berm has the ability to extract nutrients from the groundwater.

Taljaard (1991) studied the effects of the sewage effluent being discharged from the Zeekoevlei outlet on the surrounding area. NO_3 - N, NO_2 - N, NH_4 - N, SiO_2 - Si and PO_4 - P were measured. The nutrient concentrations decreased gradually to a stable concentration when the salinity approached 35 psu. The NH_4 - N concentrations were higher than the NO_3 - N concentrations in the surfzone but the NO_3 - N was higher than the NH_4 - N in the interstitial water. PO_4 - P in the interstitial zone was higher than the surfzone. It can therefore be concluded that the beach adjacent to Zeekoevlei is well oxidised. Data taken during 1988 and 1989 has indicated that the amount of nutrient loading corresponds with the surfzone nutrient concentrations. During the winter months when rain causes the maturation ponds to overflow the nutrient load of effluent increases. The data from Taljaard (1991) was compared to the nutrient concentrations collected from the surfzone and behind the surfzone. When the samples were collected water was being transported from the outlet in an easterly direction due to longshore drift. The longshore direction was not recorded in Taljaards data. When comparing the data to the CSIR (1991) the differences in the nutrient concentrations and the distance from the outlet can be accounted for as differences within the scope of the effects of the longshore current.

It was calculated that the water leaving the Zeekoevlei outlet would have to be resident in the area around the low salinity section for approximately 5 days to retain the decreased salinity. This is longer than the time scale suggested by Ollis (1997) who showed that the area of reduced salinity was affected by changes which occurred on a very short time scale (e.g. Tides). Due to the generalizations made when doing the calculation however, the time scale calculated cannot conclusively prove the source of the low salinity water.

The second section of reduced salinity was 5555m long and extended equidistant on either side of the Mitchell's Plain WWTW outlet. The freshwater input from the outlet was studied by the CSIR (1991). This study involved a dye test and measuring the dilution on either side of the outlet, it was not however as extensive as the study done on the Zeekoevlei outlet *(Figure 4.1)*. Dilutions obtained for each salinity value in the transect, were below 0.01. This means that dilution cannot be used as an accurate way of determining the extent of the effect of outlet water. The extent of the dye bomb gave an accurate account of the water movement once it left the outlet. The extent of the dye bomb was less than the salinity section, as the section stretches for 2781m to the west and 2774m to the east of the outlet. The lowest salinity was recorded to the east of the outlet. Two low salinity segments were recorded. The first was 936m long and recorded a salinity of 34.7 – 34.8 psu. This drop in salinity could be attributed to outlet water moving along the coast due to longshore drift. The salinity then decreases further at the second segment where a salinity of 34.6 – 34.7 psu was recorded. This segment was, 78m long and situated 794m offshore. Further east the salinity gradually increases again until it reaches background levels. The segment of low salinity could be attributed to outlet water moving along shore in the surfzone before breaking through in a rip current. This is very unlikely as the dilution value for this segment was close to 0.01, 1078m away from the mouth of the outlet whilst the data obtained from the CSIR report showed values exceeding 0.01, 150m east of the outlet.

The vertical CTD profiles recorded a local salinity minimum at the isolated sample BS09 *(Figure 4.2)* in both the surface and bottom waters. This sample corresponds with the position of the paleovalley identified by Hartnady and Rogers (1990). The surface salinity was at a minimum at BS14, BS15 and BS16 *(Figure 4.3, 4.4 and 4.5)*, which corresponds with the area of lowest salinity in the horizontal section. On average the vertical CTD profiles showed a decrease in salinity in the bottom samples around the area of Salinity Section Two. This indicated once again that the low salinity sections were semi- permanent or permanent features. The salinity values in the bottom samples were significantly higher than those recorded in the horizontal transect with the majority of the samples recording concentrations of 34.9 psu or above 35 psu.

Nitrate was the only nutrient to indicate any trends that corresponded with the salinity at Salinity Section Two. Samples situated in the area of lowest salinity showed an increased concentration from those immediately to the west but were lower than those found to the east. Further to the west however the nutrient concentrations increased in the surface and bottom samples. The rest of the nutrients indicated no trends comparable to the salinity and in some cases the nutrient concentrations decreased towards the outlet. The sample sites situated 400m either side of the outlet showed no sign of the nutrient rich water entering the bay. This shows that the outlet was almost definitely not the cause of the low salinity section.

Data from areas of the aquifer, which historically have recorded high nutrient concentrations, were compared to the nutrient samples taken during the project to determine whether traces of the high aquifer water could be identified in False Bay. The locations of the past studies are shown in *Figure 3.20*. The ambient concentrations stated in the literature may not represent accurate average concentrations as many were calculated from small sample sizes.

The sands of the Springfontyn Formation found in the Philippi area contain a high SiO_2 - Si content (Hartnady & Rogers, 1990). The SiO_2 - S concentrations recorded in the berm were generally higher over the western half of the study area with concentrations well above median being recorded at BM08 (63.41 umol/l), BM10 (43.35 umol/l) and BM11 (74.72 umol/l) and near to the mouth of the Zeekoevlei outlet. To the east of these samples Edwards (1989) recorded a median groundwater SiO_2 - Si concentration of 145 umol which significantly exceeds the concentrations recorded at these samples. In comparison to the other samples the surfzone samples in this area were low, they were also below the average surfzone concentration of 6.42 umol/l recorded by Taljaard (1991). *(Table 3.10)* High concentrations were however evident behind the surfzone at samples BS09 (3.04 umol/l), BS10 (3.43 umol/l), BS11 (2.37 umol/l), BS12 (3.51 umol/l) to BS13 (3.82 umol/l) and samples BB11 (4.27 umol/l), BB12 (4.95

umol/l) and BB14 (4.52 umol/l), BB15 (4.3 umol/l), BB16 (4.43 umol/l) and BB17 (3.68 umol/l) to the east of the Mitchell's Plain WWTW. These concentrations were also lower than concentrations recorded by Taljaard (1991) on two separate cruises which recorded average concentrations of 6.92 and 10.03 umol/l. The samples were taken shortly after a heavy storm event, which would increase the amount of runoff in the soil and therefore cause the dilution of the nutrients.

Grobicki (1999) has shown the groundwater in the Philippi area to be rich in NO_3– N and PO_4 – P. The berm samples south of the Philippi area recorded high NO_3– N concentrations at BM08 (133.56 umol/l), BM10 (274.04 umol/l) and BM11 (85.88 umol/l), which corresponded with high offshore concentrations recorded at BS09 (6.92 umol/l), BS10 (5.74 umol/l) and BB09 (4.83 umol/l). The surfzone did not show high concentrations compared to the other surfzone samples recorded. Ambient nitrate concentrations in the aquifer to the east of Philippi were quoted to be 110 umol/l by Edwards (1989) and in the Philippi area to range from 135 to 2700 umol/l by Grobicki (1999). The ambient concentration quoted by Edwards (1989) was exceeded at BM08 and BM10 showing that the samples were high not only in respect to the other areas within the study area but also historically. The samples fell within the lower part of the range quoted by Grobicki. The Grobicki concentrations were however recorded in the Philippi farming area a significant distance inland, dilution would therefore be expected over time as the water moves towards the coast. Taljaard (1991) recorded an average NO_3 - N concentration of 4.71 umol/l in the surfzone and concentrations between 4.00 and 7 umol/l offshore. The majority of samples fell within this range of concentrations.

The PO_4 – P concentrations were above median at BM08 (2.37 umol/l), BM09 (2.02 umol/l) and BM12 (2.22 umol/l) whilst to the west of BM08 the concentrations were below median until the border of the Cape Flats WWTW. These samples were also above the ambient concentration of 0.35 umol/l quoted by Edwards (1989), they were however significantly lower than the concentrations quoted by Grobicki which ranged from 32.25 to 80.65 umol/l. Behind the surfzone high concentrations in relation to those recorded at the other sample sites were recorded at BS09 (1.15 umol/l), BS10 (0.95 umol/l) and BS12 (1.04 umol/l). They were however lower than the average surfzone concentration of 1.70 umol/l and were within the range of the average offshore concentrations which range from 0.60 to 1.50 umol/l. There was no sign of increased concentrations in the behind surfzone bottom samples. If these increased concentrations were caused by an input of groundwater it is unlikely that the surface samples would have been affected and not the bottom samples. A large plume of PO_4 – P was recorded to the east of the Cape Flats WWTW, which could have extended causing the high surface concentrations.

Traut & Stow (2001) recorded elevated concentrations of NH_4 - N at the Swartklip Waste Disposal site. BM18 situated directly to the south of the site recorded a high NH_4 - N concentration in the berm and a very high concentration at the surface behind the surfzone in comparison to the other samples sites. The surfzone and behind surfzone bottom concentrations were low however. The behind surfzone samples were taken at a depth of 5m, this means that the high surface concentration was probably not caused by groundwater as there was no sign of the elevated concentration in the bottom sample.

The area around Seal Island often experiences an increase of nutrients due to biological activity on and around the island. No sign of these increased nutrients was seen in the behind surfzone samples near the island.

No data is available on the extent of the plume of freshwater from the Monwabisi outlet at Section Three. The vertical CTD profiles recorded a slight drop in salinity at section three. The nutrient concentrations indicated that the salinity section was caused by outlet water.

Hartnady and Rogers (1990) located a paleovalley 20m below sea level to the east of Zeekoevlei. The northward extension of the valley runs under the present day Lotus River, whilst the southward extensions of the buried tertiary drainage must run east of Seal Island, York Shoal and East Shoal in the north central part of False Bay. If a line is extended from the east of East Shoal to the east bank of Zeekoevlei, and taken to be the most easterly boundary of the valley then the valley would encompass the Mitchell's Plain WWTW and run west to Zeekoevlei. This coincides with the salinity transect stretching from Segment 5 of Section Two in the east to Segment 4 of Section One in the west.

The areas of low salinity were compared to the predicted areas of high discharge calculated from Gerber (1981) and Henzen (1973) in the previous section. The area showing the highest calculated discharge from Gerber (1981) coincided with the second section of low salinity around the Mitchell's Plain WWTW outlet, whilst the Henzen peak was situated slightly to the west. The overlapping area between the two calculated discharge peaks was the area of lowest salinity. The other two sections of low salinity coincide with areas of very low potential discharge indicating that the drop in salinity in these areas was probably linked to the outlets rather than an input of groundwater. There is an abundance of surface water behind the sand dunes at Section One in the form of the evaporation ponds at the Cape Flats WWTW. This water is likely to cause extensive seepage through the dunes into the sea. During periods of heavy rain fall events water flows out of the seaward side of the dunes and pools on Baden Powell Drive. This implies that a high discharge could take place even though the potential discharge calculated using Darcy's Law was relatively low.

The potential discharge calculated from Henzen (1973) and Gerber (1981) was compared to nutrient concentrations recorded at the corresponding samples sites. Bins where nutrient concentrations were higher than the median value were noted. The area which corresponded the most with the berm, surfzone and behind surfzone surface and bottom samples were Bins H to K. These bins coincide very closely with the peak calculated from the Henzen discharge, with the exception of Bin G where the recorded nutrient concentrations were low. The area corresponds with the western side of the Gerber (1981) peak. High concentrations were present at Bins L and M but then decrease at Bins N and O before increasing at Bin P situated infront of the Wolfgat Cliffs. Bin P is the most eastern boundary of the Gerber (1981) peak.

The effect of the aquifer on the nutrient concentrations in False Bay was determined by calculating a peak flux load from the Henzen (1973) and Gerber (1981) data. The flux load calculated from both the Henzen and Gerber data indicated a peak nutrient flux at Bins A and Bin B situated infront of the Cape Flats WWTW and between Bin H to Bin K. The first area of high flux shows the role that the Cape Flats WWTW plays in the input of nutrients into the bay, not only through the Zeekoevlei outlet but also directly through groundwater flux through the berm. This second area of high flux coincides with the most eastern two Bins of the paleovalley identified by Hartnady and Rogers (1990), once again showing that this is likely to be an area of high groundwater discharge into the bay and therefore a potential source of pollution for the bay. The area therefore also coincides with a portion of Salinity Transect Two. The NO_x - N recorded the highest flux into the bay, followed by SiO_6 - Si and then PO_4 - P and NH_4 - N which recorded similar fluxes.

The nutrient concentrations were compared to the South African Water Quality Guidelines (SAWQG) for a Coastal Marine Environment to determine whether the groundwater input from the aquifer is causing the water quality to deteriorate. The SAWQG can be found in (Appendix A).

The majority of the samples which exceeded the SAWQG were situated in front of the Cape Flats WWTW. Due to the high nutrient concentrations contained in the outlet water it is impossible to determine whether the outlet water or groundwater seepage through the berm was responsible for the increased nutrients. It does however show that the Cape Flats WWTW is a large contributor to nutrients in the bay. The sample at the Monwabisi outlet also recorded concentrations which often exceeded the guidelines.

Gerber (1981) recorded average concentrations for the aquifer, which were taken before the majority of development on the Cape Flats. The NO_3 - N and NH_4 - N concentrations exceeded the guidelines at the majority of the samples sites whilst PO_4 - P exceeded them in front of the Cape Flats WWTW. NO_2 - N was within the guideline and no guideline was given for SiO_6 - Si. This once again shows the effect of the Cape Flats WWTW on the water quality of the bay.

Further research needs to be done on the interaction between the Cape Flats Aquifer and False Bay. Engelbrecht and Tredoux (1989) suggested that there is a link between the blooms of *Anaulus birostratus*, and discharge of polluted groundwater. These blooms occur along the north shore of False Bay and have increased in intensity over the last 15 years. The scope of this project was however, not sufficient to draw any conclusions.

The threat of pollution in the Cape Flats Aquifer will increase as the informal population living on the Cape Flats continues to rise. This project gives a broad overview of the areas where the aquifer is likely to be discharging into False Bay. A more quantitative approach needs to be implemented to gain an understanding of the amounts of water entering the bay so the extent of the input of nutrients can be established.

5. Conclusions

The potential discharge calculated from Henzen (1973) and Gerber (1981) showed that discharge is not uniform along the coast but changes significantly, with distinct peaks evident. Further evidence of this was indicated by the results of the horizontal salinity transect where three distinct zones of low salinity were identified. Salinity measurements taken at the same time as the nutrient samples showed the areas of low salinity coinciding with those identified in the horizontal salinity transect, indicating that these areas were semi permanent or permanent features.

The primary cause of Salinity Section One was freshwater discharge from the Zeekoevlei outlet. This was evident from the offshore surface samples which recorded high nutrient concentrations and a low salinity near the outlet which decreased as the salinity increased with distance from the source. This pattern is typical of fresh water being mixed out with distance from the source. The effect of groundwater on Salinity Section One was also evident. A marked increase in salinity and decrease in nutrients was recorded at the eastern boundary of the Cape Flats WWTW. It is unlikely that the outlet water would mix out exactly at the boundary of the WWTW, indicating the effect of seepage through the berm from the evaporation ponds on nutrient concentrations and salinity. Further evidence of groundwater seepage was indicated by a further reduction in salinity approximately 2km from the outlet. This reduction in salinity corresponded with the peak in nutrient concentrations recorded in the berm samples and by Parsons (2000a) infront of the Cape Flats WWTW.

The second low salinity section stretched for 5555m and was situated roughly equidistant on either side of the Mitchell's Plain WWTW. The area covered by the Gerber (1981) discharge peak coincides with this salinity section, whilst the segment of lowest salinity in the section corresponds with the area between the two peaks of Henzen (1973) and Gerber (1981). The segment of lowest salinity was recorded to the east of the outlet but was not in the area of influence of the outlet identified by the CSIR (1991). The recorded nutrient concentrations support the CSIR (1991) report, showing traces of the outlet water mixing out within 100m.

Consistently high nutrient concentrations were recorded in the areas of the study area which coincide with the Henzen (1973) peak and the western side of the Gerber (1981) peak. A palleovalley which was located by Hartnady and Rogers (1990) coincides with the discharge peak of Henzen (1973), and the eastern part of Salinity Section One and the western part of Salinity Section Two. This area along with the Cape Flats WWTW recorded the peak flux load of nutrients.

The nitrate, phosphate and silicate nutrient concentrations in the berm and behind the surfzone were high in comparison to the other sample sites south of the Philippi Agricultural Area. This corresponds with high concentrations of these nutrients found recorded in the aquifer in this area. To the south of the Swartklip Waste Disposal Site high berm and offshore concentrations of ammonia were recorded, which corresponds with those recorded in the groundwater at the site.

Despite the three sections of low salinity corresponding with fluvial inputs into the bay, it can be seen that these fluvial systems cannot fully account for the changes in salinity and nutrients that were evident. Taking into account an input of groundwater helps to explain the observed salinities. The methods used in the study were not sufficient to quantify the non- fluvial input. A future study, incorporating refined methodologies should be undertaken to address the preliminary results obtained as a result of this work. At present there is tentative evidence in support of the working hypothesis.

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Appendix A: The South African Water Quality Guidelines

The nutrient concentrations recorded were compared to the SAWQG. According to the South African Water Quality Guidelines for Coastal Marine Waters False Bay is situated on the south – west coast. False Bay was experiencing winter conditions with a prevailing north westerly wind at the time of sampling. Upwelling was therefore not taking place so the guidelines for the south coast were used.

Nitrate

In well oxygenated sea water with a salinity of 35 psu, NO_3 - N can be expected to be found in concentrations of between 0.1and 45 umol/l with an average of 30 umol/l. NO_3 - N concentrations increase with depth, which is referred to as a nutrient type distribution. The south coast average concentration is 6 umol/l and should not be exceeded in unimpacted water.

NO_3 - N is a minor constituent, but a major nutrient in seawater. It is extracted from the surface waters by photosynthesising plankton to make organic tissue. It is totally depleted in the surface water where production is high, which means that it is a biolimiting constituent and is considered to be the micronutrient controlling primary production in the euphotic layers. The concentration of NO_3 - N in the ocean is close to 0, as the uptake rate of NO_3 - N is usually faster than transport to the surface. The molar ratio of NO_3 - N to PO_4 - P is 16:1 for organic tissues.

Anthropogenic sources of NO_3 - N include sewage discharge, runoff from agricultural areas, especially fertilisers and septic tank runoff.

Nitrite

There is limited information available on the occurrence of NO_2 - N along the South African coast but an average concentrations of 0.2 umol/l has been recorded on the south coast.

NO_2 - N may be excreted by phytoplankton especially during periods of luxury feeding i.e. when there is a surplus of NO_3 - N and PO_4 - P present in the water. Natural levels may be very low, but in transitions zones where oxic conditions change to anoxic ones thin layers of high NO_2 - N coupled with low dissolved oxygen concentrations may occur. In upwelling areas elevated levels of high NO_2 - N values indicate high activity of primary producers. Natural levels of NO_2 - N are 0.1 umol/l but in anoxic zones concentrations in excess of 2 umol/l have been measured. Under upwelling conditions concentrations range between 1 and 2 umol/l.

The anthropogenic pollution sources for nitrite are the same as nitrate.

Phosphate

The phosphate compounds found in seawater are decomposition and excretion products from organisms. Like NO_3 - N it is used to form soft tissue of organisms with a molar ratio of NO_2 - N / PO_4 - P of 16:1. In salt water with a salinity of 35 psu the mean concentration is estimated to be 2 umol/l with a range between less than 1 to 3.5 umol/l and an average of 2.3 umol/l. On the south coast the average is 1.2 umol/l which should not be exceeded in unimpacted waters.

The PO_4 - P concentration at the surface is low due to steady down drift of organic debris as phytoplankton only lives in the euphotic zone. Phytoplankton is consumed by zooplankton and other animals that package most of their waste into faecal pellets. Only about 1% of this organic matter reaches the sediment as most of it is crushed by pressure and the PO_4 - P is released before it reaches the bottom. The concentration of PO_4 - P increases with depth. Upwelling returns PO_4 - P to the surface whilst anoxic conditions will facilitate the return of PO_4 - P from the sediment into solution.

Anthropogenic sources of PO_4 - P pollution include waste products from manufacturing phosphoric acid for fertilisers, phosphatisation of metals in plating and metal processing industries, sewage discharges including household detergents and agricultural runoff (over fertilisation with super PO_4 - P is a common problem and enormous amounts of PO_4 - P are brought to the sea by rivers in some areas).

Ammonia

In oxygenated and unpolluted sea water the concentrations of NH_4 -N and NO_3 - N rarely exceed 5 umol/l. NH_4 -N is excreted directly by animals together with urea and peptides.

NH_4 -N is often the most abundant form of inorganic nitrogen in the surface layers after a period of productivity when the phytoplankton blooms have removed the greater part of nitrate and phosphate. In the assimilation processes of phytoplankton, ammonium is preferentially used for synthesising protein. When nitrate is incorporated it must first be reduced to ammonia before it can be transferred into amino acid compounds

Soluble and particulate organic nitrogen compounds resulting from decaying organisms together with those excreted by plants and animals are rapidly broken down to ammonia by various species of proteolytic bacteria.

When organisms sink below the euphotic zone, they decompose as a result of oxidative bacterial action releasing nitrate and phosphate. As the water approaches anoxic conditions, bacteria utilise the nitrate ions to continue the oxidation process. This denitrification leads to the production of molecular nitrogen and ammonium. Interaction between nitrate and ammonia produces more nitrogen gas. At the onset of sulphate reduction, ammonia and hydrogen sulphide are often produced in high concentrations

Ammonia is the dominant form of combined inorganic nitrogen when anoxic conditions have developed to the stage when all the nitrate-nitrogen has been reduced, and if the system becomes anoxic, the concentration of ammonia-N can become high. Dead or senescent algal cells will autolyse, and this effect coupled with bacterial action will release ammonia-N, a large proportion of the organic nitrogen originally bound in particulate form. For aquatic animals, ammonia-N is usually the main soluble form. Utilisation of proteinaceous organic matter by bacteria in the sea as a source of energy probably causes some liberation of ammonia-N as a result of oxidation-deamination reactions.

Anthropogenic sources of ammonia pollution include sewage discharges, run off from agricultural areas, especially when fertilisers are applied and septic tank seepage.

Silicate

SiO_2 - Si is a major constituent of diatoms which form a large proportion of marine phytoplankton. Seawater is quite unsaturated in SiO_2 - Si since its solubility is 1.8 umol/l. The concentration of SiO_2 - Si in surface to deepwaters range from less than 1 to 180 ug/l with an average of 100 umol/l. On the south coast the average is 5.2 umol/l which should not be exceeded in unimpacted waters.

SiO_2 - Si is a biolimiting nutrient as it is used to make the hard parts of some planktonic organisms. The skeletal remains dissolve slowly as they fall through the water column after death and accumulate as sediments on the sea floor. It is a biolimiting nutrient whose availability in the surface waters limits biological production. Its profiles therefore show almost total depletion in surface waters because they are controlled principally by biological processes.

Water Quality Guidelines for Groundwater Samples

The Department for Water Affairs and Forestry has not released specific guidelines for groundwater quality. After personal communication with the department the Guidelines for freshwater Aquatic ecosystems were used.

Tables

Author	Description
Henzen 1973:	Studied the western section of the aquifer. Focused on the feasibility of reclamation, storage and abstraction of water and purified sewage effluent.
Gerber 1976:	Studied the central section of the aquifer, focusing on hydraulic characteristics.
Wessels and Greef 1980:	Investigated the use of water from the Eerste and Kuils Rivers through storage in the sand deposits on the Eastern Cape Flats.
Gerber 1981:	Developed a simulation model to describe the subsurface flow of the southern parts of the Cape Flats Aquifer.
Tredoux et al 1980:	Did an artificial recharge study using partly reclaimed stabilisation pond effluent.
Tredoux 1984:	Monitors the groundwater quality at the site on the Cape Flats.
Bertram 1987:	Dealt with the establishment of a wellfield for irrigation purposes, in the grounds of the Psychiatric Hospital in Mitchell's Plain.
Bertram 1989:	A hydrological investigation was done to update and gain accurate information on abstraction and water quality in the Philippi farming area.
Vandoolaeghe 1989:	Reports on the Cape Flats Groundwater Development Pilot Abstraction Scheme, which was established to test the aquifer yield, monitor the water quality and the effect of water abstraction on the environment.
Edwards 1989:	Monitored the groundwater quality and to gain an understanding of changes in the ambient water quality during the operation of the Pilot Abstraction scheme in the area between Weltevreden and Swartklip Roads in the central Cape Flats.
Vandoolaeghe 1990:	Summarised the last twenty years of work done on the aquifer.
Ransome and de Wit 1992:	Studied pollution migration emanating from the Coastal Park Waste Disposal Site.
Wright and Conrad 1995:	Compiled the research findings from the previous 30 years and attempted to define the relevance of the Cape Flats Aquifer to the Cape Town Metropolitan Area.
Jolly 1996:	Investigate impact of the proposed Capricorn Park Development on the groundwater body with regards abstraction and water quality.
Parsons 2000abc:	Investigated the impact of the Cape Flats WWTW on surrounding water bodies as well as the relationship between groundwater and Zeekoevlei, Rondevlei, Princess Vlei and Little Princess Vlei.
Cave 2000:	Assessed the impact of waste disposal on the groundwater at the Swartklip Waste Disposal site.
Mehlomakulu 2000:	Studied the water quality of 15 samples taken from the Cape Flats Aquifer.
Fraser and Weaver 2000a:	Reviews available information on the Cape Flats Aquifer and comments on the development of a production wellfield and the promotion of private wellpoints and boreholes.
Fraser and Weaver 2000b:	Identified the potential impacts that bulk abstraction of groundwater from the Cape Flats Aquifer may have on the environment, on the aquifer itself and the social impacts directly related to groundwater users.
Traut and Stow 2001:	Summarizes the monitoring of water quality at the Coastal Parks Landfill site since 1985. There are numerous other reports from this site.

Table 1.1: Previous Studies done on the Cape Flats Aquifer

Bin ID	Henzen (1973)				Gerber (1981)			
	Q (m^3/day)	T (m^2/day)	I	W (m)	Q (m^3/day)	T (m^2/day)	I	W (m)
A					3	50	0.002	24
B	31	400	0.004	20	3	100	0.001	24
C	37	400	0.005	20	6	150	0.002	23
D	73	500	0.007	22	7	150	0.002	25
E	66	400	0.007	22	10	150	0.002	28
F	72	400	0.008	23	8	100	0.003	30
G	93	550	0.007	24	10	100	0.003	31
H	100	600	0.007	25	13	125	0.004	30
I	119	800	0.006	24	18	175	0.004	27
J	107	800	0.006	23	20	225	0.004	22
K	71	650	0.006	19	24	280	0.004	21
L	59	600	0.005	19	27	340	0.004	21
M	40	500	0.004	18	31	375	0.004	22
N					24	350	0.003	20
O					13	200	0.003	18
P					10	150	0.003	19
Q					11	175	0.003	21
R					11	225	0.003	19
S					9	250	0.002	15
T					8	250	0.002	15
U					5	200	0.002	14
V					4	150	0.002	15

Table 3.1: Calculated Discharge Rates (Q) for Henzen (1973) and Gerber (1981)

		Latitude	Longitude
Section One	Start Co -Ordinates	34° 06' 16"	18° 30' 31"
	End Co - Ordinates	34° 06' 11"	18° 32' 30"
Section Two	Start Co -Ordinates	34° 05' 46"	18° 34' 08"
	End Co - Ordinates	34° 05' 01"	18° 38' 07"
Section Three	Start Co -Ordinates	34° 04' 41"	18° 42' 02"
	End Co - Ordinates	34° 04' 36"	18° 42' 18"

Table 3.2: The Three Sections of Low Salinity

Segment Number	Salinity Range (psu)	Distance Offshore (m)	Segment Length (m)	Distance from Outlet (m)
1	34.5 – 34.8	879	104	400
2	34.8 – 34.9	879	205	504
3	34.5 – 34.6	920	220	709
4	34.6 – 34.7	1131	994	929
5	34.6 – 34.8	1131	162	1858
6	34.8 - 34.9	1225	370	2020
7	34.7 – 34.8	167	167	2390
8	34.6 – 34.7	1376	444	2557
9	34.8 – 34.9	1430	382	3001

Table 3.3: The segments of low Salinity Section One. The distance from outlet column is positive to the east and negative to the west and gives the distance from the Zeekoevlei Outlet.

Segment Number	Salinity Range (psu)	Distance Offshore (m)	Segment Length (m)	Distance from Outlet (m)
1	34.8 – 34.9	1300	635	- 2781
2	34.8 - <34.9	1300	400	- 2146
3	34.8 – 34.9	1104	200	- 1746
4	34.8 – 34.9	469	1688	- 1546
5	34.7 – 34.8	876	936	142
6	34.6 – 34.7	794	78	1078
7	34.7 – 34.8	825	394	1156
8	34.8 – 34.9	835	865	1550
9	< 34.9	978	359	2415
10	34.8 – 34.9	1064	63	2774

Table 3.4: The segments of low Salinity Section Two. The distance from outlet column is positive to the east and negative to the west and gives the distance from the Mitchell's Plain WWTW outlet.

Segment Number	Salinity Range	Distance Offshore (m)	Segment Length (m)	Distance from Outlet (m)
1	34.8 – 34.9	606	151	182
2	34.8 – 34.9	480	277	333

Table 3.5: The segments of low Salinity Section Three. The distance from outlet column is positive to the east and negative to the west and gives the distance from the Monwabisi Outlet.

Sample Site	Sample ID	PO_4 - P	NO_3 - N	NO_2 - N	SiO_2 - S	NH_4 - N
1	**BM01**	3.12	114.50	0.22	40.60	3.13
2						
3	**BM02**	31.27	722.79	0.37	43.29	11.77
4	**BM03**	1.61	134.83	0.24	85.12	4.71
5	**BM04**	25.75	520.04	0.53	116.52	6.48
6	**BM05**	6.97	17.76	0.24	13.73	2.08
7	**BM06**	1.49	11.41	0.13	4.14	6.74
8	**BM07**	1.36	5.24	0.13	2.75	0.53
9	**BM08**	2.37	133.56	0.21	63.41	2.04
10	**BM09**	2.02	17.85	0.28	6.55	6.76
11	**BM10**	0.64	274.40	0.14	43.35	1.94
12	**BM11**	1.27	85.88	0.36	74.72	12.98
13	**BM12**	2.22	24.25	0.48	4.65	4.64
14	**BM13**	1.93	14.61	0.39	30.93	4.55
15	**BM14**	1.07	5.49	0.13	9.28	2.80
16	**BM15**	3.21	17.44	0.33	21.39	8.73
17	**BM16**	0.75	16.19	0.23	11.15	5.63
18	**BM17**	1.77	8.61	0.17	7.34	1.88
19	**BM18**	0.73	6.31	0.34	6.63	5.67
20	**BM19**	3.60	64.22	0.66	23.25	3.49

Table 3.6: The concentrations of nutrients recorded in the berm samples (umol/l).

Sample Site	Sample ID	PO_4 - P	NO_3 - N	NO_2 - N	SiO_2 - S	NH_4 - N
1	**SZ01**	0.40	2.48	0.22	1.46	2.27
2						
3	**SZ02**	27.31	68.12	8.61	21.08	136.89
4	**SZ03**	1.00	7.34	0.88	3.14	41.74
5	**SZ04**	1.13	9.36	0.39	4.21	21.31
6	**SZ05**	0.70	2.13	0.34	0.96	49.81
7	**SZ06**	0.52	2.82	0.41	1.05	4.22
8	**SZ07**	0.39	2.32	0.39	0.61	5.92
9	**SZ08**	0.36	3.06	0.29	2.21	4.88
10	**SZ09**	0.70	2.95	0.44	1.59	3.16
11	**SZ10**	0.25	5.30	0.28	1.32	2.95
12	**SZ11**	0.57	3.27	0.38	3.40	3.22
13	**SZ12**	0.47	2.66	0.34	1.28	4.11
14	**SZ13**	0.67	3.52	0.33	1.32	4.66
15	**SZ14**	0.62	1.70	0.11	no data	3.33
16	**SZ15**	0.92	10.65	0.47	4.03	3.96
17	**SZ16**	0.99	7.58	0.45	2.68	3.18
18	**SZ17**	0.77	4.75	0.45	2.56	2.38
19	**SZ18**	0.16	1.48	0.18	2.92	1.72
20	**SZ19**	1.58	45.67	6.37	17.55	42.46

Table 3.7: The concentrations of nutrients recorded in the surfzone samples (umol/l).

Sample Site	Sample ID	PO_4 - P	NO_3 - N	NO_2 - N	SiO_2 - S	NH_4 - N	Salinity
1	**BS01**	0.58	3.25	0.46	2.52	5.11	34.16
2	**BS02**	0.35	2.10	0.33	1.49	3.82	34.20
3	**BS03**	0.33	1.55	0.27	2.04	2.17	34.21
4	**BS04**	0.85	58.56	1.44	5.23	14.73	34.03
5	**BS05**	1.40	6.42	0.93	2.44	8.42	33.72
6	**BS06**	1.26	5.89	0.83	1.34	7.32	33.77
7	**BS07**	1.52	6.66	0.90	2.84	7.06	34.11
8	**BS08**	0.76	3.70	0.50	1.67	4.33	34.44
9	**BS09**	1.15	6.92	0.61	3.04	6.12	34.31
10	**BS10**	0.95	5.74	0.49	3.43	3.40	34.61
11	**BS11**	0.80	4.95	0.43	2.37	2.39	34.76
12	**BS12**	1.04	3.85	0.34	3.51	2.59	34.70
13	**BS13**	0.71	3.61	0.39	3.82	2.74	34.76
14	**BS14**	0.68	5.01	0.36	1.86	2.36	34.55
15	**BS15**	0.54	4.67	0.33	2.65	2.55	34.66
16	**BS16**	0.69	6.71	0.41	4.70	2.25	34.67
17	**BS17**	0.85	5.85	0.54	1.93	4.97	34.72
18	**BS18**	0.44	2.83	0.35	1.86	2.15	35.00
19	**BS19**	0.73	4.27	0.49	2.78	7.58	34.28
20	**BS20**	0.40	4.42	0.46	3.17	2.69	34.99

Table 3.8: The concentrations of nutrients recorded in surface samples behind the surfzone (umol/l).

Sample Site	Sample ID	PO_4 - P	NO_3 - N	NO_2 - N	SiO_2 - S	NH_4 - N	Salinity
1	**BB01**	0.44	2.63	0.41	1.31	2.27	34.94
2	**BB02**	0.49	2.32	0.34	1.47	2.98	34.04
3	**BB03**	1.58	6.96	0.91	3.41	9.96	34.99
4	**BB04**	0.70	3.05	0.45	4.22	3.45	35.03
5	**BB05**	0.46	2.30	0.36	1.56	3.83	35.09
6	**BB06**	0.75	3.60	0.46	2.56	5.23	35.16
7	**BB07**	1.03	4.60	0.60	2.27	5.60	34.96
8	**BB08**	0.92	4.32	0.55	3.22	6.19	34.93
9	**BB09**	0.78	4.83	0.49	2.89	6.10	34.77
10	**BB10**	0.68	4.03	0.38	3.16	2.75	34.98
11	**BB11**	0.63	3.63	0.34	4.27	3.28	34.38
12	**BB12**	0.65	3.62	0.36	4.95	2.90	34.98
13	**BB13**	1.01	5.29	0.51	2.84	2.57	34.98
14	**BB14**	0.54	4.04	0.33	4.52	2.48	34.98
15	**BB15**	0.74	4.60	0.41	4.30	3.50	34.95
16	**BB16**	0.51	3.58	0.40	4.43	3.61	35.00
17	**BB17**	1.03	5.61	0.63	3.68	9.44	35.07
18	**BB18**	0.68	4.03	0.48	3.31	2.96	35.05
19	**BB19**	0.71	4.23	0.47	3.37	2.71	35.04
20	**BB20**	0.34	4.36	0.43	1.22	3.31	34.94

Table 3.9: The concentrations of nutrients recorded in bottom samples behind the surfzone (umol/l).

Distance from Zeekoevlei Outlet (m)	Sample ID	NO_3 - N (umol/l)	PO_4 - P (umol/l)	SiO_2 - S (umol/l)
0	Taljaard	118.48	39.56	97.11
100	Taljaard	32.32	22.78	20.37
200	Taljaard	23.62	13.19	10.43
250	**SZ02**	**68.12**	**27.31**	**21.08**
300	Taljaard	12.21	6.89	8.83
600	Taljaard	5.50	1.20	2.81
950	**SZ03**	**7.29**	**1.00**	**3.14**

Table 3.10: The concentrations recorded by Taljaard (1991) to the east of the Zeekoevlei outlet. Bold values show corresponding surfzone samples.

Henzen (1973)	**Q (m^3/d)**	**Flux (m^3/d/m)**	**Flux Load (g/d per unit length)**			
			NO_x - N	**PO_4 - P**	**NH_4 - N**	**SiO_2 - S**
A						
B	30.61	1.53	7.02	0.65	0.12	4.32
C	36.53	1.83	0.46	0.39	0.05	0.70
D	73.16	3.33	0.54	0.15	0.31	0.39
E	65.91	3.00	0.23	0.13	0.02	0.23
F	71.68	3.12	5.84	0.23	0.09	5.53
G	93.15	3.88				
H	100.18	4.01	7.09	0.16	0.41	4.66
I	118.57	4.94	1.71	0.34	0.32	0.64
J	106.93	4.65	0.67	0.22	0.24	2.62
K	70.64	3.72	0.89	0.23	0.37	1.69
L	59.01	3.11				
M	40.41	2.24	0.28	0.12	0.06	0.46
N						
O						
P						
Q						
R						
S						
T						
U						
V						

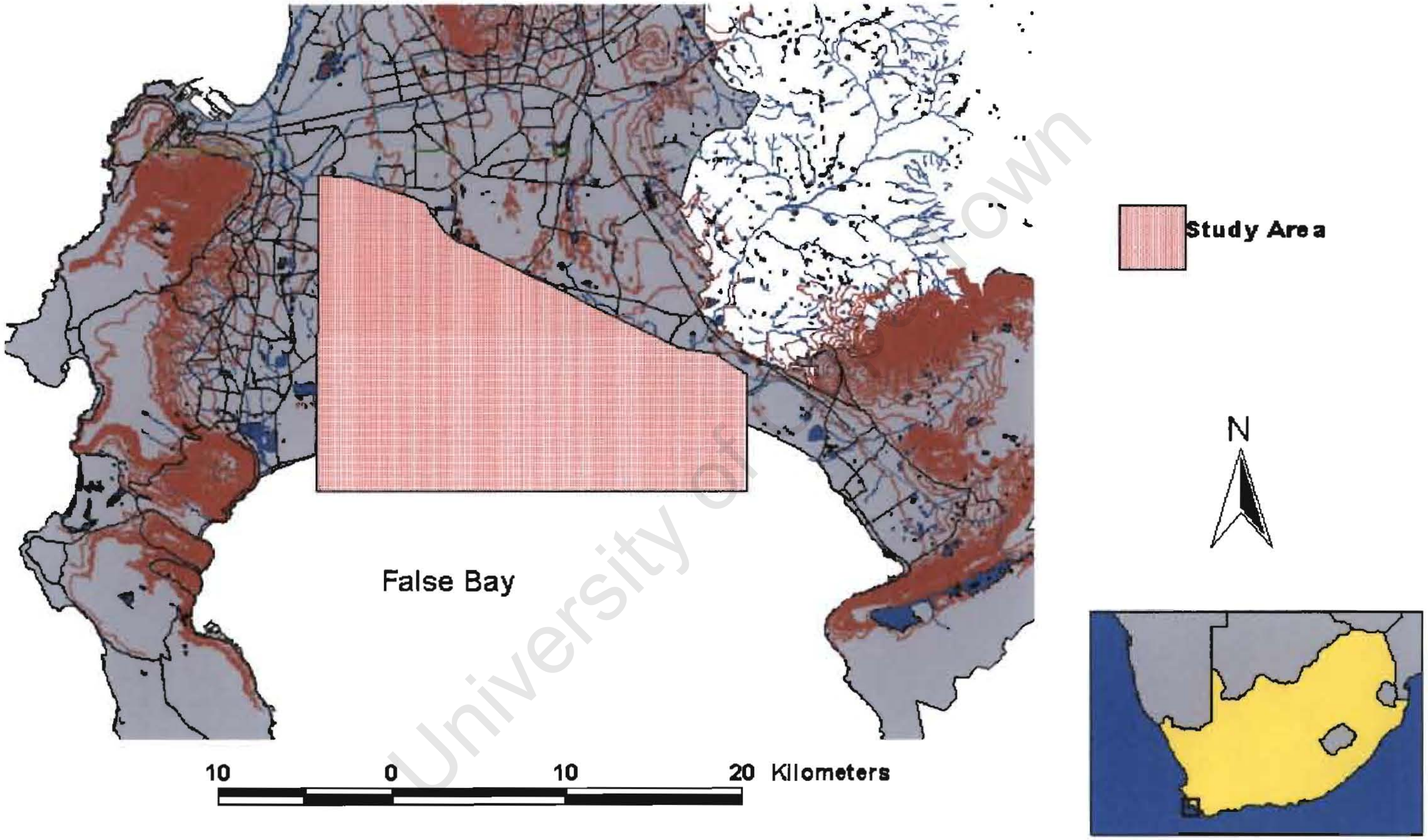
Table 3.11: Flux and flux load per unit length calculated for each bin described in Chapter 2 from data taken from Henzen (1973)

Gerber (1981)	Q (m^3/d)	Flux (m^3/d/m)	Flux Load (g/d per unit length)			
			NO_x - N	PO_4 - P	NH_4 - N	SiO_2 - S
A	2.82	0.12	1.19	0.11	0.02	0.14
B	3.27	0.14	0.63	0.06	0.01	0.38
C	5.52	0.24	0.06	0.05	0.01	0.09
D	6.90	0.28	0.04	0.01	0.03	0.03
E	9.59	0.34	0.03	0.01	0.00	0.03
F	7.77	0.26	0.49	0.02	0.01	0.46
G	9.74	0.31				
H	13.39	0.45	0.79	0.02	0.05	0.52
I	18.49	0.68	0.24	0.05	0.04	0.09
J	20.25	0.92	0.13	0.04	0.05	0.52
K	23.74	1.13	0.27	0.07	0.11	0.51
L	27.19	1.29				
M	31.19	1.42	0.17	0.08	0.04	0.29
N	23.94	1.20				
O	12.56	0.70	0.07	0.02	0.06	0.13
P	9.52	0.50				
Q	10.80	0.51	0.47	0.06	0.03	0.33
R	11.22	0.59				
S	9.14	0.61				
T	8.44	0.56				
U	5.27	0.38				
V	4.24	0.28				

Table 3.12: Flux and flux load per unit length calculated for each bin described in Chapter 2 from data taken from Gerber (1981)

Figures

Figure 1.1: Location of Study Area



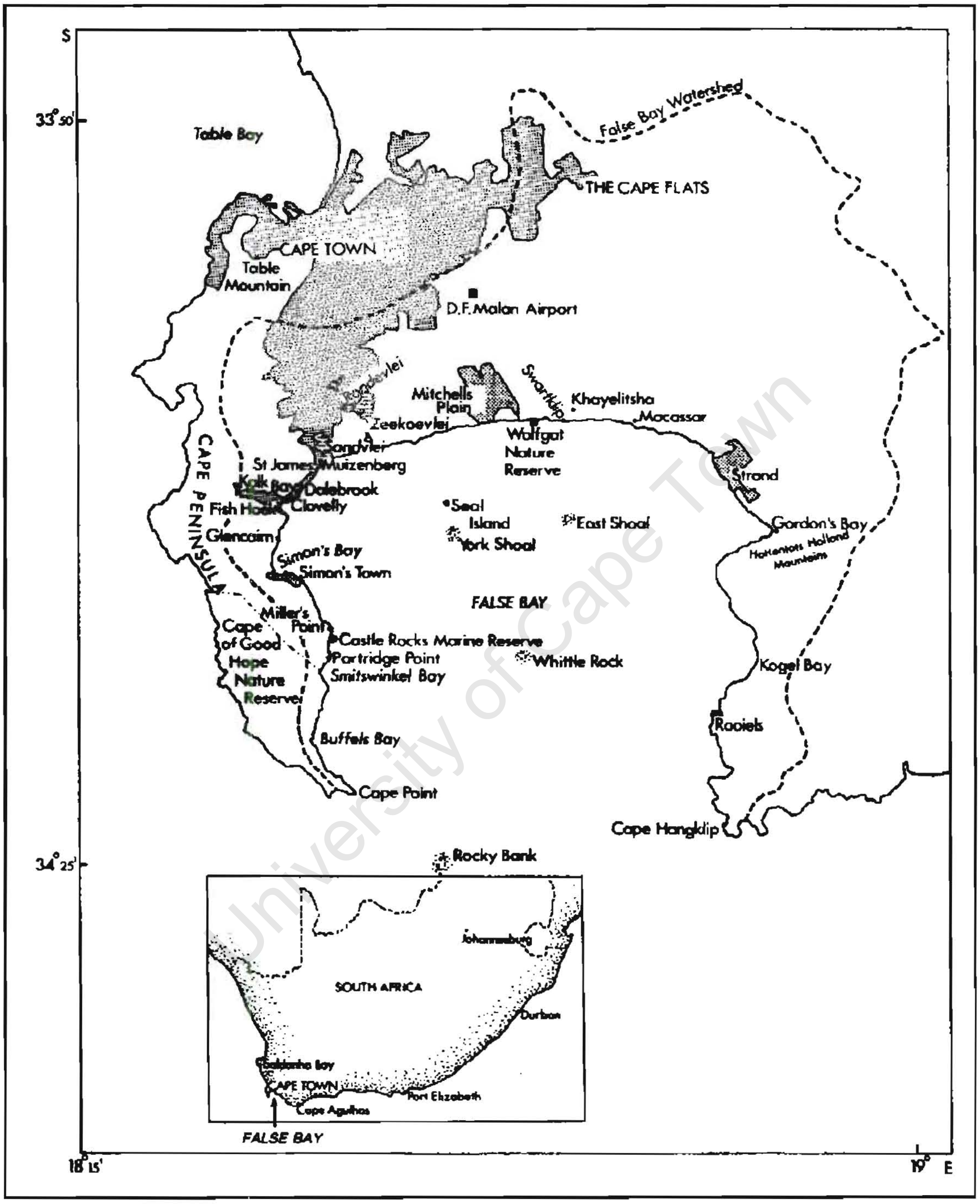
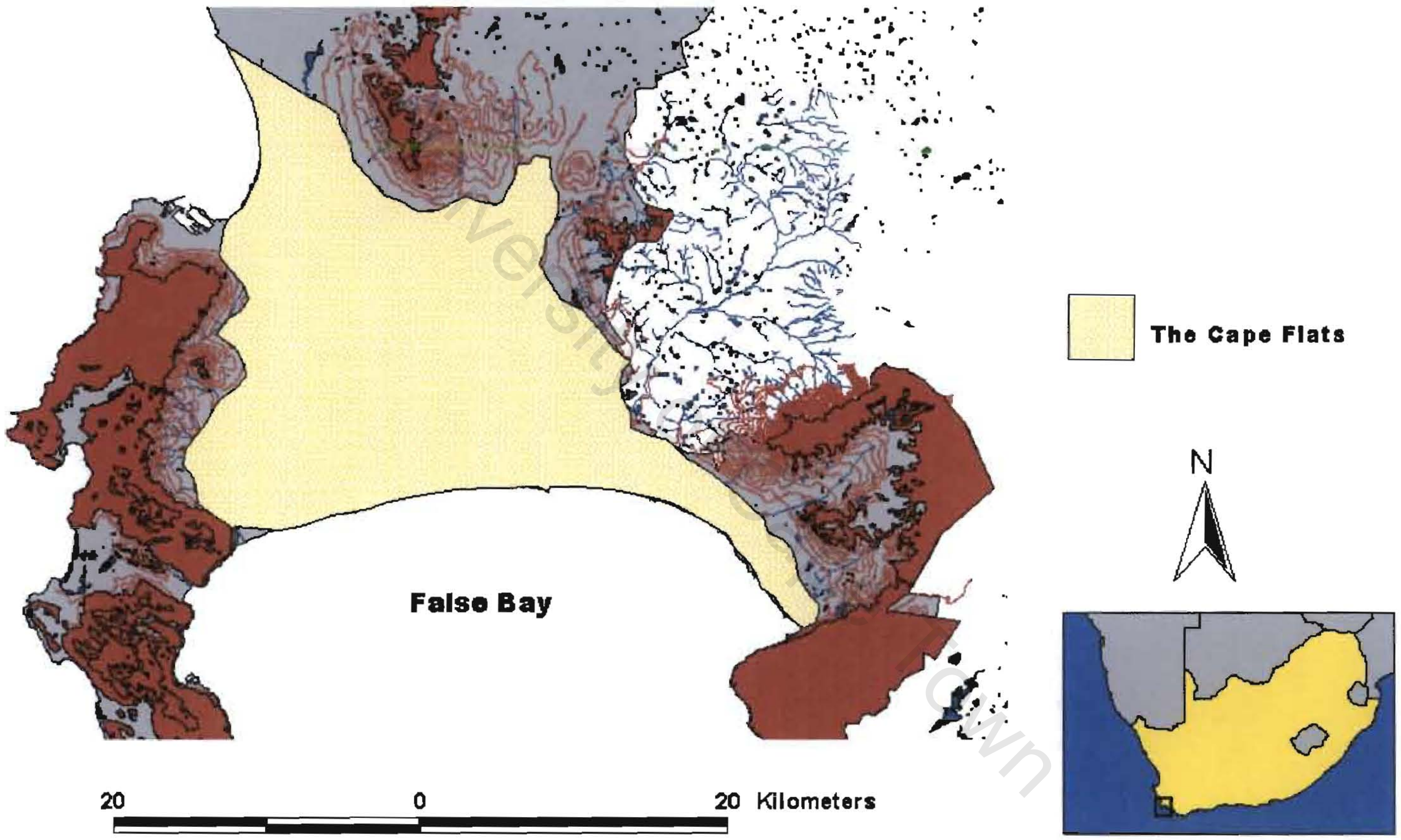


Figure 1.2: A map depicting False Bay, and its position in relation to the rest of South Africa. (Spargo, 1991)

Figure 1.3: The Cape Flats



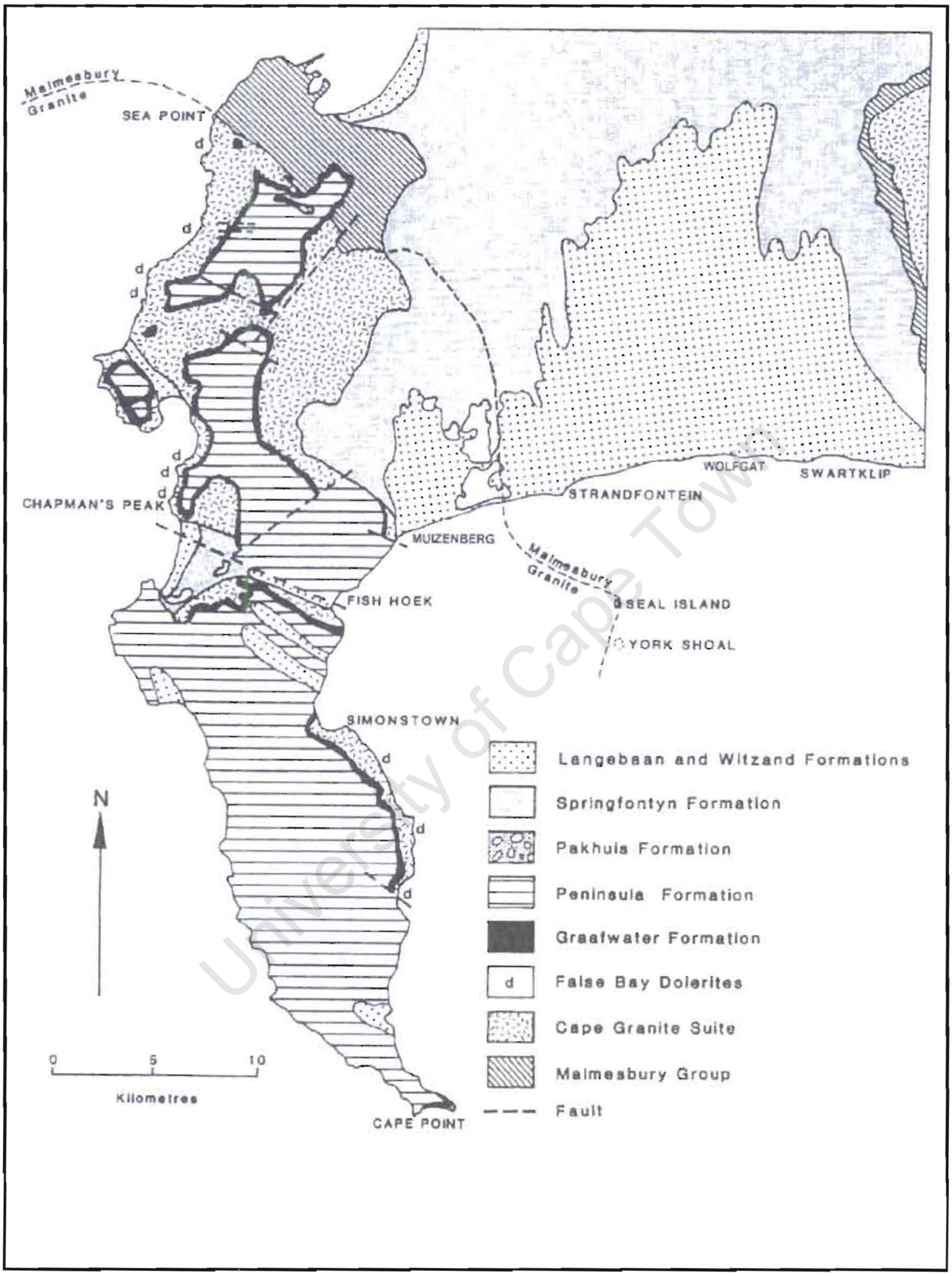


Figure 1.4: Geological map of the Cape Peninsular and the Cape Flats. (Reid, Rogers, Hartnady & De Wit, 1993)

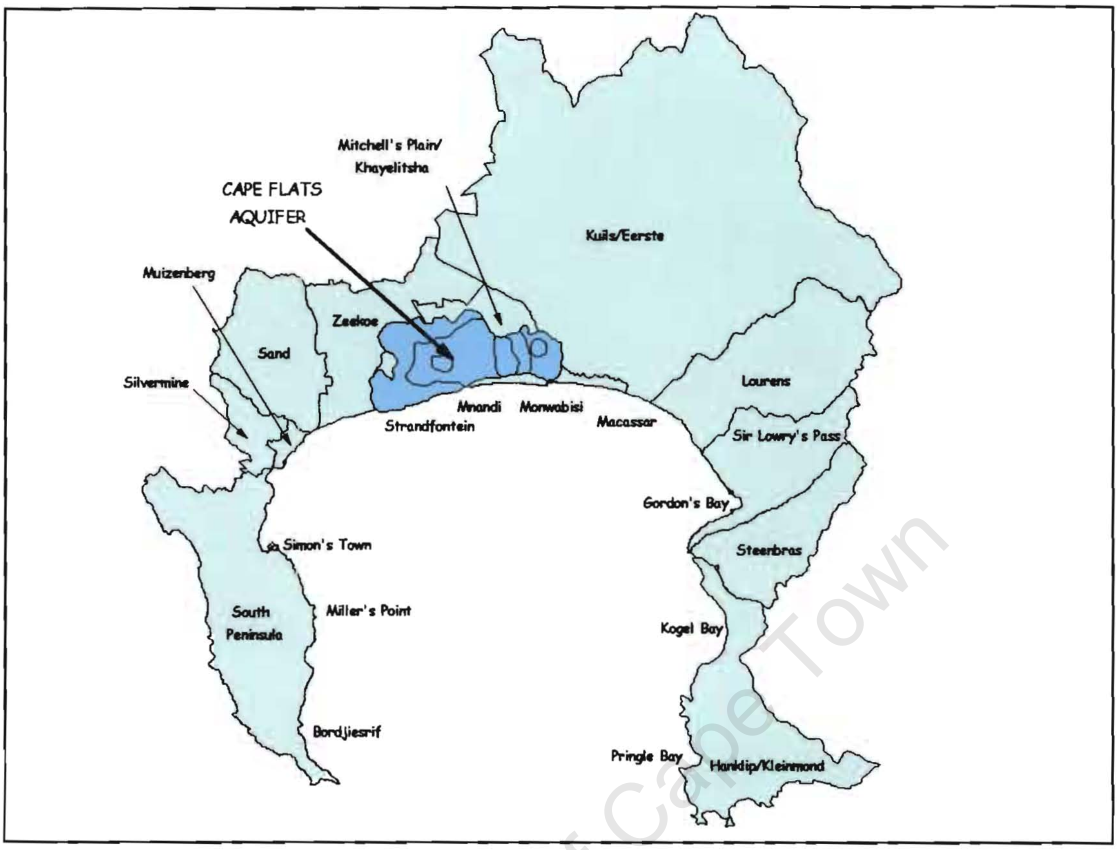


Figure 1.5: The location of the Cape Flats Aquifer

Figure 1.6: Potential Impacts on the Cape Flats and False Bay

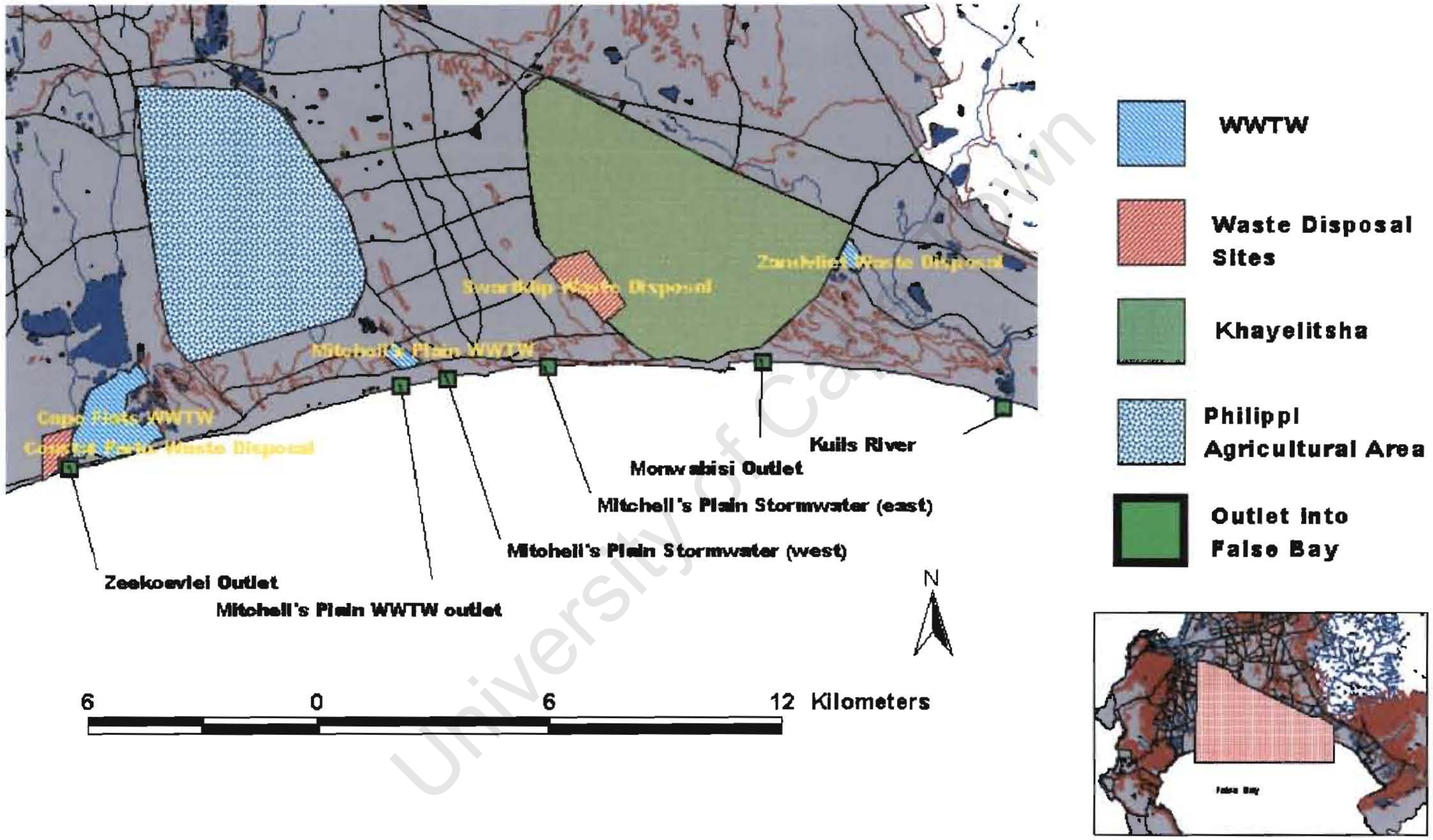


Figure 2.1: Discharge Bins

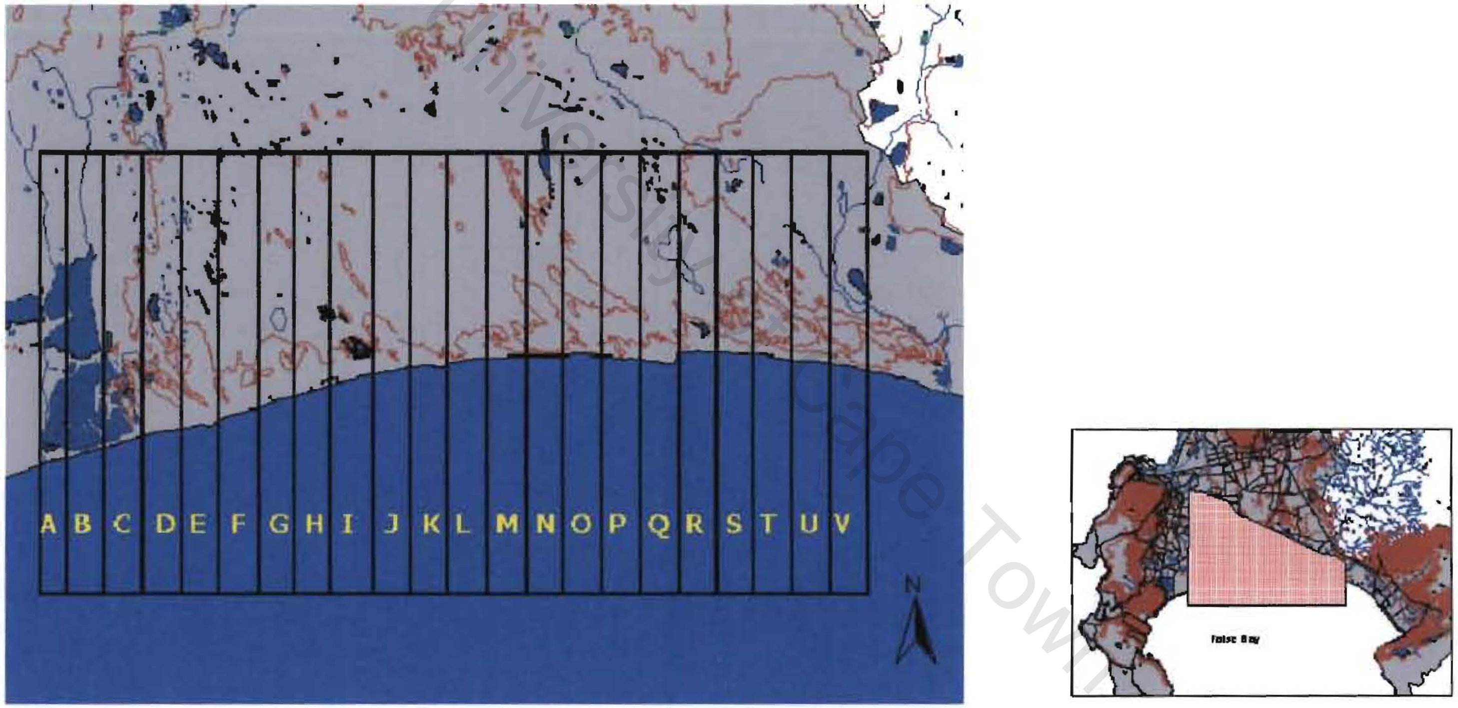


Figure 2.2: Nutrient Sample Sites

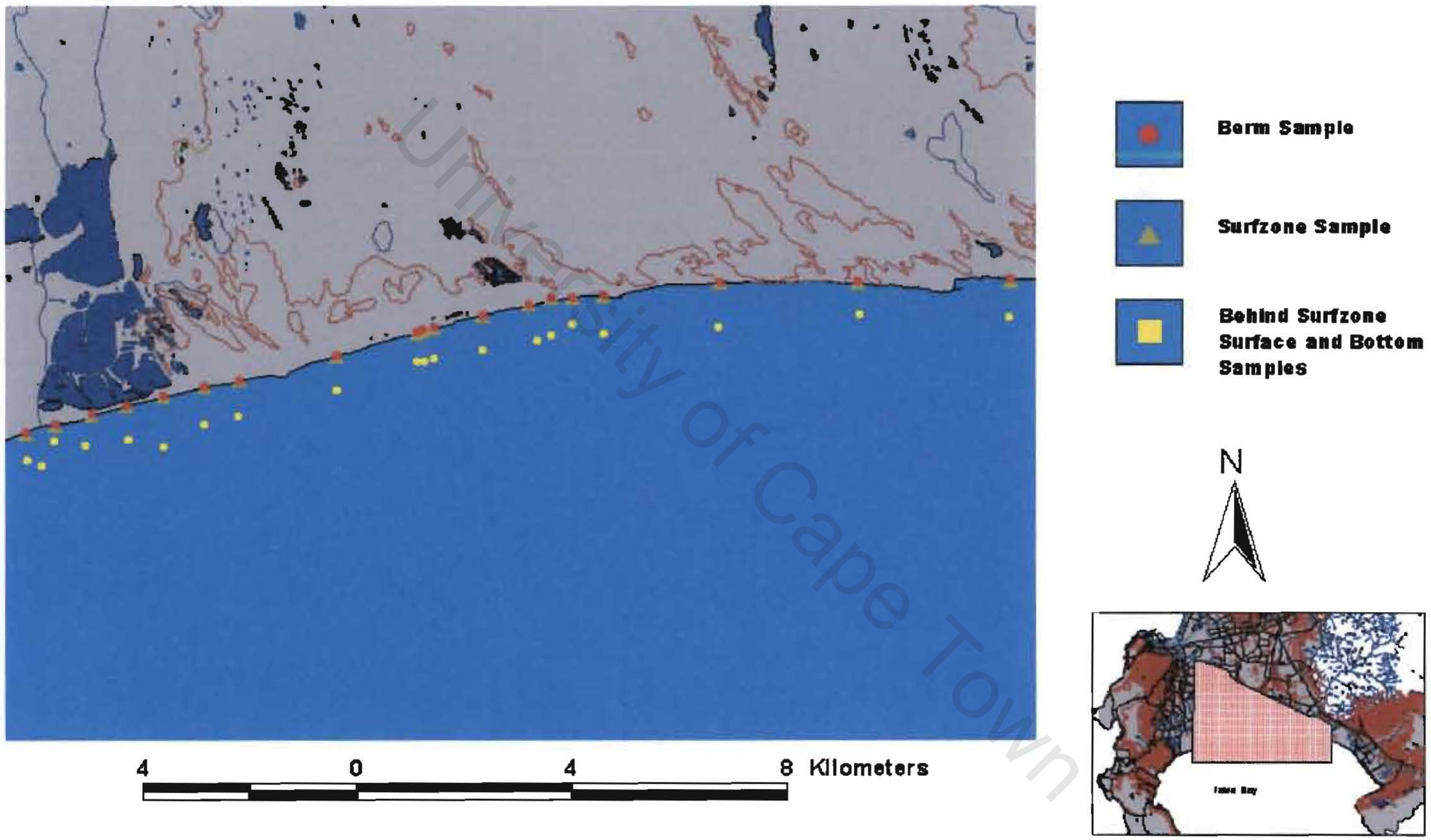


Figure 2.3: The Horizontal Salinity Transect

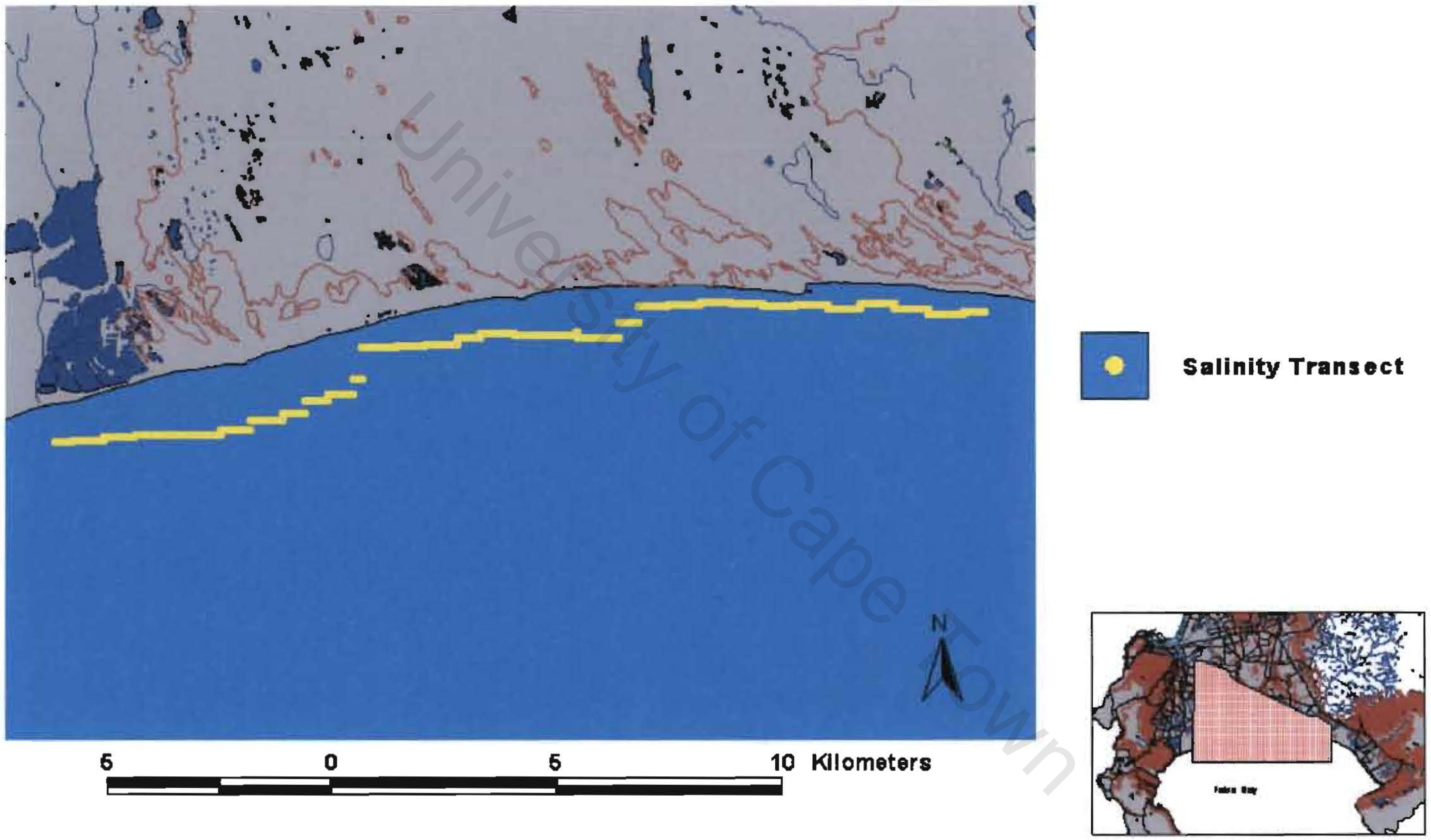


Figure 2.4: Berm Samples

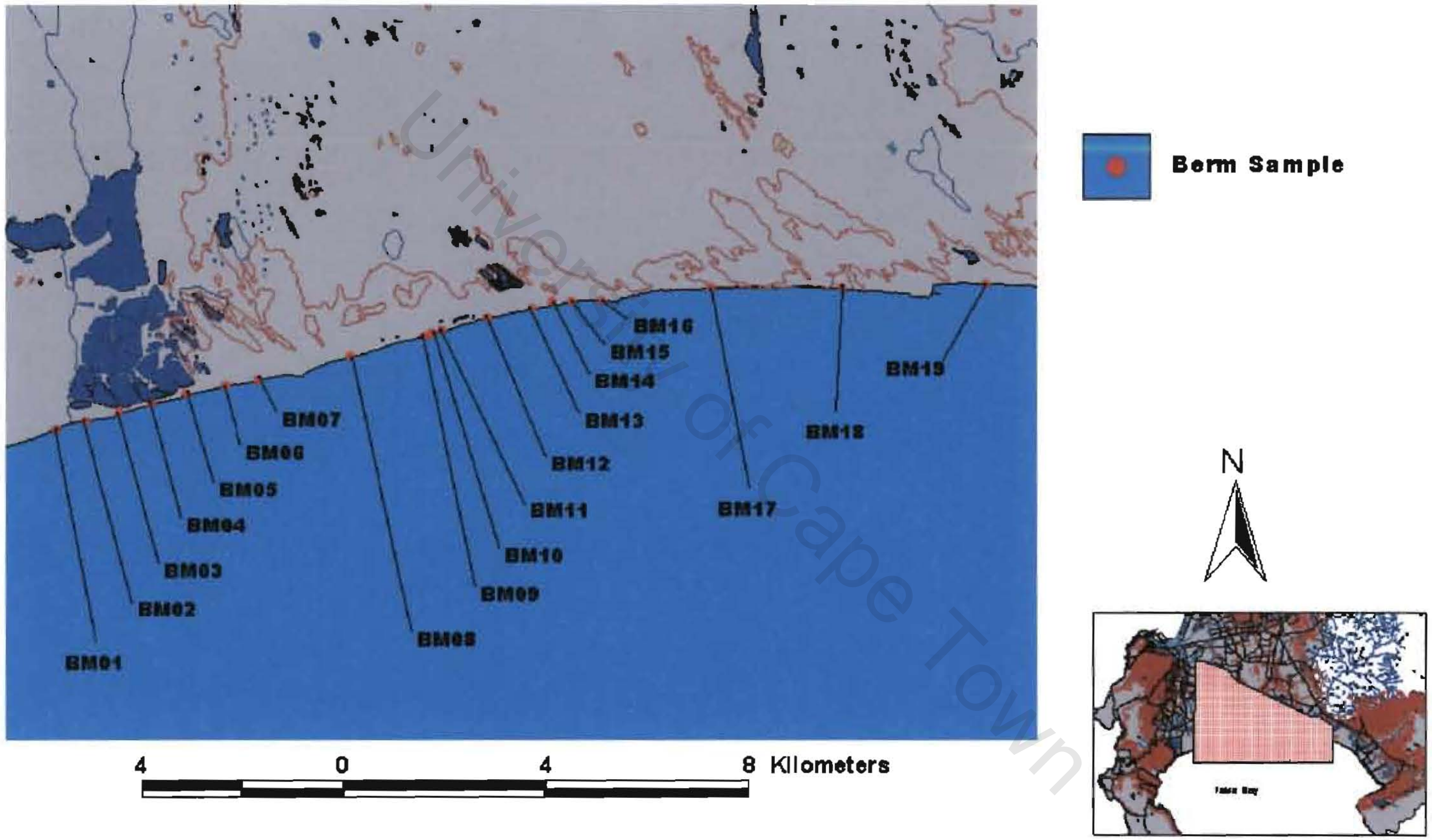
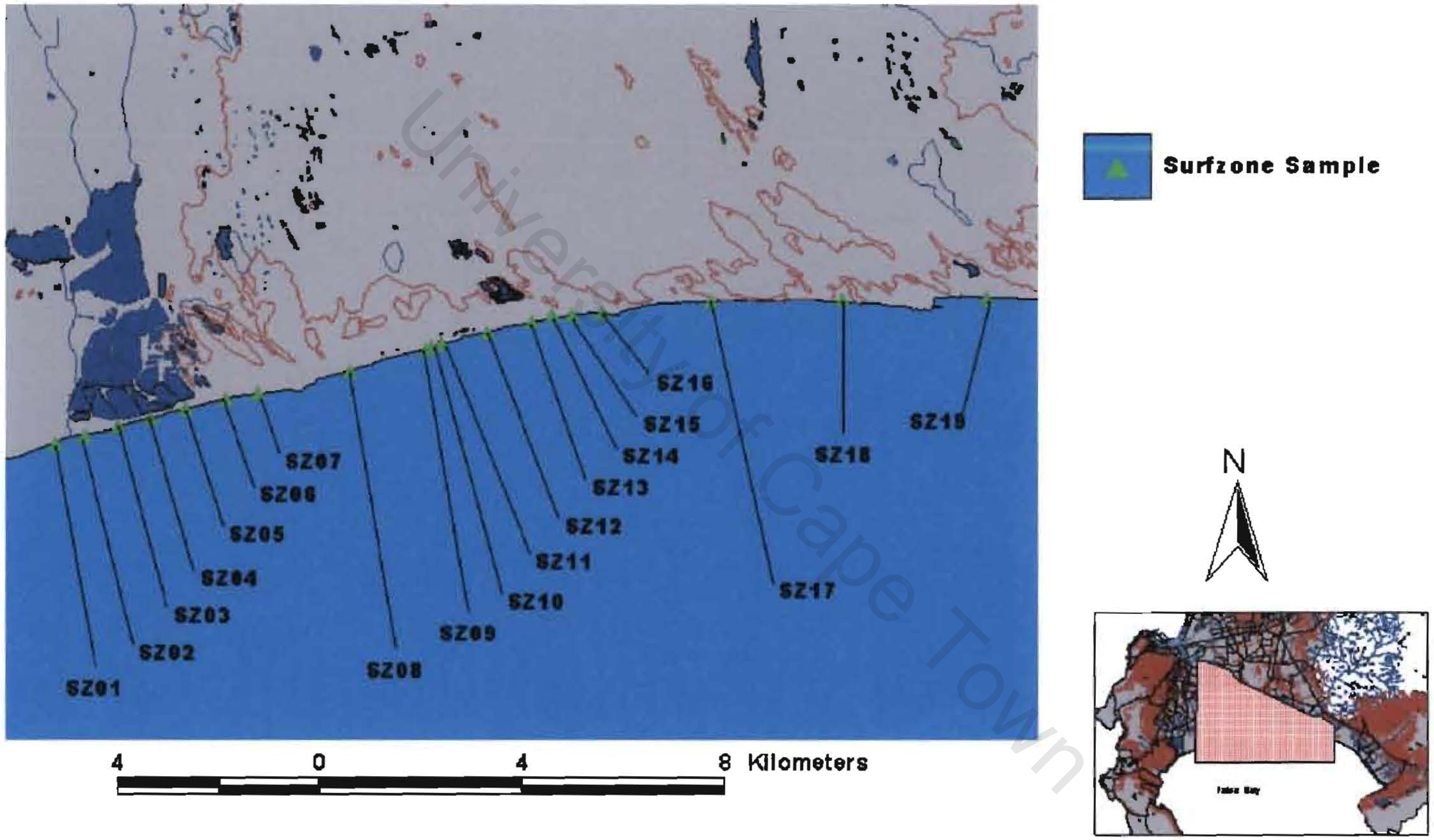


Figure 2.5: Surfzone Samples



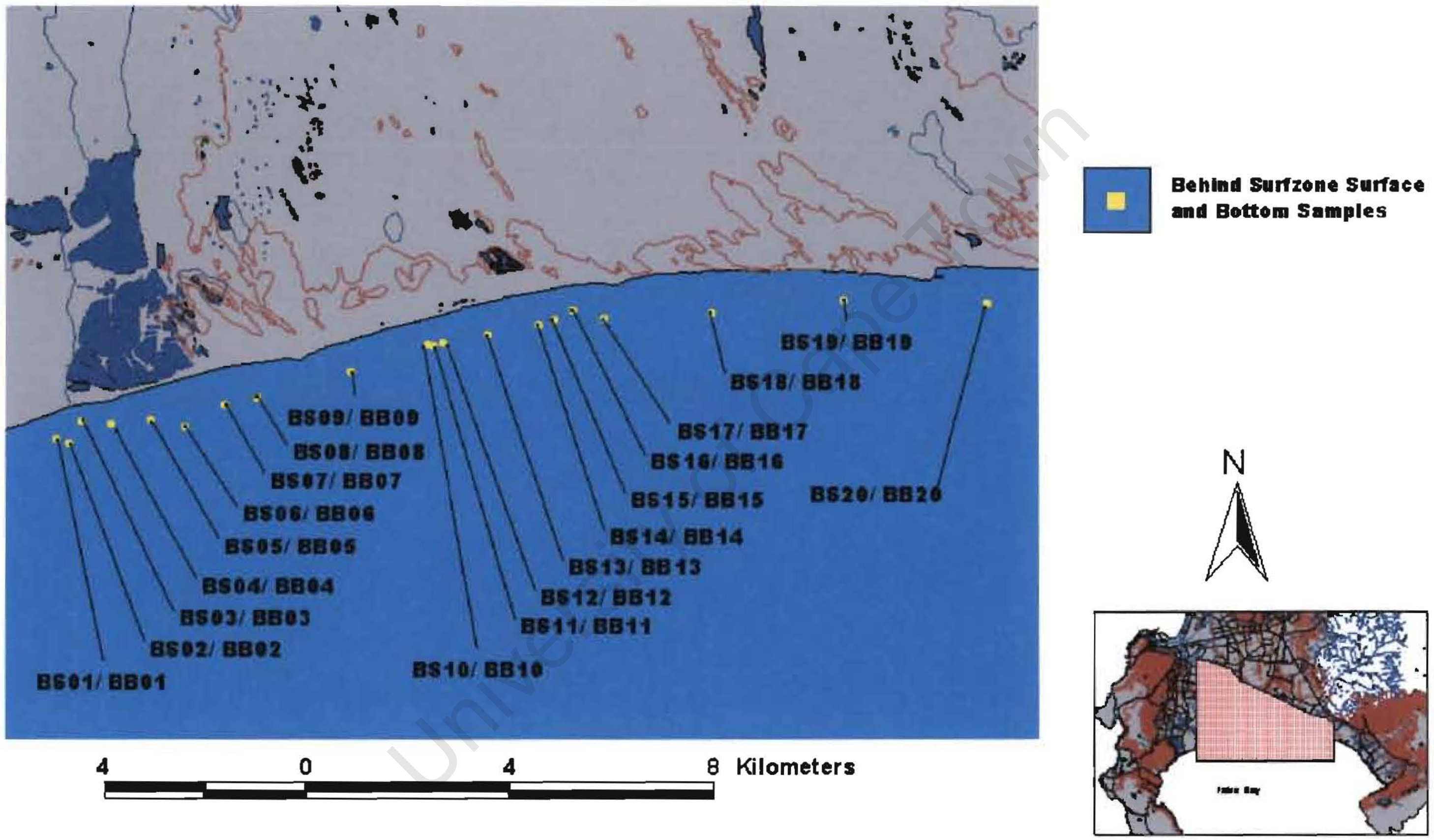


Figure 2.6: Behind Surfzone Surface and Bottom Samples

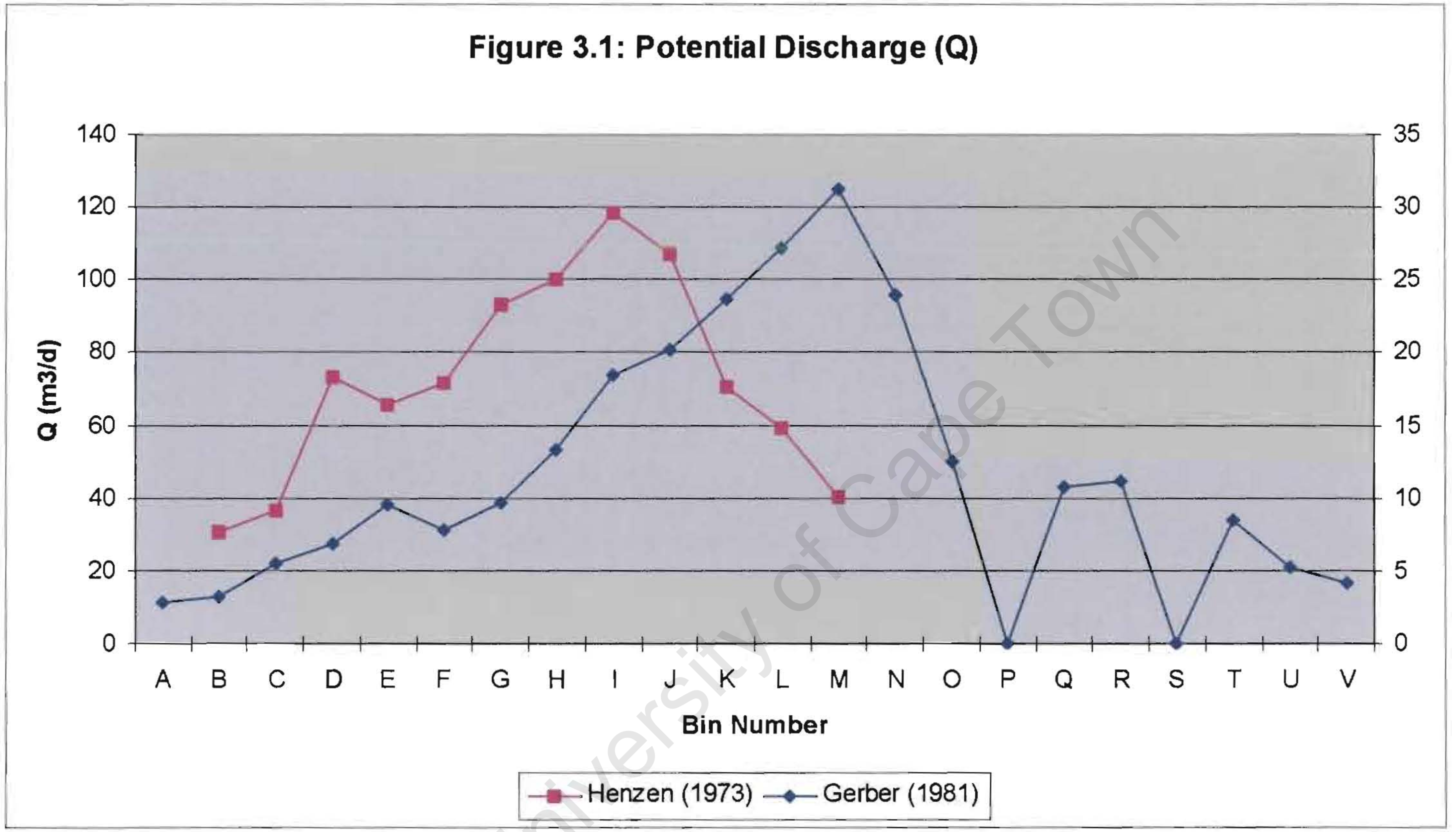


Figure 3.1: Potential discharge calculated using Darcy's Law. The right axis shows the discharge calculated using data from Henzen (1973) and the left axis data from Gerber (1981).

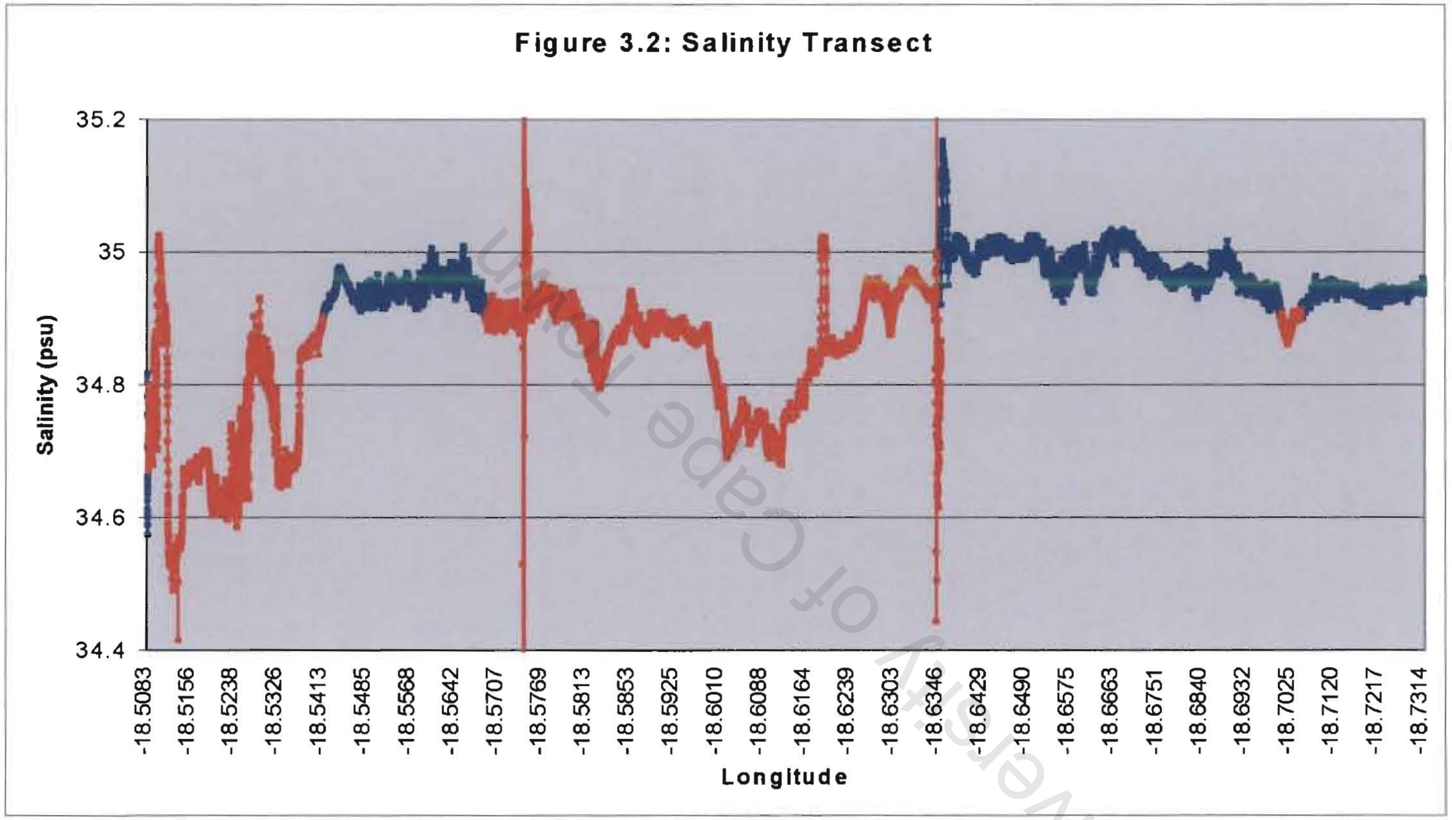


Figure 3.2: The horizontal salinity transect. Areas of low salinity (below 34.9 psu) are shown in red.

Figure 3.3: The Position of the Three Low Salinity Sections

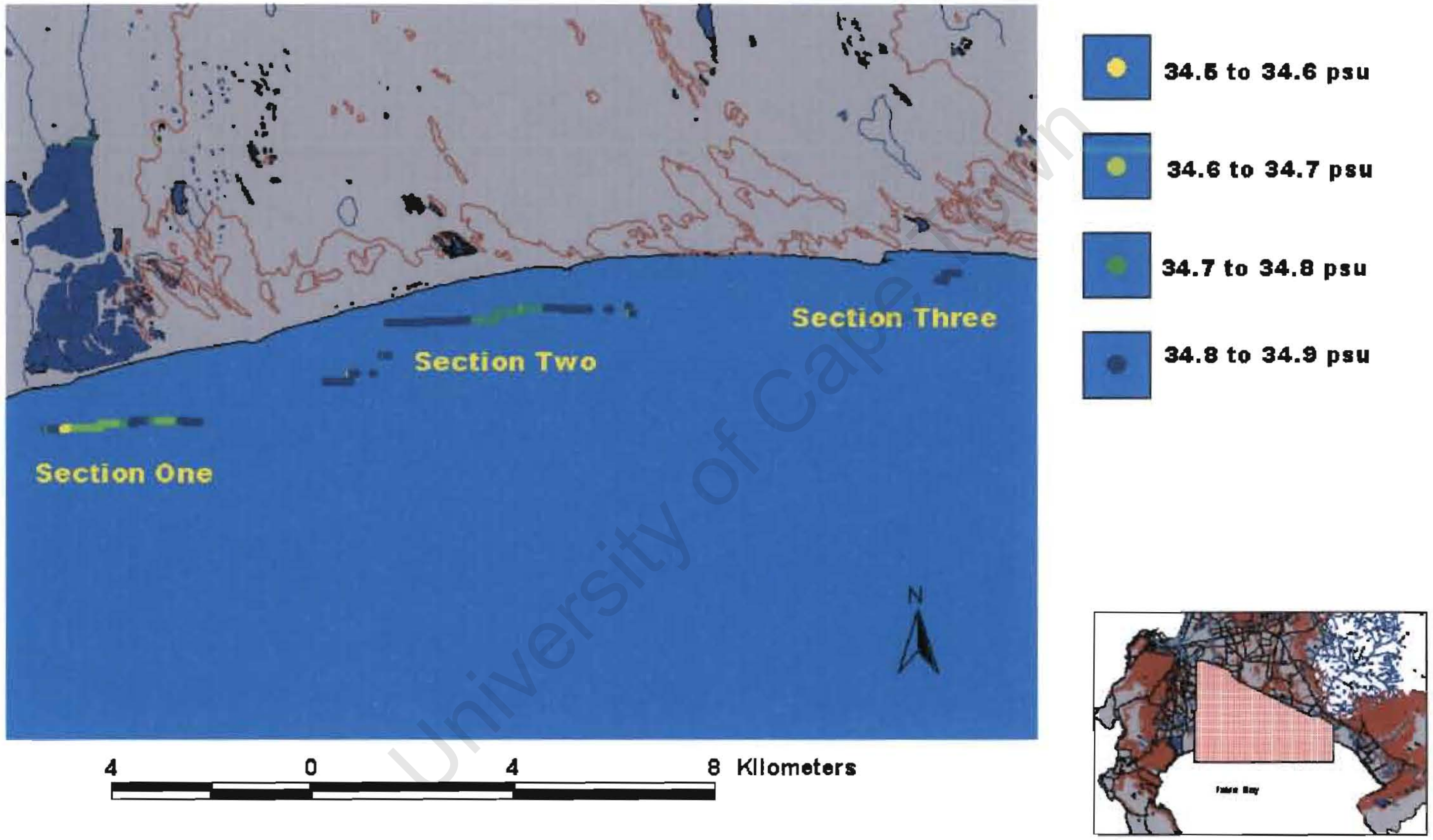
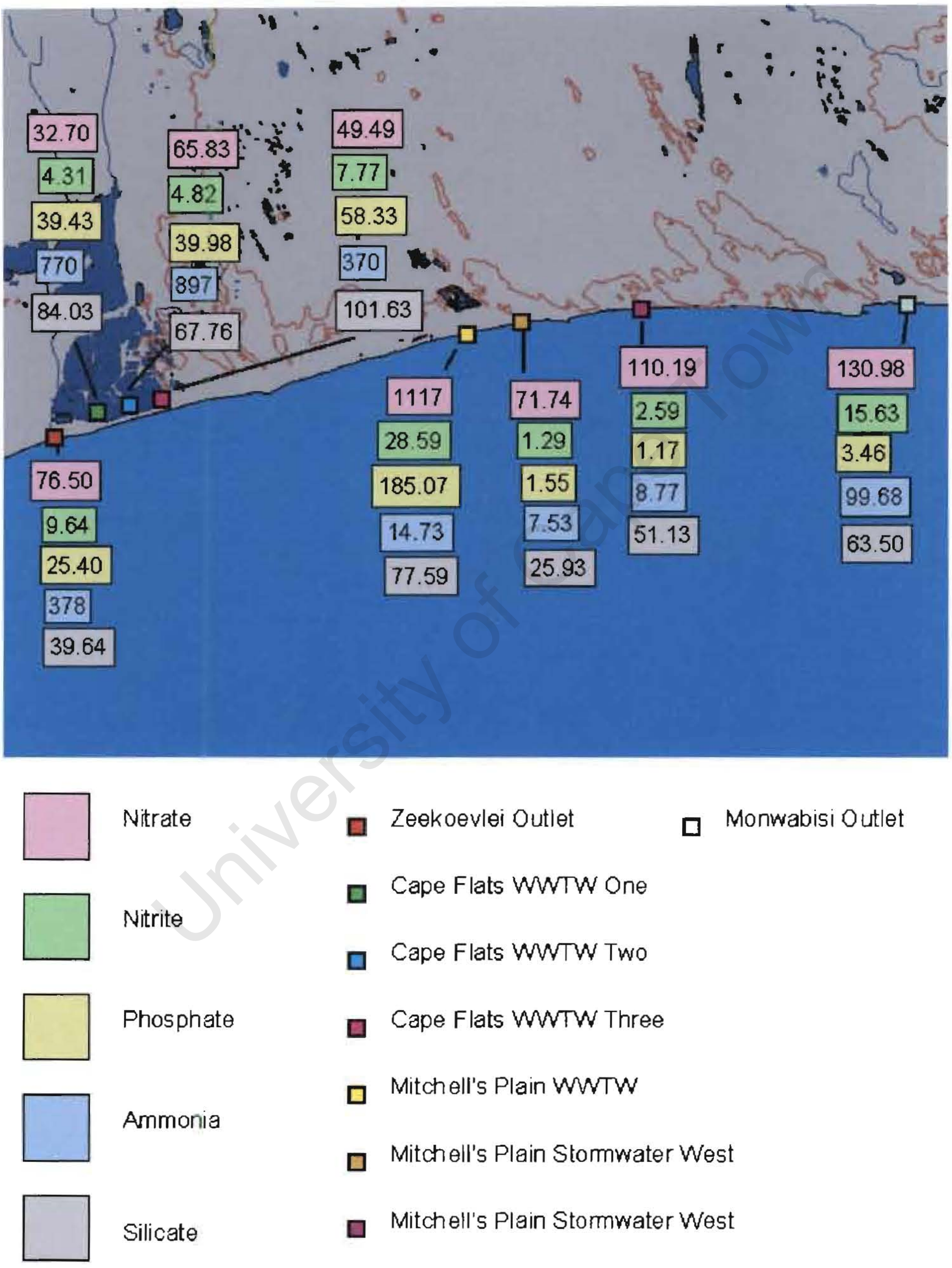


Figure 3.4: Nutrient concentrations (umol/l) of fluvial inputs entering False Bay



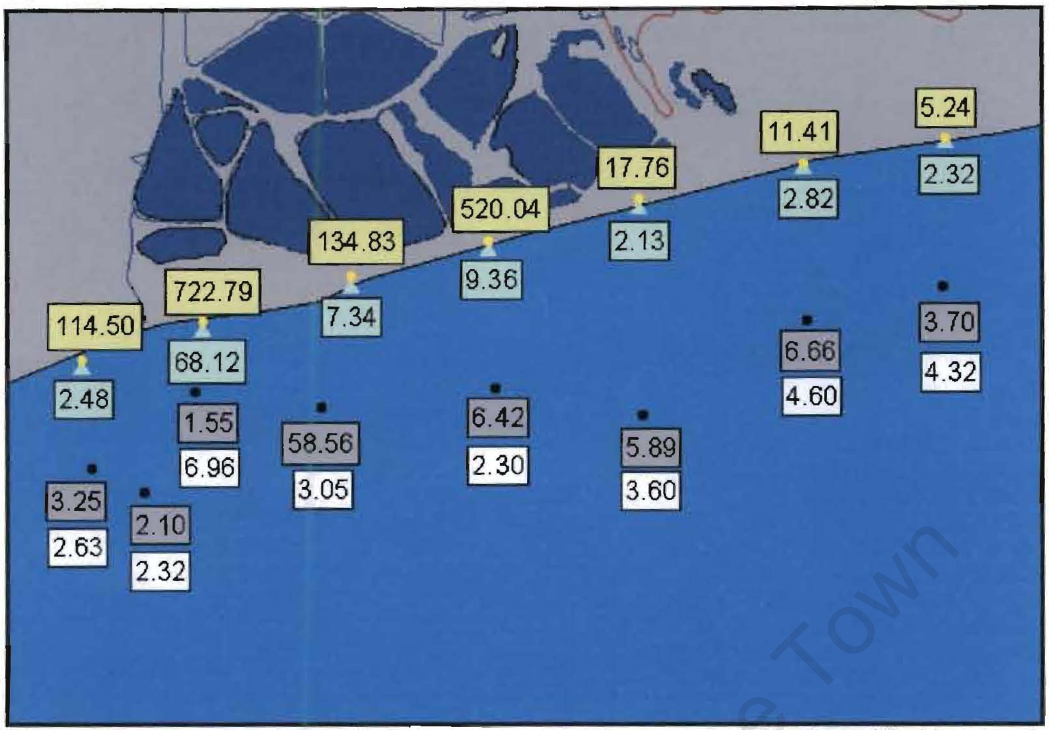


Figure 3.5: Nitrate concentrations recorded at Salinity Transect One (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

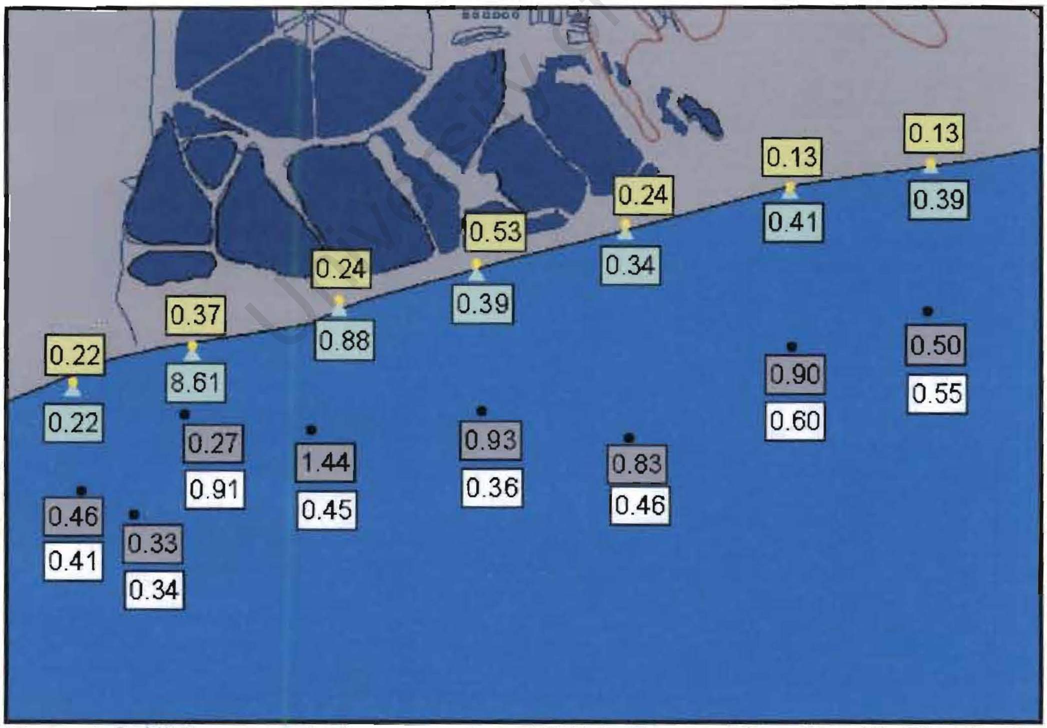


Figure 3.6: Nitrite concentrations recorded at Salinity Transect One (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

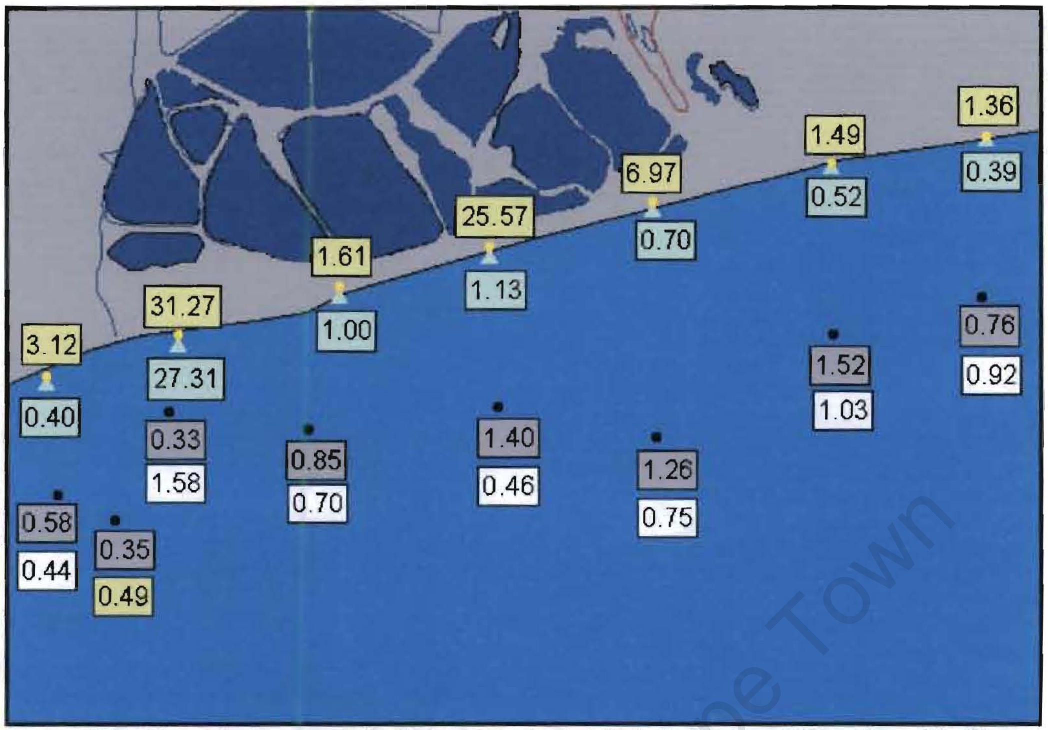


Figure 3.7: Phosphate concentrations recorded at Salinity Transect One (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

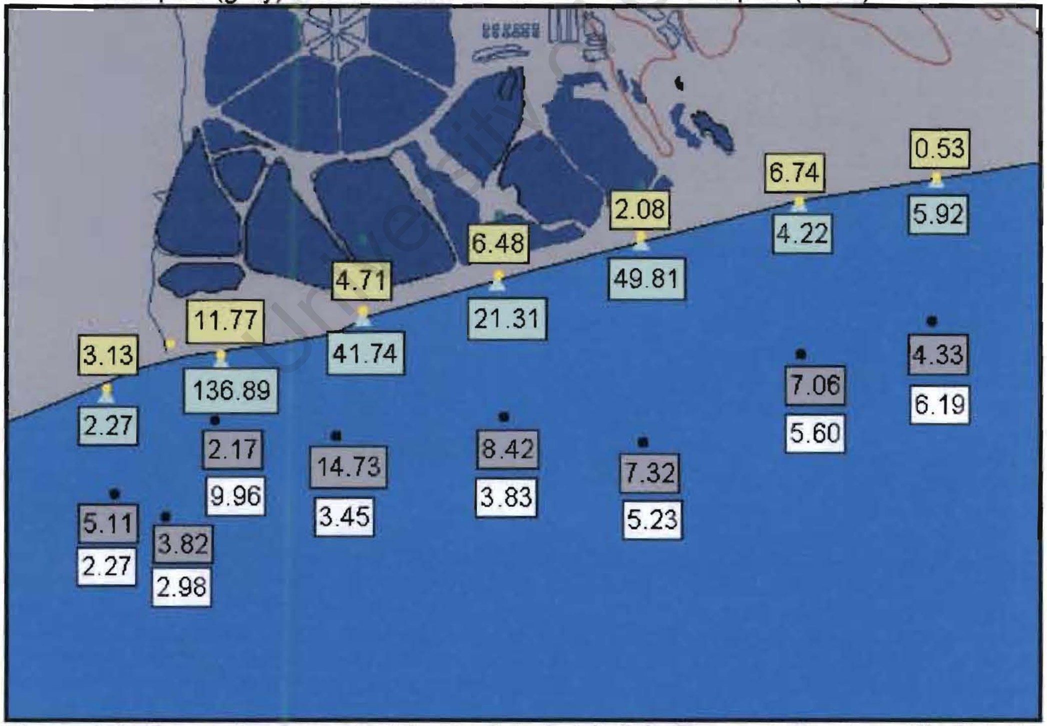


Figure 3.8: Ammonia concentrations recorded at Salinity Transect One (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

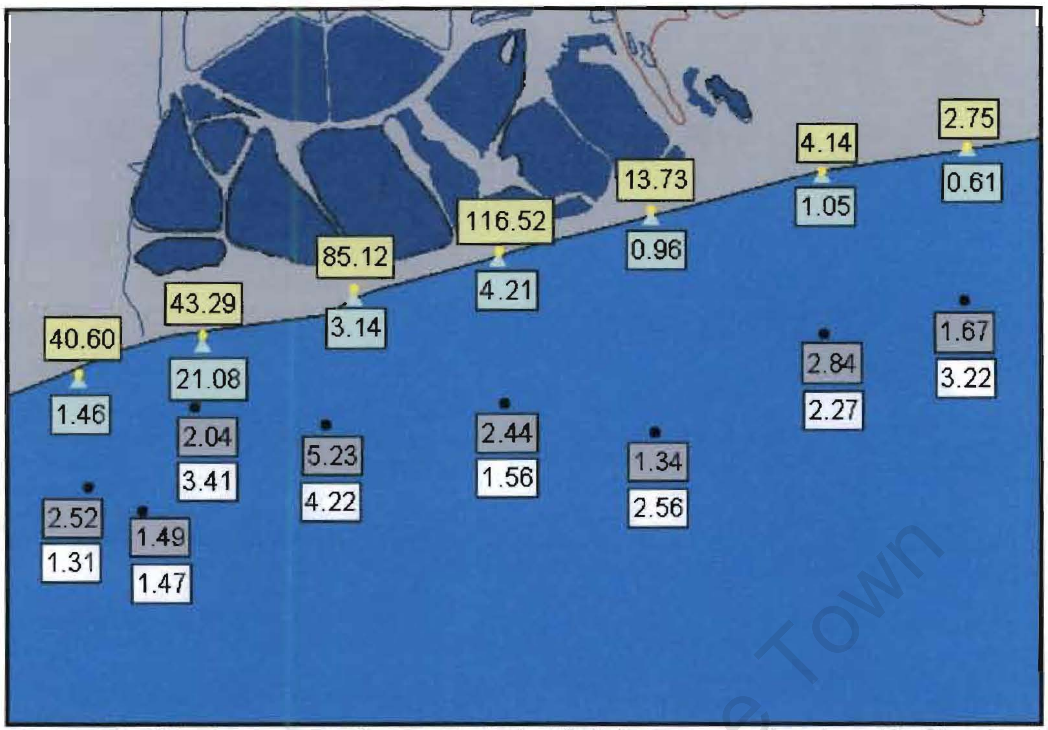


Figure 3.9: Silicate concentrations recorded at Salinity Transect One (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

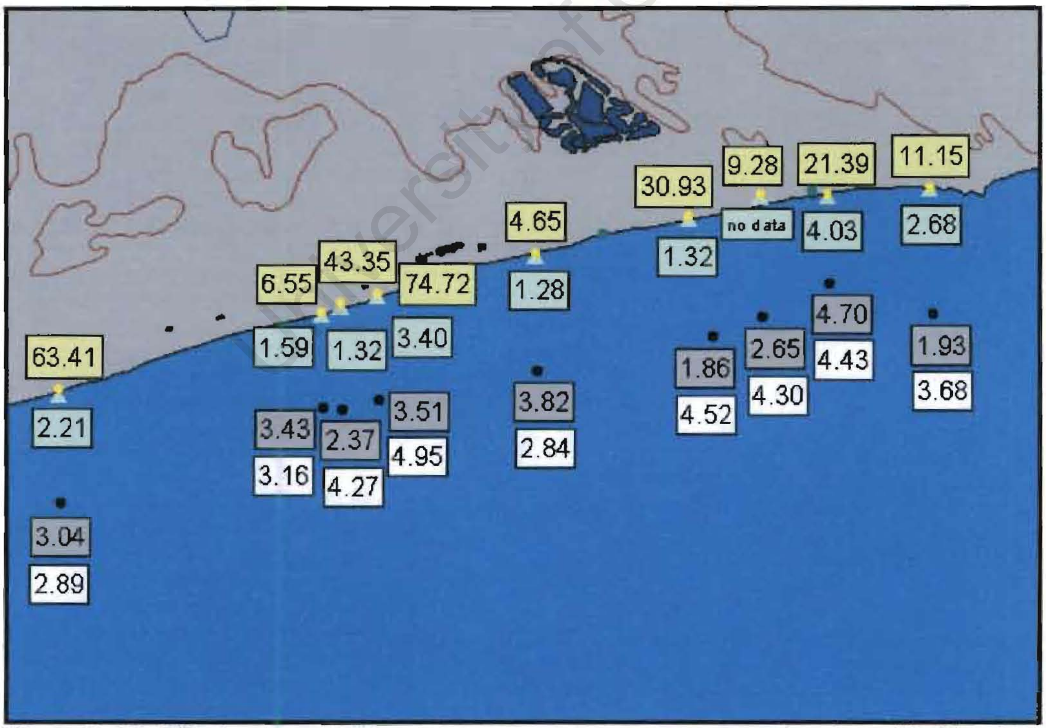


Figure 3.10: Silicate concentrations recorded at Salinity Transect Two (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

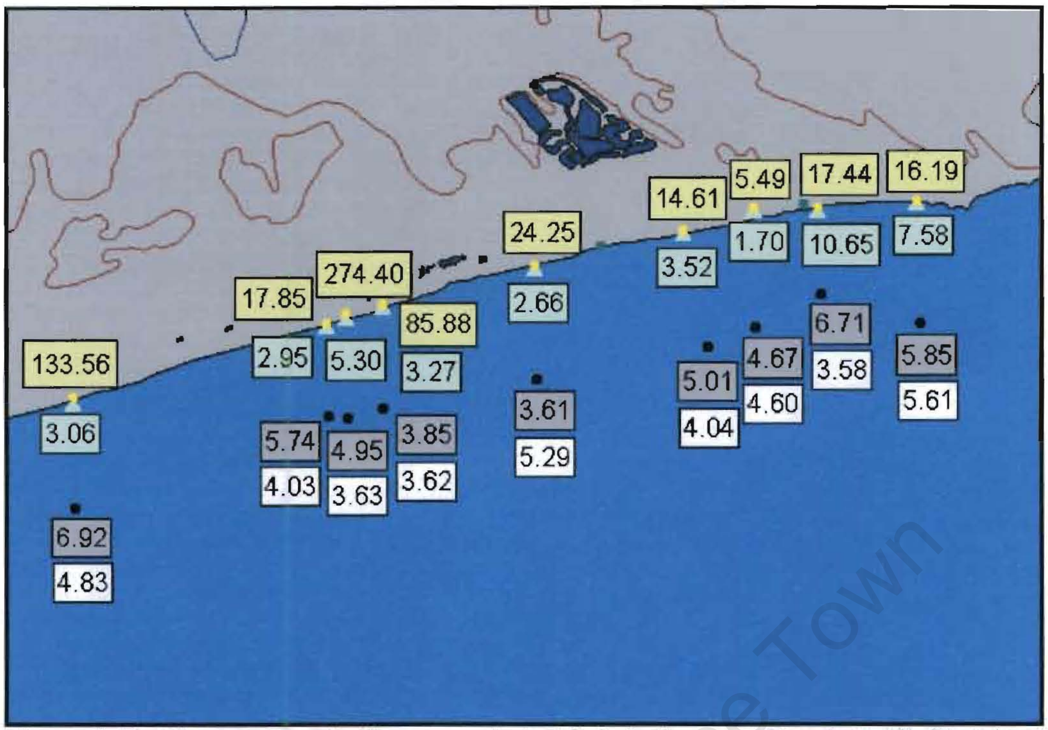


Figure 3.11: Nitrate concentrations recorded at Salinity Transect Two (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

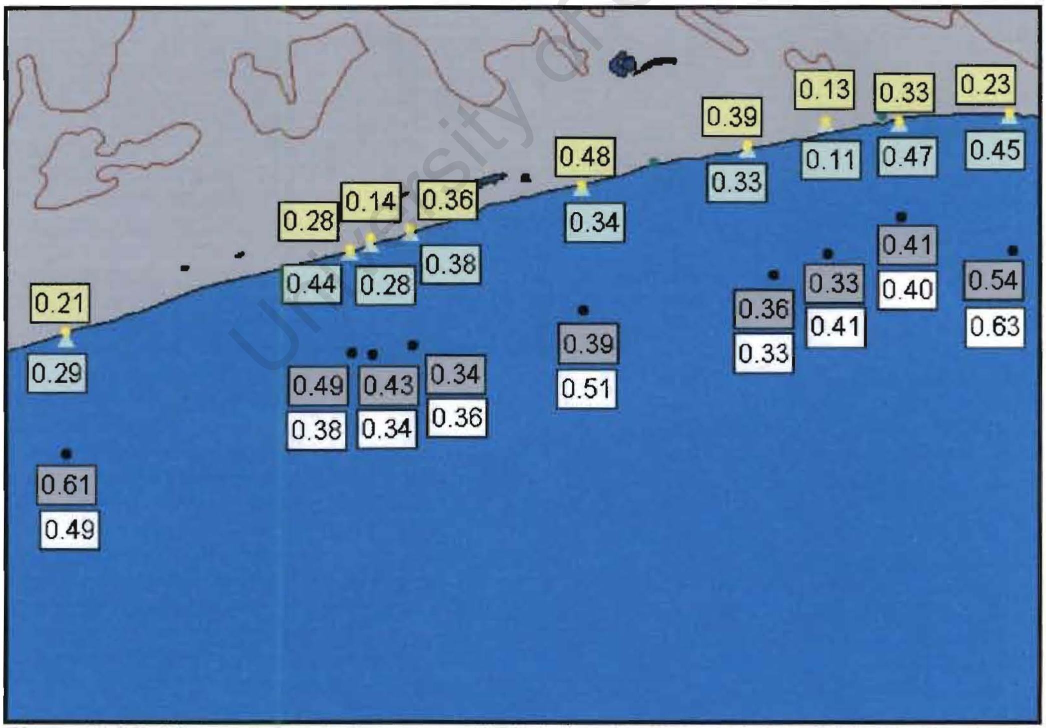


Figure 3.12: Nitrite concentrations recorded at Salinity Transect Two (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

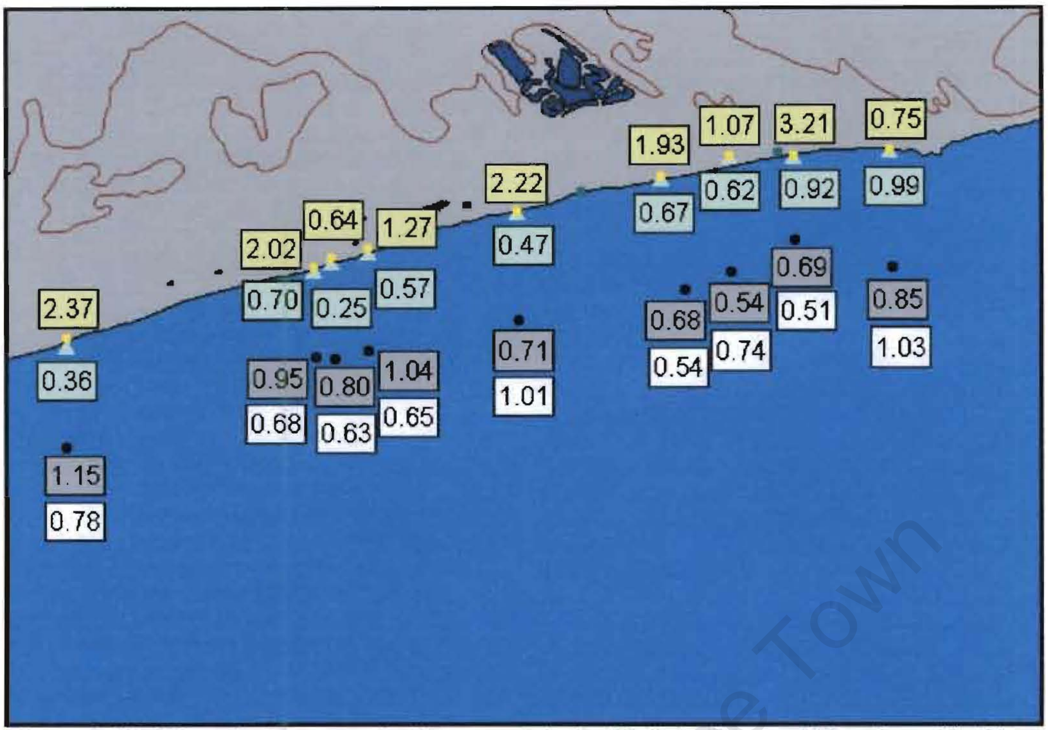


Figure 3.13: Phosphate concentrations recorded at Salinity Transect Two (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

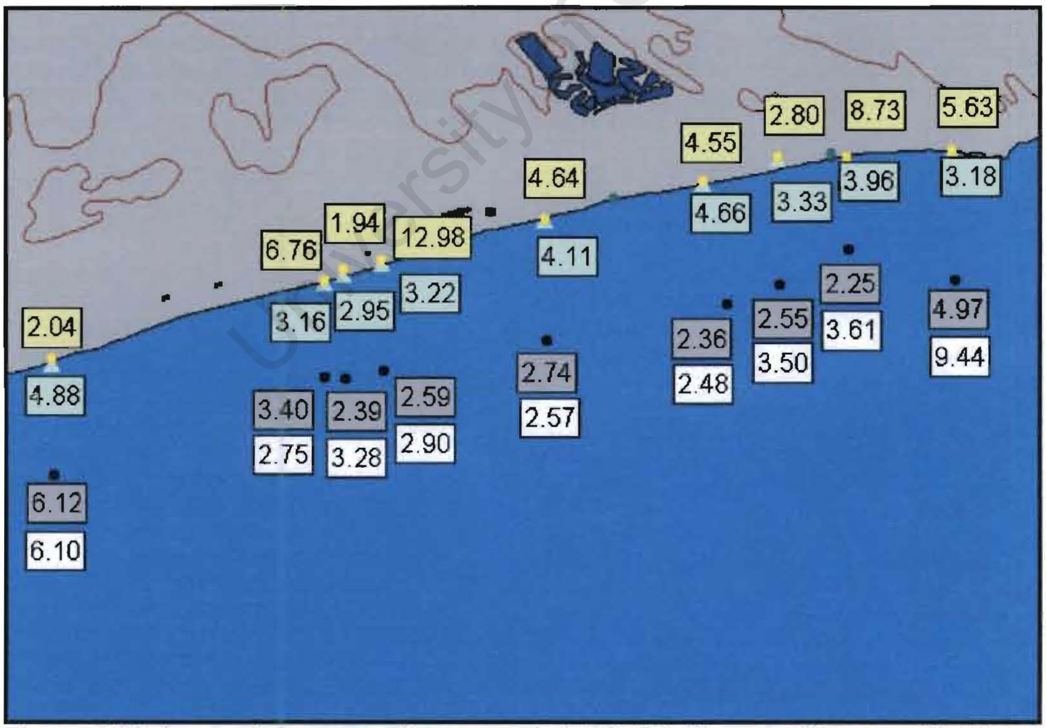


Figure 3.14: Ammonia concentrations recorded at Salinity Transect Two (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

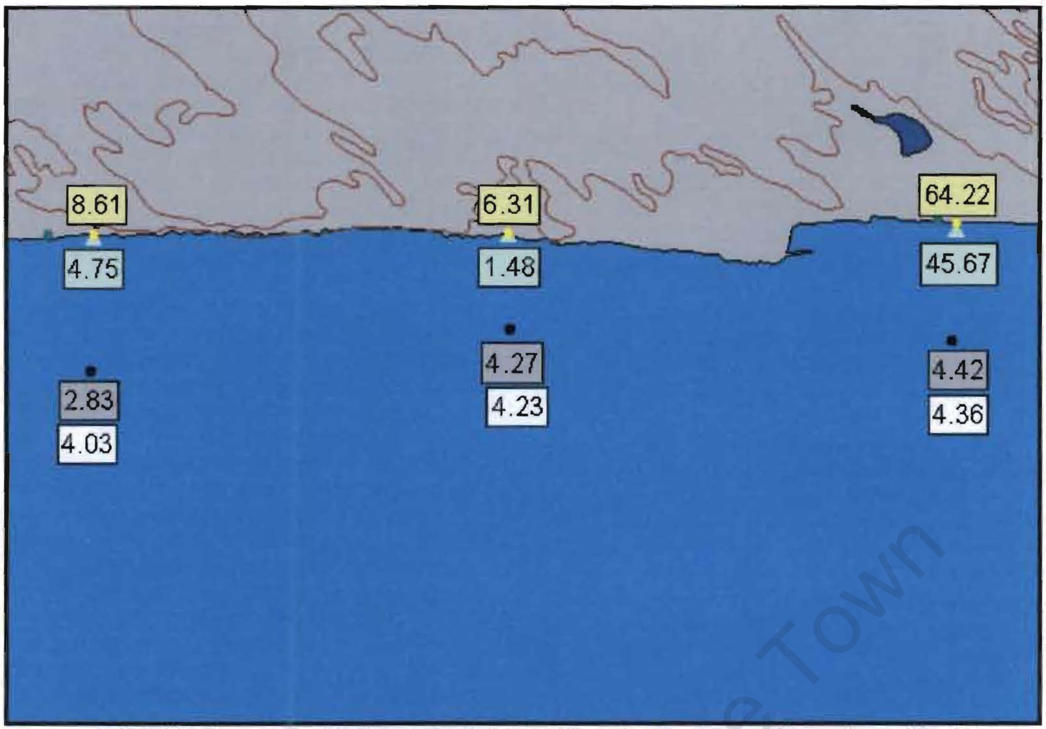


Figure 3.15: Nitrate concentrations recorded at Salinity Transect Three (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

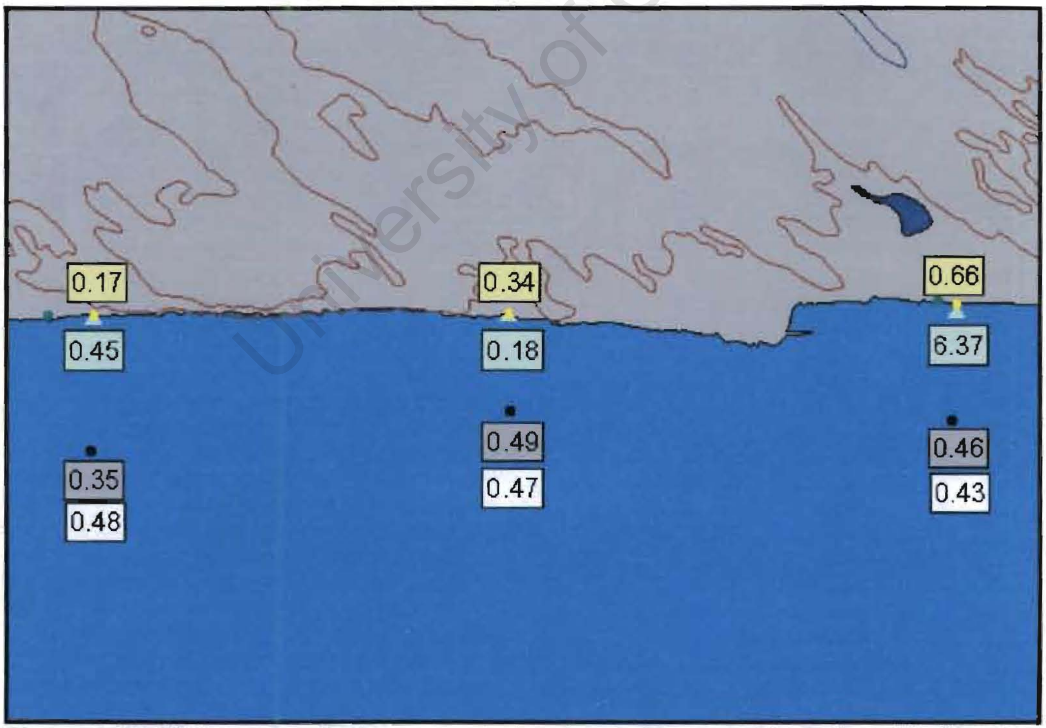


Figure 3.16: Nitrite concentrations recorded at Salinity Transect Three (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

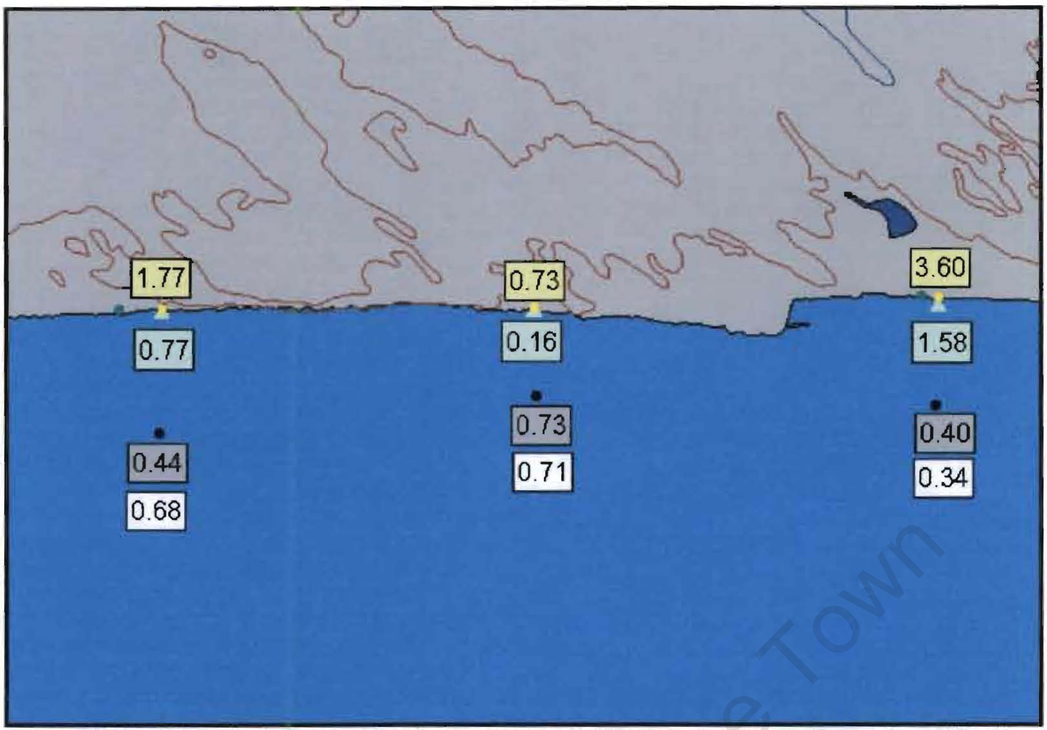


Figure 3.17: Phosphate concentrations recorded at Salinity Transect Three (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

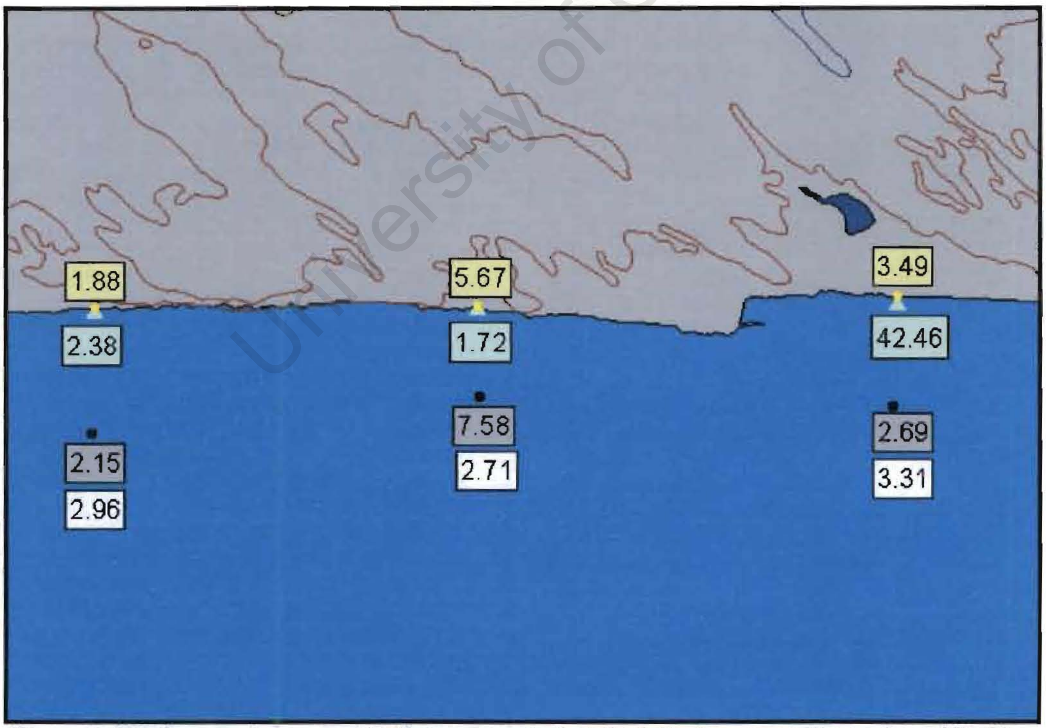


Figure 3.18: Ammonia concentrations recorded at Salinity Transect Three (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

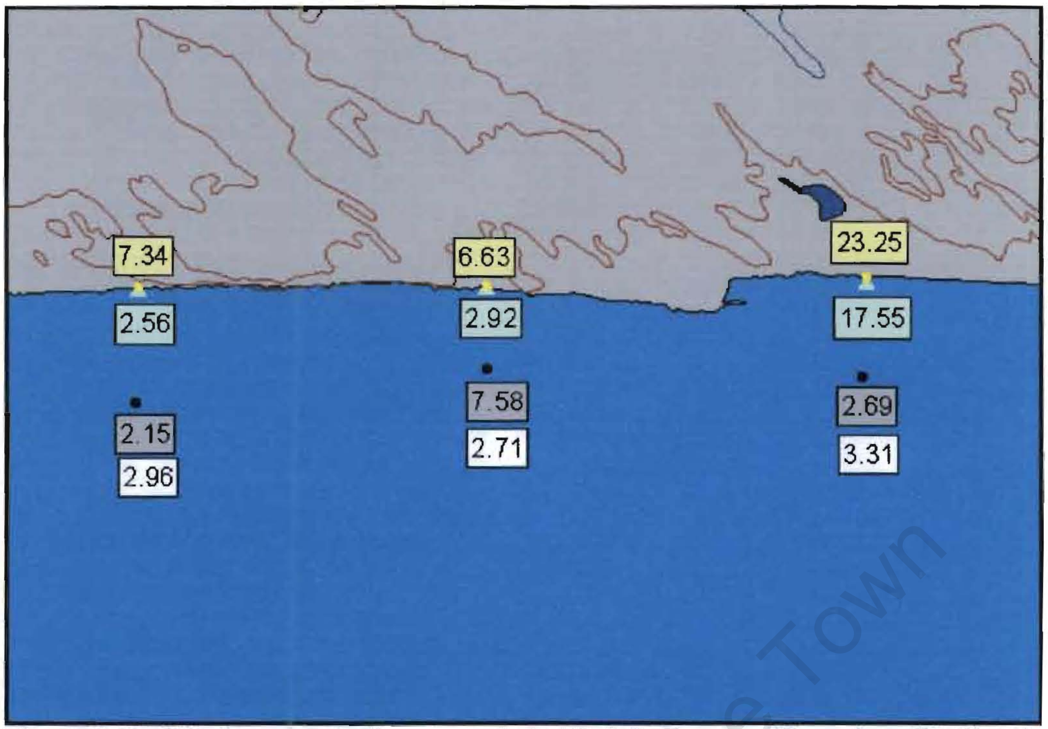


Figure 3.19: Silicate concentrations recorded at Salinity Transect Three (umol/l). Showing the concentration of the Berm samples (yellow), the Surfzone Samples (green), the Behind Surfzone Surface Samples (grey) and the Behind Surfzone Bottom Samples (white).

Figure 3.20: The Position of Previous Study Areas on the Cape Flats

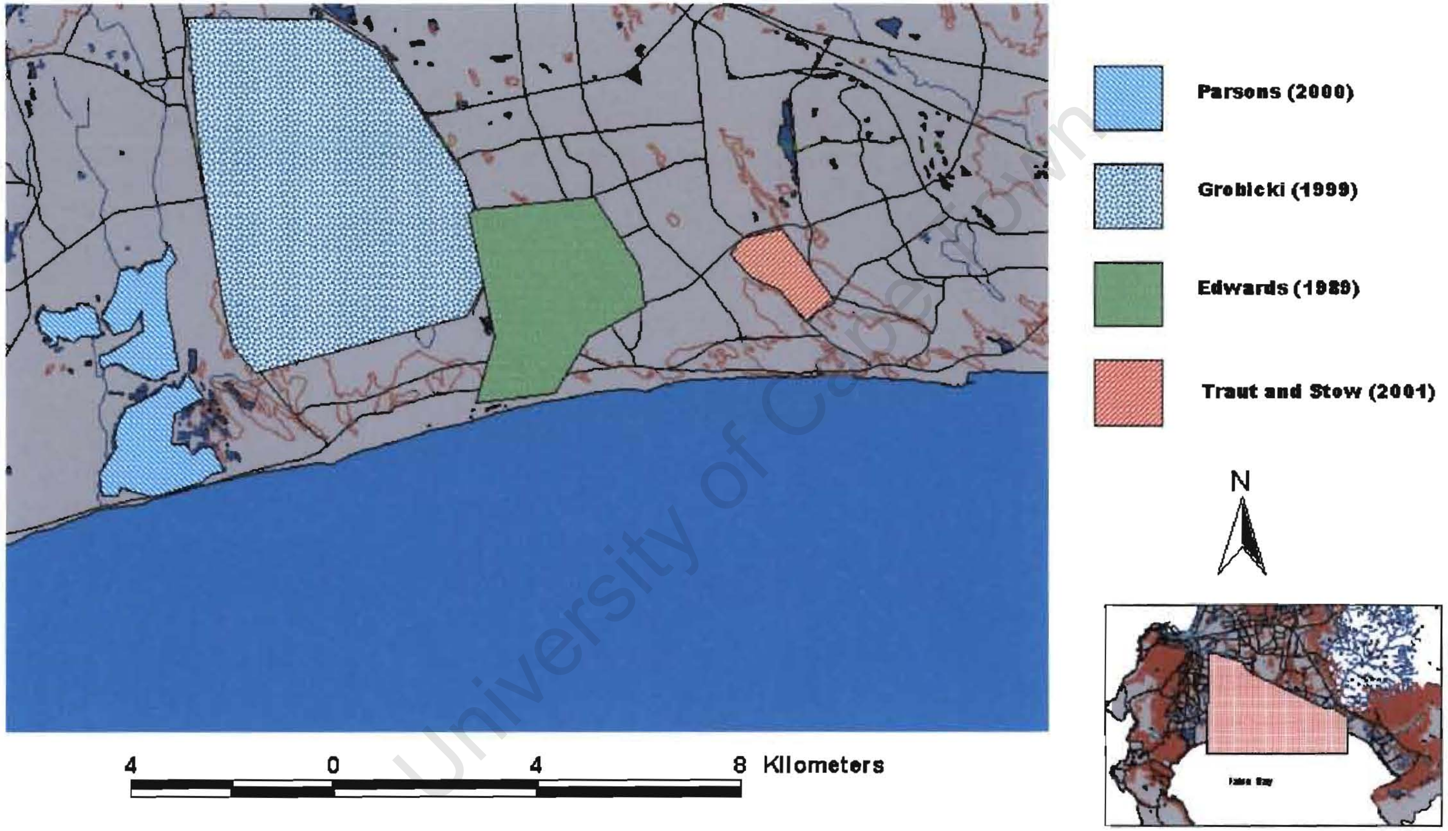
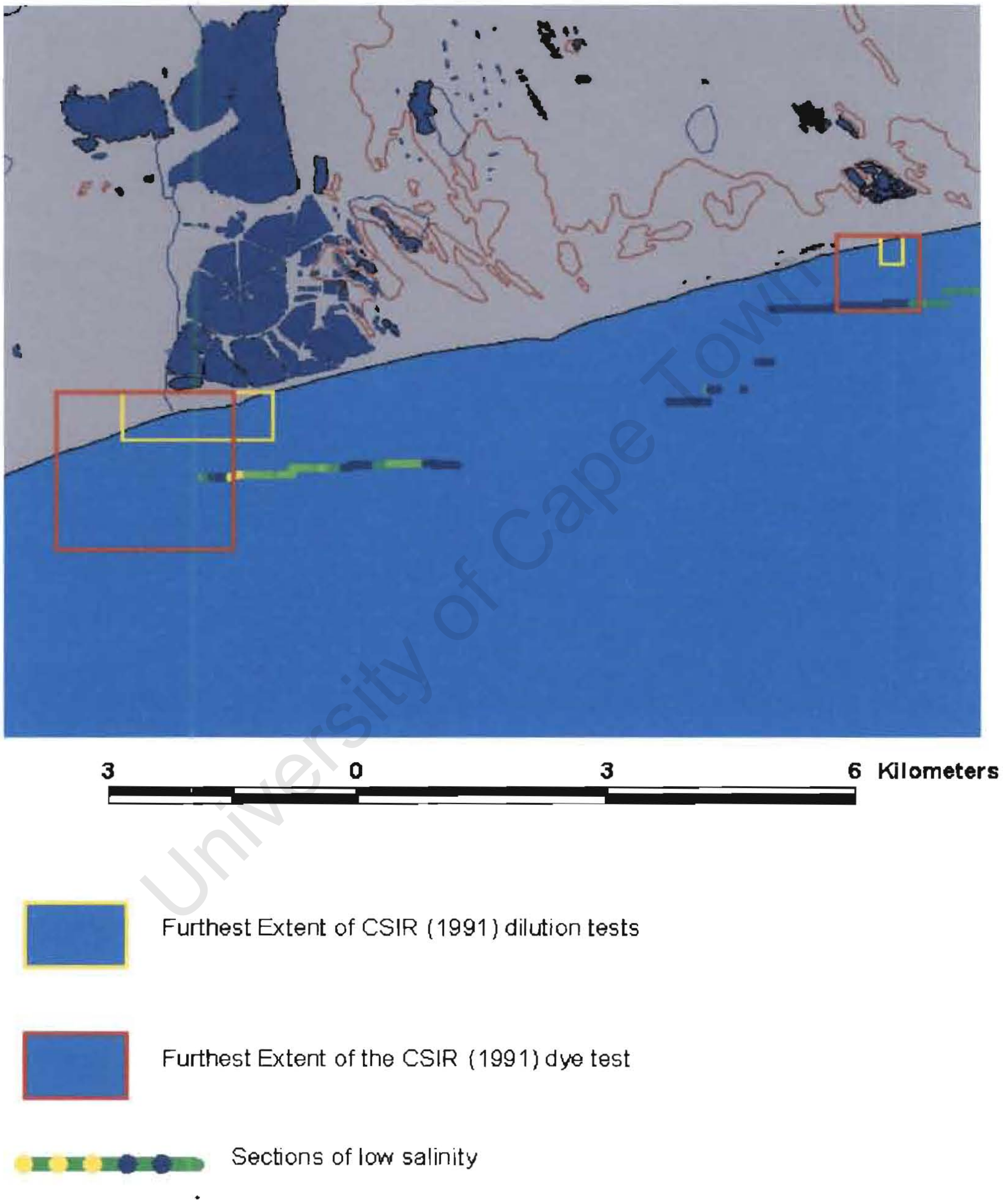


Figure 4.1: The extent of the dilution and dye tests at the Zeekoevlei and Mitchell's Plain WWTW outlets.



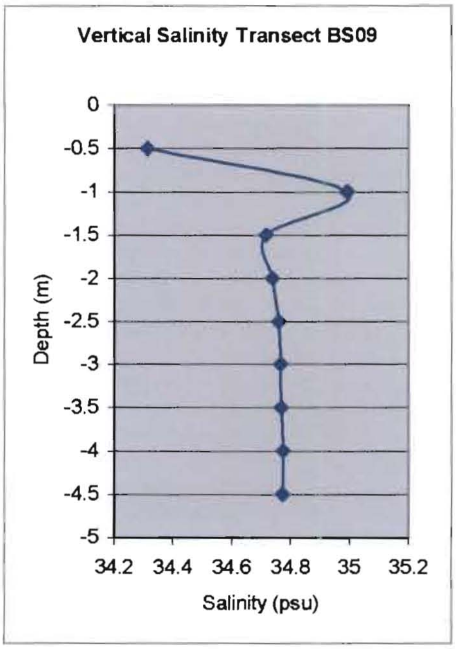


Figure 4.2: Vertical Salinity Profile at BS09

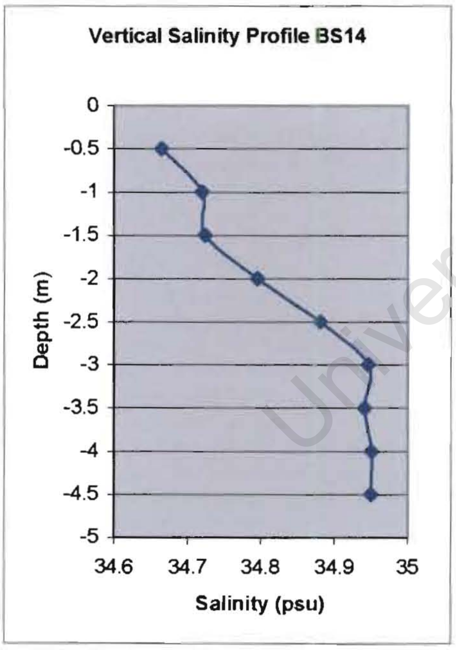


Figure 4.3: Vertical Salinity Profile at BS14

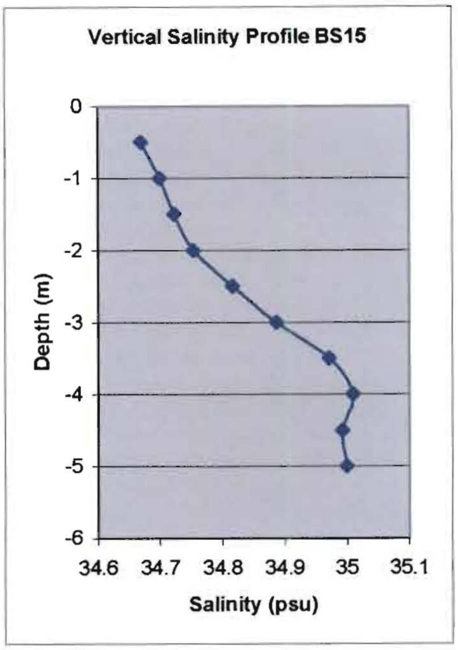


Figure 4.4: Vertical Salinity Profile at BS15

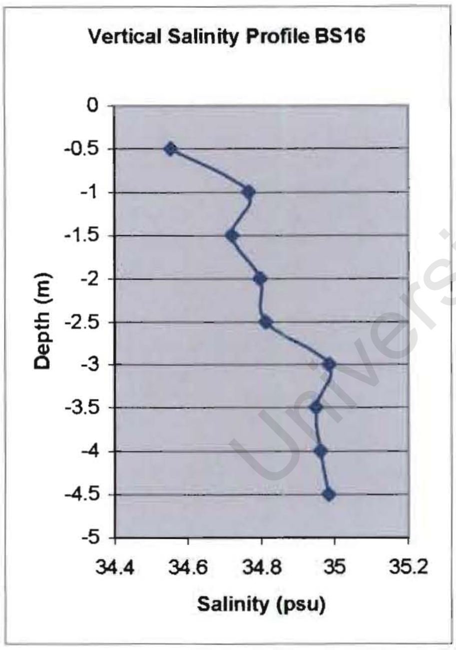


Figure 4.5: Vertical Salinity Profile at BS16