A STUDY OF THE NET FLUX OF NITRATES FROM THREE ESTUARIES OF THE ETHEKWINI MUNICIPALITY OF DURBAN, KWAZULU-NATAL

BY

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As the candidate's supervisor I have/have not approved this thesis/dissertation for submission.

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ABSTRACT

Estuaries, the interface of interaction of fluvial discharge and marine action serve as temporary repositories of materials (solid and dissolved) before finally exporting them to sea. This interchange of material is dependent on a range of factors such as tidal range, prism, and symmetry; fluvial flows and estuarine morphodynamics. The efficacy of transfer of materials to the marine environment is important for estuarine health particularly in estuaries located in highly developed areas such as the major coastal metropolitan areas of many countries. This study assesses the efficacy of the export of nitrates from three estuaries of the eThekwini Municipality of the city of Durban, South Africa which maintain an open mouth status, ensuring tidal exchange throughout the year.

The focus of this study was to determine and analyze the net flux of nitrates between the Isipingo, Mgeni, and Tongati estuaries of the eThekwini Municipality, and their adjacent nearshore environments. It questioned whether the Isipingo, Mgeni, and Tongati estuaries were efficient at exporting nitrates to their adjacent marine environments. The abovementioned estuaries are classified as temporarily open/closed estuaries, and were chosen for this study, as they maintain an open mouth status for most of the year. An open mouth condition was critical in order to conduct this study, as tidal exchange, and the resulting nitrate fluxes, could occur. The net flux of nitrates was measured for these estuaries on a seasonal basis for both spring and neap tides. Measurements were taken over the tidal cycle, ensuring that the peak high and low tides were sampled. To determine the values of net flux, the cross-sectional area of the estuary mouths were measured; average flow velocities of water were measured; and average concentrations of nitrates were obtained.

Results indicate that although there is a net export of nitrates to the nearshore environment, there were instances, particularly on the spring tide, when a net import of nitrates into the estuary occurred. The origin of the latter is likely derived from nearshore upwelling; unusually high biotic decomposition at sea and/or the longshore drift transport of decomposing sewage outfall.

This creates an added dimension for consideration in estuarine management plans. Taking all three estuaries studied into consideration, a net export of nitrates for all seasons for the eThekwini Municipality was measured with a clear seasonal influence

detected where high rainfall seasons led to greater export as a consequence of greater fluvial flows, erosion and leaching of agricultural lands and longer ebb duration.

PREFACE

The work described in this dissertation was carried out in the School of Environmental Sciences, University of KwaZulu-Natal from January 2008 to April 2011, under the supervision of Dr. Srinivasen Pillay.

This study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

DECLARATION 1 – PLAGIARISM

I, ... declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
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DECLARATION 2 – PUBLICATIONS

1. Publication 1: Fernandes, S. & Pillay, S. (In Review). A Study of The Net Flux of Nitrates From Three Estuaries Of The Ethekwini Municipality Of Durban, KwaZulu-Natal, South Africa. *Environmental Earth Science.*

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

APPENDICES

ACKNOWLEDGEMENTS

To my parents and friends – thank you for spending long hot/cold/rainy/windy days on the beaches helping me sample. Thank goodness we only heard about the crocodiles in Blue Lagoon after sampling was complete.

To Prof. Garland, Prof. Forbes, and Nicky Forbes – you are all an inspiration.

CHAPTER 1: INTRODUCTION

1.1 General Introduction

The coastal zone is a dynamic environment where the land, atmosphere and sea meet. It is where people enjoy settling, which may result in environmental degradation, as well as socio-economic degradation. Haslett (2000) states that coasts are not isolated environments, they receive and give off energy and materials, and in addition coasts are diverse making them interesting to study. It is difficult to define a beach or a coast because it is difficult to distinguish the area where the land ends and where the sea begins. Thus it is suggested that we do not refer to this area as coastlines, but rather as coastal zones, which is a "spatial zone between the sea and land" (Haslett, 2000: p3). The key reason as to why coastlines are studied is that the processes that shape the coast need to be understood, in order for appropriate management to be implemented.

Over the recent past, concern has been growing with regard to coastal problems. Sandy beaches backed by dunes and other forms of sandy topography characterize 20% of the worlds' coastlines, and the key issue according to Viles & Spencer (1995) is that 70% of these coastlines have experienced erosion over the preceding decade. Another pressing issue regarding the worlds' coastlines is that 50% of the population residing in industrialized countries live along the coastline, and this percentage is continuously growing. Populations moving to the coastline, especially to low-lying areas, results in many fatalities when natural phenomena such as tropical cyclones strike, resulting in increased concern about coastal issues.

Coastal problems are classified as natural or human-induced, and are events that affect the environment and society at the coast (Viles & Spencer, 1995). Examples of coastal problems include beach pollution, shoreline erosion, coastal flooding, and the depletion of coastal biodiversity. These issues are the result of the manner in which people interact with the coastal environment. The interaction of human and natural stressors on coastal environments is resulting in large scale damage of coasts, for example, in the United States of America, 25% of the coastline is heavily affected by erosion, costing US$300 million each year from loss of property and from building structures to try protect the coasts (Viles & Spencer, 1995). Coastal zone management is thus becoming an important tool in order to protect the world's coastlines from further damage.

Coasts attract human settlement as they are beautiful places in which to reside. This is especially the case in coastal areas which are flat and low-lying, making them suitable for agriculture and construction. Coasts act as a buffer zone between the land and sea, and this buffer zone is being developed at a rapid rate. There has always been development along coastlines – this is evident along the KwaZulu-Natal coast, where old beach towns such as Kelso and Clansthal continue to flourish. However, development along coastlines and specifically beaches and dunes, is increasing at a rapid rate.

Beaches and dunes are often chosen for recreational activities and tourism, and in addition they act as sediment stores that change in response to varying conditions of erosion and deposition. Dunes (with their natural vegetation intact) act as a buffer to the sea, and are a vitally important feature of beaches. Unfortunately, the development of dunes involves the removal of dune vegetation, and therefore they lose their function as natural sea defences, resulting in erosion (Breetzke *et al*., 2008). Erosion and deposition are two coastal processes that continuously take place in order for beaches to reach a state of equilibrium; however, increased development along beaches coupled with sea level rise, are rapidly increasing erosion (Breetzke *et al*., 2008; Davis Jr. and FitzGerald, 2004; Komar, 1976). Estuaries are also becoming negatively impacted due to human interference and development (Frick *et al*., 2007).

An estuary is an area where fresh and salt water meet; can either be closed to the sea or open depending on environmental conditions; and estuaries are considered to be some of the most productive ecosystems on earth (Dyer, 1973; Paerl, 2005). Estuarine environments are commonly used for recreation, industrial development, agriculture, and are also popular for residential development. Within the South African context, estuary mouths may be open to the sea, or closed by barriers for part of, or throughout the year depending on their characteristics and prevailing environmental conditions. Some, such as Kosi Bay in the far north-east of South Africa, are little affected anthropogenically, and thus retains an almost pristine character. The most severely impacted estuaries have catchments that are heavily developed such as those lying within the Durban Municipality (known as the eThekwini Municipality) of the province of KwaZulu-Natal, on the eastern seaboard of South Africa. In the case of the eThekwini Municipality, which is the largest urban developed area on the eastern seaboard of South Africa, the major degradation problem is that of pollution of the estuarine waters and the subsequent threat to aquatic biota. In fact, many estuaries in the eThekwini Municipality are no longer fit for recreation due to their highly polluted waters (Hatton, 1990; Kalicharran and Diab, 1993; South Durban Community Environmental Alliance, 2004).

Water, on the other hand, is an essential element for all forms of life – not many living organisms can survive without water. Not only is the supply and quantity of water important, but it has been argued that the quality of water is more important than the quantity of water. Tchobanoglous and Schroeder (1987) states that water must have certain characteristics, and water quality is defined by these characteristics.

Historically, the most studied water characteristic was the concentration of dissolved solids, or salts, due to the fact that there is a relationship between salts and land productivity. Over time, there has been an increase in population density globally, and as a result, the study of pathogenic or disease-causing bacteria in water has become an important water characteristic to research (Tchobanoglous and Schroeder, 1987). Obviously this is due to the fact that the chances of disease contaminating water resources are higher when there is a higher population density, which has an effect on human health. As time has moved on, industrial development has increased significantly, and so water characteristics such as temperature and ion content have become important characteristics to monitor (Tchobanoglous and Schroeder, 1987). However, the most recent problem is the introduction of manufactured chemicals into our water systems. These chemicals, whether they occur in low concentrations or not, have a great impact on human health. Therefore, different land uses and activities have different impacts on our water sources. Clearly, if activities in a watershed or along a river system are contaminating that system, then the estuary downstream will be impacted. One of the key elements that can contaminate estuaries are nutrients, specifically nitrates, which, in abundance, can become problematic in the estuarine environment.

Nitrates fall under the category “nutrients”. Nutrients are vital elements, and are required for plant growth, and they include carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphate, as well as silica. These examples are termed macronutrients, while micronutrients are required in smaller quantities (Dallas and Day, 2004). Nitrogen occurs abundantly in the environment, and it is an essential constituent of proteins – it is therefore a major component of all living organisms. Inorganic nitrogen may be present in many forms in both polluted and unpolluted water, but the forms that are most commonly tested regarding water quality are ammonia, ammonium, nitrites and nitrates – the latter being the focus of this study.

Numerous studies have attempted to quantify the pollution status of estuaries and other coastal water bodies (Brownlie, 1988; Binning and Baird, 2001; Buggy and Tobin, 2008; Chen and Kandasamy, 2008) and the range of contaminants studied is impressive. Lately, much research has focused on heavy metal contamination of sediments and waters of these aquatic environments (Buggy and Tobin, 2008; Kandasamy, 2008; Ram *et al.*, 2009). However, little emphasis has been placed on the fate of contaminants accumulated in estuaries and notably, the exchange of contaminants with the adjacent marine environment. Often, the presumption implied is that contaminant concentrations measured within estuaries also represent their exchange amounts with the adjacent nearshore environment. However, such exchanges are difficult to quantify since this involves quantifying the total contaminant transport through complete tidal cycles. The net exchange of any particular contaminant is usually the transport difference between two large values: the flood and ebb transports. Difficulties in measuring flood and ebb transports at the estuary mouth arise as a consequence of the continuous change in water levels with time, as well as the reversal in flow direction when flood changes to ebb. Furthermore, flow velocities change continuously through individual flood and ebb events of tidal cycles, which themselves may be of unequal duration. Other complications arise through tidal and seasonal variations.

Within estuaries themselves, physio-chemical conditions may induce a number of interactions that may concentrate contaminants in the water column, cause temporary sequestration, or simply flush material out of the system in the course of strong fluvial flows following heavy precipitation in the catchment hinterland.

1.2 Motivation for the Study

Some of KwaZulu-Natal's estuaries, such as the Durban embayment and the Mgeni estuary, are regularly tested for pollutants (for example by Umgeni Water), as they are highly impacted systems that are used for recreational and industrial activities. However, for reasons outlined above, no previous study in the region has focused on the net flux or exchange of pollutants between the estuarine and the marine environment. This study therefore represents the first attempt at quantifying the net flux of material in estuaries of this region. Given the importance of the eThekwini

Municipality as a major developed region within the province of KwaZulu-Natal, and that several river systems traverse this area, three estuaries within it, namely the Mgeni, Isipingo, and Tongati estuaries have been chosen as the focus of this study.

The reasons why these estuaries were chosen for this study are that they form part of the total drainage system of the eThekwini Municipality, a highly developed region of Southern Africa. Furthermore it was necessary to conduct this study in estuaries that remain open to the sea for most of the year, in order to quantify the exchange of nitrates between the estuarine and marine environment. The Tongati, Isipingo, and Mgeni estuaries all fit this requirement. With the exception of the Isipingo estuary, these estuaries can of course close during the year as a result of low riverine discharge; however closure of these systems is rare, and they are still classified as temporarily open/closed estuaries. Estuaries that remain closed during most of the year, such as the Mhlanga, Mdloti, and Mvoti estuaries, were therefore not appropriate estuaries for this study.

Chemical nutrients are a major pollutant of estuaries. Whilst there are several such nutrients, those emanating from both natural and anthropogenic sources (agriculture and industry) and from faecal pollution, such as nitrates, readily accumulate and become problematic in aquatic systems.

In assessing estuarine health status or the degree of pollution in estuaries, this type of research is vital. Thus, to summarise, there has been no attempt to quantify the exchange of nitrates between the estuarine and nearshore environment in any of KwaZulu-Natal's estuaries. There are, therefore, gaps in knowledge about this process which provides the motivation for this study. Such information would provide valuable baseline data for management of these sensitive environments.

1.3 Aim and Objectives

1.3.1 Aim of the Study

This research aims to quantify the flux of nitrates between each of the three dominantly opened estuaries of the eThekwini Municipality and their adjacent marine environments: the Isipingo, Mgeni, and Tongati estuaries; and to ascertain the implications of these transfers.

1.3.2 Objectives of the Study

The objectives of this research are as follows:

1. At each site, to measure, at predetermined intervals, the parameters required to facilitate quantification of net nitrate fluxes: cross-sectional area flow, flow velocity and direction, and nitrate concentrations;
2. To use this data to determine the instantaneous nitrate flux and the total nitrate flux over ebb and flood components of the tidal cycle; and
3. To obtain the net flux as a difference of the ebb and flood flows i.e. to assess the efficacy of the system in exporting nitrates to the nearshore environment.

1.4 Outline of the Thesis

The remainder of this thesis may be outlined as follows:

Chapter 2: THEORETICAL FRAMWORK
This chapter provides a general understanding of estuarine characteristics, particularly tidal currents, the classification of estuaries, as well as some hydrological characteristics of estuaries, which was required as background for this research. Chapter 2 also includes literature on nitrates and the typical sources thereof, and the consequences of nitrate enrichment are explored.

Chapter 3: REGIONAL SETTING
This chapter describes the regional setting of KwaZulu-Natal in general, as well as the three estuaries focused on in this study. Land uses surrounding the estuaries are identified with the aid of ©Google Earth satellite images.

Chapter 4: METHODOLOGY
Water levels, flow rates, and nitrate concentrations are the three main aspects of the methodology that were adopted for this study. This chapter provides a description of the techniques used to measure these parameters in the field and the methods used to analyze the data.

Chapter 5: RESULTS

The results of the field work are outlined in this chapter. Tables and graphs are provided to aid in determining whether the estuaries are efficient at exporting nitrates to the nearshore environment. This chapter addresses the aim of this study.

Chapter 6: DISCUSSION

This chapter presents a detailed discussion and explanation for the results presented in Chapter 5. The use of tables, photographs and satellite images aid in the discussion of the results. An overall assessment of nitrate contribution from the estuaries studied to the nearshore environment of the eThekwini Municipality is also discussed.

Chapter 7: CONCLUSION AND RECOMMENDATIONS

Finally, conclusions concerning the key questions outlined in the objectives of this study are summarised. Additionally, recommendations in light of this study are provided.

1.5 Conclusion

This study focuses on attaining quantitative values for the net flux of nitrates between the Mgeni, Isipingo, and Tongati estuaries and their adjacent nearshore environments. These estuaries were chosen for this study due to the fact that they remain open to the sea for the majority of the year – an essential component for researching fluxes. The question of whether these estuaries are effective at exporting nitrates to the nearshore environment will be answered, and the associated impacts to the estuarine environment will be assessed in this study.

CHAPTER 2: THEORETICAL FRAMEWORK

2.1 Introduction

Estuaries are very important assets of coastlines, socially and economically, and KwaZulu-Natal is home to 72 estuaries, more than any other province in South Africa (Begg, 1984). Estuarine environments are studied and researched so that the processes that shape them can be understood, which enables appropriate management to be implemented. However, estuaries are heavily impacted by activities that occur upstream, as well as in the vicinity of the estuary itself, especially by pollution that emanates from a variety of sources, both natural and anthropogenic. Amongst the myriad of pollution sources and types, an important pollutant is nitrates. In this chapter, the main concept of the coastal phenomenon tides will be explored; estuaries and their importance will be discussed; and nitrates and their associated impacts on the estuarine environment will be explained.

Whilst this study focuses on the flux of nitrates at selected estuaries and does not attempt to quantify or identify study area catchment sources, it is important to contextualize nitrates as a pollutant in general in terms of likely sources, characteristics and impacts on estuarine environments. Since this information is related to the focus of this study, they are addressed in this chapter.

2.2 Tides

Many peoples' lives revolve around the tides. Whether it is commercial fishermen who plan their day around the low and high tides; a person who pumps for prawns or searches for mussels at low tide; or a ship entering a harbour during the ebb tide. These motions of rising high tide and lowering low tide are some of the major and important movements that takes place on our Earth, and has a direct impact on our shorelines and coasts (Davis Jr. and FitzGerald, 2004). If tides did not exist, there would be an absence of natural harbours such as the Durban and Richards Bay, or tidal inlets.

Tides are a "manifestation of the Moon's and the Sun's force of the gravity acting on the Earth's hydrosphere, as well as the relative orbits of these celestial bodies" (Davis Jr. and FitzGerald, 2004, p189). In other words, tides are the gravitational pull that is caused by the alignment of the Earth, sun, and moon. In order to understand this, it is important to understand how the different phases of the moon associates with the position of the earth, the moon, and the sun. When the earth, sun, and moon are aligned (known as syzygy), new and full moons are the result. A new moon occurs when the moon is situated between the Earth and the sun, while a full moon occurs when the moon and the sun are situated on the opposite sides of the Earth (Davis Jr. and FitzGerald, 2004). When the moon forms a right angle with the sun and the Earth (known as the quadratic position) the well-known crescent shape moon is visible, and this occurs during the moon's first and third quarters. Over 29.5 days, the moon will have gone through all these phases (Davis Jr. and FitzGerald, 2004).

During the periods of the full and new moons (when the moon, Earth and sun are aligned), the gravitational force produced on the Earth's hydrosphere is at its greatest, because the forces are acting in the same direction, creating a cumulative effect (Davis Jr. and FitzGerald). The sun and moon act together to produce this strong pull (SANHO, 2008). This results in a spring tide, which is characterized by very high flood tides and very low ebb tides i.e. the maximum tidal range is experienced. When the moon is at its quadratic phase, its pull on the Earth is partially counteracted by the sun, therefore there is less gravitational pull. The result is a neap tide, which produces low high tides and high low tides – i.e. the minimum tidal range is experienced. The average tidal range is when the Earth, moon and sun are situated in positions between the syzygy and quadratic phases; this is called the mean tide (Davis Jr. and FitzGerald, 2004).

In South Africa, semi-diurnal tides are experienced, which means that two high tides and two low tides occur every day. The tidal range is small, meaning that the range between high tide and low tide is not more than two meters (referred to as microtidal). This is due to the fact that the coastline, particularly that of KwaZulu-Natal is fairly straight. Furthermore, it is important to remember that non-gravitational factors such as wind, air pressure and wave climate also have a large influence on the sea level (Whitfield and Bate, 2007).

It is important that tides are briefly discussed, as for this study it was important to understand tidal currents. Tidal currents are the result of water rising and falling with the tides; they are vitally important as they play a major role in sediment transportation (Haslett, 2000). Tides act just like waves – the only difference is that they are much longer than waves. When a tide reaches a shallow depth or is constricted, such as at an entrance to a harbour or estuary, a tidal current is produced. A flood tidal current occurs when water flows into a tidal inlet and floods an estuary, while an ebb tidal current occurs when water is discharged out of an estuary and back into the sea. Slackwater occurs at low and high tide and takes place when the level of the water inside an estuary and out in the ocean is equal (Davis Jr. and FitzGerald, 2004). During the period of midtide (between the low and high tide) the velocity of water flooding or leaving the estuary is at its strongest.

2.3 Estuaries

An estuary is a "semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Pritchard in Head, 1985, p2). Estuaries are highly variable and dynamic in nature, resulting in many arguments over how estuaries should be defined.

There are various types of estuaries. Sea level rise may causing river valleys to become flooded and ultimately drowned by the sea. If the valley becomes an estuary it is called a ria, and all the characteristics of a river will remain, such as meanders and tributaries (Haslett, 2000). A fjord is a ria that contains a glaciated river valley. In both rias and fjords, the rate of sea level rise is greater than sediment deposition in the drowned valley, resulting in the sides of the former valley determining the estuary morphology, and an open-ended estuary mouth. If sediment supply is high and the rate of sediment deposition is equal to that of sea level rise, depositional features such as salt marshes at the margins of the estuary will occur. Salt marshes narrow the tidal channel (Haslett, 2000). If sediment deposition is very high, a spit may be produced by waves and the longshore drift current, which may partially block the estuary mouth to become a bar-built or partially-closed estuary.

From the above, it can be seen that the different types of estuaries, and where they occur, could become confusing. Therefore, much effort has been spent over the years attempting to classify estuaries. Two methods of estuarine classification will be discussed: firstly, classifying estuaries according to fresh and salt water interaction; and secondly, classifying estuaries according to how long they remain open or closed.

2.3.1 Mixing in Estuaries

The degree of mixing of salt and fresh water in estuaries is one of the most common methods of classifying estuaries. There are two different flows that occur in an estuary: salt water from the ocean that enters an estuary on the flood tide, and fresh water input from the river that drains into the estuary. Salt water is denser than fresh water and slides underneath the fresh water as it enters an estuary, creating a salt wedge (Allanson and Baird, 1999; Davis Jr. and FitzGerald, 2004; Haslett, 2000; Head, 1985).

There are three types of circulation conditions in estuaries outlined by Davis Jr. and FitzGerald (2004) namely stratified, partially mixed, and well mixed circulations. A stratified estuary is one where there is minimal mixing of salt and fresh water. A very distinct separation of salt and fresh water commonly occurs. For example, the salt wedge in the Hudson River estuary extends tens of kilometers upstream. The lack of mixing in the estuary could result from a lack of strong tidal currents, or from low wave energy. A partially mixed estuary is one where there is some mixing of salt and fresh water. This is often the case in most estuaries. Tidal currents influence these estuaries (although not essential), and there is a significant intensity of wave energy to enable mixing. Finally, a well mixed estuary experiences complete mixing to produce a vertically homogenized water column, and is characterized by brackish waters. These estuaries are the result of very strong tidal currents, or the occurrence of waves in shallow estuaries (Davis Jr. and FitzGerald, 2004). Importantly, tidal currents and residence time in estuaries play an important role in nutrient availability (Bouvy *et al.*, 2010).

It is uncommon for the ebb and flood tidal currents in estuaries to completely balance and cancel. Instead, there is a slight imbalance so that the current produces a residual upstream or downstream current, referred to as the non-tidal “net drift”, or simply residual current (Bowers and Al-Barakati, 1997). Typically, these currents are slow but persistent, and are the result of the interaction between river flow, wind and the tide. Residual currents consist of a fresh, shallow outward flow that is almost balanced by a salty inward flow (Cheng *et al.*, 2010; Sylaios and Boxall, 1998). Residual currents play a role in the longitudinal mixing processes as described above, which have a major impact on water quality.

Estuaries can change from one type of mixed estuary to another, for example from a partially mixed estuary to a well mixed estuary. This would depend on external factors such as wave climate, topography, and seasonal variations in climate and runoff.

2.3.2 Opening and Closing of Estuaries

In South Africa, estuaries are classified according to the length of time that they remain open to the sea. According to this classification, estuaries can be classified as estuarine lakes, estuarine bays, river mouths, permanently open, and temporarily open/closed. The different types of estuaries will now be briefly explained.

Estuarine lakes such as Kosi Bay and St. Lucia (refer to Figures 2.1 and 2.2) are coastal lakes that are connected to the sea via a channel, and they can be permanently or temporarily open (Breen and McKenzie, 2001; Whitfield and Bate, 2007). The salinity in these lakes varies over time, and is dependent on the amount of freshwater and salt water entering the lake as well as the amount of evaporation taking place.

Figure 2.1: Aerial photograph showing the Kosi Bay estuarine lake (CERM, 2009)

Figure 2.2: Aerial photograph showing the St. Lucia estuary (CERM, 2009).

Estuarine bays such as Durban (refer to Figure 2.3) and Richards Bay are estuaries with wide mouths, with tidal exchanges significant enough to maintain a permanently open mouth. Thus estuarine bays are tidally-dominated features (Whitfield and Bate, 2007). Human interference such as dredging has made it possible for large ships to enter these harbours when there is excessive sedimentation at the mouth.

Figure 2.3: Aerial photograph showing the Durban Harbour (Forbes & Demetriades, 2008).

River mouths such as the Tugela and the Mvoti (refer to Figures 2.4 and 2.5) are commonly permanently open estuaries, where river discharge is the dominant influence. In these estuaries, salt and freshwater mixing upstream is uncommon as the river flow is too strong, thus exporting any incoming marine flow back towards the sea (Breen and McKenzie, 2001; Whitfield and Bate, 2007).

Figure 2.4: Aerial photograph showing the Tugela river mouth (CERM, 2009).

Figure 2. 5: Aerial photograph showing the Mvoti estuary (CERM, 2009).

Permanently open estuaries such as the Mgeni (refer to Figure 2.6) and Mkhomazi (refer to Figure 2.7) are large systems that contain a perennial river and/or a strong tidal exchange. When the river flow is low, the tidal exchange is sufficient enough to keep the mouth open. The sea is the dominant influence in permanently open estuaries, however the river can have a large influence when it is in flood. During periods of very low flow, these systems can close (the Mgeni has been known to close).

Figure 2.6: Aerial photograph showing the Mgeni estuary (Forbes & Demetriades, 2008).

Figure 2.7: Aerial photograph showing the Mkhomazi estuary (Forbes & Demetriades, 2008).

Finally, temporarily open/closed estuaries such as the Mpenjati (refer to Figure 2.8) and Zinkwazi (refer to Figure 2.9) make up 70% of South Africa's estuaries, and are characterized by small catchments, sandbars, and limited tidal exchange and penetration upstream (Whitfield and Bate, 2007). The cumulative effect of river flow and tidal exchange are insufficient to maintain an open mouth, however, during very high seas marine water can break over the sandbar and into the estuary (overwash). A number of temporarily open/closed estuaries are closed for most of the year, and are usually only opened after high rainfall when the river is in flood.

It is important to note that there is a continuum across these estuaries ranges with different influences, meaning that estuaries can either be tide-dominated or wave dominated.

Figure 2.8: Aerial photograph showing the Mpenjati estuary (CERM, 2009).

Figure 2.9: Aerial photograph showing the Zinkwazi estuary (CERM, 2009).

Tide-dominated estuaries occur along macrotidal coastlines with low wave energy, where tidal influences are significant enough to maintain an open mouth. In such cases, tidal influences dominate marine influences, thus these estuaries are characterized by a large tidal prism. Due to the fact that tide-dominated estuaries occur along macrotidal coastlines, they are not commonly found along the KwaZulu-Natal coastline.

Wave-dominated estuaries are found along microtidal coastlines that do not have strong tidal currents. Marine influences dominate tidal influences, resulting in small tidal prisms. These estuaries are influenced by high wave energies, which deposit sediment forming a barrier or spit across the mouth (Whitfield and Bate, 2007). The estuaries occurring along the KwaZulu-Natal coastline are commonly wave-dominated, partially mixed, and temporarily open/closed.

In contrast to the abovementioned estuaries, closed estuaries are formed due to estuarine water levels being higher than that of the open sea , which in turn is related to the height of the berm crest of the barriers that enclose these estuaries. Closed estuaries are subdivided into perched and non-perched estuaries. Perched closed estuaries, such as the Mhlanga estuary, are characterized by the presence of a course grained barrier sediment and relatively low wave energy. Water is impounded behind the barrier at elevations higher than that of most high tides (Cooper, 2001). Non-perched closed estuaries are not characterized by a high berm, however they are impounded close to high tide levels. The beaches fronting these systems typically contain wide surf zones and low gradient profiles. Wave (barrier) overwash is dominant in these systems, resulting in non-perched closed estuaries becoming saline.

Now that the classification of estuaries has been outlined, the different estuarine processes that take place will be discussed. If one is to have a general understanding of how estuaries function and how different activities impact them, it is necessary to understand the various chemical and biological processes that drive production.

2.3.3 Chemical and Biological Processes in Estuaries

The physical and chemical characteristics of an estuary are vitally important as they enable estuarine environments to support plants and animals. There are no chemical processes that are unique to specific estuaries. Estuarine chemistry is dependent on the way in which chemicals processed are maintained and changed in estuarine environments (Head, 1985). As mentioned above, estuaries show signs of mixing of fresh water that is brought into the estuaries by rivers, and salt water that is brought into estuaries by the sea. In addition to water, rivers transport material derived from the catchment, and the sea imports materials derived from the ocean into the estuary. The growth, death and decomposition of estuary-dwelling organisms adds to this mix, and this material is either trapped in the estuary during sediment deposition, or it may be transported into and out of the estuary during sediment re-suspension (Breen and

McKenzie, 2001). It is this mixing and transport that provides estuaries with a variable chemical environment which can change suddenly at any time. With regard to estuarine chemistry, focus is commonly placed on parameters such as pH, temperature, dissolved oxygen and salinity. These parameters sustain the high productivity of estuaries and therefore their value, and without them, organisms and estuarine processes in general will disappear.

There are many reasons as to why estuaries are so highly productive. Estuaries are highly efficient at trapping carbon and other nutrient inputs derived from upstream as well as the sea, which enables increased plant growth (material is transported into the estuary but it is difficult to go out to sea). As a result, organisms and plants that reside in estuarine environments thrive, assuming favorable conditions.

Estuarine biota are plants and algae that are visible, and function as primary producers as well as habitat producers (CERM, 2009). These biota are critical to the existence of estuaries as they are the base of the food web providing energy to the primary consumers when they consume the producers. Estuarine biota live in a fluctuating environment, coping with changing salinity levels, currents and waves, varying levels of sunlight and wind, nutrient inputs, as well as varying oxygen levels. As mentioned above, biota are habitat makers (they provide food and shelter to other organisms) as well as habitat breakers. Thus they can also have a disruptive nature in estuaries (such as invasive species), but this would only occur as a result of an imbalance of some kind.

Estuarine biota are a component of a large and complex food web that exists in estuaries. Fish, invertebrates, birds, as well as bacteria and fungi are all essential components of the food web. Nutrients and other materials enter the estuaries via rivers and the sea. These materials are trapped in estuaries, and consumed by many different organisms. Fungi and bacteria, which decay dead organisms and transfer the released energy into a form which could be utilized by other organisms in order to complete the food web (River Science, 2005). The food web is a complex structure, which is highly sensitive to change. If any of these vital links were to be eliminated, there would be a decrease in productivity.

Ultimately, the success of all organisms flourishing in estuaries is linked to physical and chemical processes. For example, many prawn and fish species rely on estuaries to breed or lay eggs, and thus the length of time that an estuary mouth remains open is critical (CERM, 2009). Mouth closure is dependent on sedimentation, which in turn depends on marine conditions, or what activities are occurring upstream.

2.3.4 Tidal Cycling in Estuaries

Each estuary is unique with regard to morphology, amount of fresh and saltwater inputs, and tidal cycles. The tidal cycle (ebb and flood tide) controls the manner in which materials, such as sediments and nutrients, are transported within an estuary (Christian, 2009). Furthermore, tidal cycles influence the residence time of materials in the estuarine environment.

Moving water is the main component with regard to material transport. The daily flood tide brings salt water, nutrients, sediment, and oxygen into the estuary, and transports medium-grained sediment into the main body of the tidal flats of the estuary. During the ebb tide, water containing nutrients and sediment is discharged out of the estuary, resulting in scouring of the estuary mouth under flood conditions.

One would assume that during the tidal cycle, there is an equal period of flooding and ebbing, known as tidal symmetry. However, this may not be the case. In some estuaries, depending on the tides and wave conditions, estuaries may exhibit periods of unequal flooding and ebbing, known as tidal asymmetry. For example, there may be more flooding than ebbing or vice versa. Tidal symmetry and asymmetry will thus influence the transport of materials and nutrients within estuaries, as well as the residence time of materials within estuaries.

2.3.5 The Value of Estuaries

Estuaries provide us with goods, services and benefits, and are thus nodes that attract people. In fact, out of the 32 largest cities in the world, 22 are situated on estuaries, such as New York on the Hudson River, and Sydney on the Paramatta River. The factor that results in estuarine damage is that they provide people with free benefits, resulting in over exploitation. Estuarine environments are vulnerable in this sense. Healthy estuaries are valuable to people and wildlife due to the following reasons, according to Demetriades, (2009):

- They provide food for a variety of life forms;
- They provide shelter and are a safe haven for organisms

- Estuarine vegetation aid to filter polluted water;
- Large estuaries provide water ways for transportation;
- They provide the essentially important food webs for a large number of organisms; and
- Estuaries act as a buffer, and so protects the coastline from natural hazards.

Furthermore estuaries are valuable to people due to their aesthetically pleasing nature. It can be seen along the KwaZulu-Natal coastline just how valuable estuaries are for development – there has been great interest in developing housing adjacent to estuaries to such an extent that it is difficult to point out an estuary that has no housing or some form of development. Apart from the aesthetic appeal, estuaries have a cultural and spiritual significance attached to them. If one were to visit the Isipingo estuary on a weekend, even in its degraded state, sacrifices and baptisms continue to take place. A vital value of estuaries is that they provide the basic needs of people i.e. food. No matter how badly degraded an estuary is, there will always be people fishing or pumping for prawns. Not forgetting the recreational activities estuaries provide, for example, the Mgeni estuary is a popular site for canoeists and fishermen. Lastly, if an estuary is in good health, there may be good economic opportunities that the estuary would provide, such as tourism. More examples of estuarine goods and services are given below in Table 2.1.

Table 2.1: Examples Of Estuarine Goods & Services (Breen and McKenzie, 2001)

Goods & Services	**Examples**
Migration Opportunities	Provide nurseries for fish, crustaceans and birds – allows species to complete their life cycles
Disturbance Regulation	Control flooding and other natural hazards, as well as mitigating human impacts
Water Supply & Regulation	Supplies water to the marine environment as well as for industry and agriculture
Sediment Supply & Regulation	Create beaches, spits and sandbanks and maintain them
Erosion Control	Estuarine vegetation such as mangroves and reedbeds prevents soil loss by binding the soil
Soil Formation	Sediment accumulates on floodplains and in mangroves
Nutrient Supply	Some nutrient cycles are enhanced in estuaries. E.g. Nitrogen

Goods & Services	Examples
& Cycling	cycle
Waste Treatment	Waste and pollution are broken down in estuaries by organisms
Food & Bait Production	Fish, crustaceans and worms are all found in estuaries and are used for eating or collected for bait
Raw Materials	E.g. reeds are harvested and used for weaving
Genetic	Act as a nursery for many organisms, so creates a gene pool
Nature Appreciation	Bird watching, walks and trails
Sport Fishing	Fly fishing in estuaries or normal fishing
Water Sports	Canoeing, swimming, kayaking, skiing
Scenic Views	Aesthetically beautiful for residences and offices
Transport Services	Marinas, harbours, bays, and ski boat launching
Cultural & Spiritual	Provides a site for cultural and spiritual events

The goods and services of estuaries need to be recognized in order for estuaries to be valued. Demetriades (2009) argues that it is important to value estuaries because the benefits to people and the economy can be highlighted; to show that estuarine degradation does indeed carry a cost; and to help with the improved managing of estuaries. Unfortunately, it is perceived that the benefits of damaging activities to an estuary are greater than the benefits of conservation and sustainable land use. It is for this reason that estuaries need to be valued.

Estuaries can have a direct, indirect, or a non-value use. Direct use is split into consumptive and non-consumptive values. An example of a consumptive value would be fishing, while a non-consumptive value would be bird-watching. An indirect use value means that the estuary provides an input into production by other sectors of the economy, for example, water purification. Finally, a non-use value is the most difficult to judge, as it is the value of having the option to use the estuary in the future, and is based on peoples' willingness to pay, for example, for conservation. This is challenging, as people are different; some people may not care about conservation and not be willing to pay much for it, while some people are passionate about conservation and are willing to pay a substantial amount for an estuary's conservation.

To conclude, the sum of the indirect and direct use values results in a total economic value of an estuary. An estuary will have a high total economic value if there is no development surrounding the estuary or upstream. However, if there is heavy development of an estuary and its surrounds, the total economic value will decrease. It is human impact on estuaries that influence their value, and so it is important that the impact of human activities should be explored.

2.3.6 Threats Affecting Estuaries

Any activity that occurs in an estuary, surrounding an estuary, upstream of an estuary or in the catchment as a whole, will ultimately impact the estuary itself. Unfortunately many of the impacts on estuaries have been negative. The main threats to estuaries are threats to water quantity, water quality, and habitat loss. Each of these threats will now be discussed in detail.

Water Quantity

Water quantity is directly impacted by abstraction. These activities directly decrease the amount of water entering an estuary. Activities that decrease the supply of water to estuaries include the construction of dams, the cultivation of plantations and alien plants.

Dams are constructed for many purposes: for agriculture; for providing towns and cities with water; as well as flood control. By placing a barrier such as a dam on a river, it is directly stopping stream flow, and therefore discharge. Water is abstracted from dams, which directly impacts the supply of water reaching an estuary. An important impact of dams on estuaries is that in addition to holding back water, they retain sediment, especially larger sized particles, pebbles and boulders (Breen and McKenzie, 2001; Garland and Moleko, 2000). Thus most dams will only allow for the transportation of finer sediments downstream.

Constructing a dam in a river will alter the hydrology of the stream, which will ultimately have an effect on the mouth dynamics of an estuary. For example, the construction of the Inanda dam has had various negative impacts on the Mgeni estuary. Due to the periodic opening of the dam gates, flushing and scouring of the estuary occurs at a faster rate than before the dam was constructed, resulting in the estuarine bed lowering. This is due to excessive scouring occurring in the estuary, as there is not enough sediment derived from upstream to replace the scouring (Garland and Moleko, 2000).

Another problem with dam construction is that the lack of sediment that is flushed out of the estuary will cause the beaches to narrow, as they are being starved of sediment. Due to only finer sediments entering the system, the lower Mgeni will no longer be suitable for sand mining (Garland and Moleko, 2000). It is the opinion of the researcher of this study that this is the only positive impact of the construction of the dam. Ultimately, an increased abstraction of water may lead to mouth closure, which may result in the artificial breaching of the mouth. Demetriades (2009) argues that breaching is harmful to the estuarine environment and decreases estuarine productivity, as it disrupts the life cycle of many organisms.

Plantations and alien plants pose a serious threat to estuarine environments. They directly decrease the amount of water entering an estuary as they are very thirsty plants. Approximately 750 tree and 8000 other plant species have been introduced to South Africa. Out of these species, 161 are known as alien invasive species, and they impact 10 million hectares (8%) of South Africa (Mondlane *et al.,* 2002). Plantations such as eucalyptus, pine, and timber have good economic benefits, but at a cost. Commercial plantations are estimated to have reduced surface runoff by approximately 1.4 billion m^3 per year or 3.2% nationally (Mondlane *et al.,* 2002). These reductions are serious as South Africa has a mean annual rainfall of only 490mm, and less than 10% of this ends up as surface runoff. Water use increases where alien trees, which use an estimated 7% of the country's runoff, invade short vegetation (Mondlane *et al.,* 2002). Decreased stream flow increases sedimentation, as sediment settles out of solution more readily, and estuaries can become shallow. This can result in rivers becoming choked with terrestrial vegetation, such as the reed *Phragmites.*

Water Quality

Unfortunately, many human activities that take place along a watercourse, river catchment, or estuary, will have a negative impact on the water quality. An activity of any kind produces waste, discharge or pollution, and if this waste finds its way into a river, the estuary downstream will be heavily impacted (Naijar *et al*., 2010). There are two different types of sources of pollution, namely diffuse and point sources. Diffuse source is pollution that is produced by a broad ranging group of activities, such as from agricultural land uses (Wang *et al*., 2011). For example, if a river is flanked by many farms, and the river is polluted with fertilizer leachate, it is very difficult to point out which farm is the polluter as all use fertilizers. Diffuse source pollution is therefore problematic to manage as the polluter in most cases is unknown. Point source pollution is pollution that is produced by a known source, such as industry (Whitfield and Bate, 2007). An example would be an industry that pumps waste or discharge out of a pipe into a river – the pollution is directly linked to that industry. Particular industries produce defined wastes, thus the pollution can generally be linked back to the polluter, and action for discipline can be taken.

Water quality is impacted by the introduction of excess nutrients, infrastructure failure, and by industrial discharges. One of the pressing issues is the release of nutrients such as nitrates and phosphates into river systems. These nutrients may come from fertilizers as well as from sewage works, resulting in eutrophication and algal blooms. Eutrophication and algal blooms both deplete dissolved oxygen in the water to such an extent, that organisms such as fish die, and productivity in estuaries decreases dramatically (Breen and McKenzie, 2001; Whitfield and Bate, 2007). The impacts of nitrates and the effects of over enrichment of nitrates in natural systems will be discussed in more detail in the next section. Infrastructure failure seems to be occurring more often, and when this occurs, the industry in question discharges waste into the river or watercourse. A good example would be the sewage plant that is situated on the Isipingo River, south of Durban. In 2008 when load shedding was rife in the country, millions of tons of raw sewage was pumped directly into the river due to a power outage following structural failure. The decomposition of the sewage by bacteria deprived the Isipingo estuary of dissolved oxygen, and fish kills were the result.

Finally, industrial discharges, whether legal or illegal, impact the water quality in the same way as mentioned above. Of vital importance is that water quality and water abstraction are linked – a decrease in the supply of freshwater to an estuary combined with an increase in pollutants entering the system has a compounding effect (Demetriades, N., 2009, *pers. comm.*). Having either a low water supply or low water quality is bad in itself, but if a system were to have both these problems, the productivity of the estuary downstream would be highly threatened.

Habitat Loss

Apart from impacting water quality and quantity, anthropogenic activities ultimately results in the loss of habitat around estuaries and rivers. Demetriades (2009) states that bridge construction, farming, infilling for development, and sand mining all result in habitat loss. As stated earlier on in this chapter, estuaries are highly variable, and it is their hydraulic conditions that determine the estuarine processes that take place. Bridges, for example, alter these hydraulic conditions, which then has an effect on sedimentation, scour, and of course, flow patterns (Breen and McKenzie, 2001). Bridges obstruct water flowing downstream and change the velocity of flow (riverine flow as well as tidal flow), which will in turn affect the erosion and sedimentation patterns upstream as well as downstream. In order to construct a bridge, part of the river is usually cut off to allow for construction, and infilling of these areas below the high water mark is the result. Subsequently these areas (especially on the floodplains) are encroached by terrestrial plants, and the former riverine habitat is transformed into a terrestrial habitat.

As stated above, general construction and development along an estuary results in habitat loss which is evident along the Mgeni estuary. The Mgeni River posed a problem with the development of the Springfield Flats industrial area, due to the fact that in periods of heavy rain, the river is highly vulnerable to flooding (Begg, 1978). To overcome this problem, the upper reaches of the river were canalized, restricting the estuary to the size of a canal. Industry has now choked the estuary, and its natural floodplain has been replaced by concrete – a complete loss of habitat.

Under the water quality section, it was mentioned how excess nutrients entering a system affects estuaries. The load of nutrients in rivers (primarily nitrogen and phosphorous) has been increasing as a result of increased population growth and settlement in river catchment areas (Falco *et al.*, 2010). This increase is a result of changing land use practices, increased urban runoff (wastewater), as well as the increased use of fertilizers and animal manure, with consequent leaching into the river course (Falco *et al.*, 2010; Wen *et al.*, 2008). This study is focused on nitrates specifically, and their origin and impacts will now be discussed.

2.4 Nitrates

Nitrates fall under the category “nutrients”. Nutrients are vital elements, and are required for plant growth, and they include carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphate, as well as silica. These examples are termed macronutrients, while micronutrients are required in smaller quantities (Dallas and Day, 2004). Nitrogen occurs abundantly in the environment, and it is an essential constituent of proteins – it is therefore a major component of all living organisms (Stamatis *et al.*, 2011). Inorganic nitrogen may be present in many forms in both polluted and unpolluted water, but the forms that are most commonly tested regarding water quality are ammonia, ammonium, nitrites, and nitrates – nitrates being the focus of this study.

The Department of Water Affairs and Forestry (DWAF) state that “nitrite is the inorganic intermediate, and nitrate the end product, of the oxidation of organic nitrogen and ammonia” (DWAF Water Quality Guidelines, 1996, p81). In other words, nitrates are “the end products of the aerobic stabilization of organic nitrogen” (Dallas and Day, 2004, p88). Nitrates are negatively charged ions that are easily dissolved in water and in nature are formed by the nitrification of nitrous oxides. These nitrous oxides are formed from ammonium (Dudley, 1990). Nitrogen is essential for life – it is a major constituent of amino acids, which are like building blocks for proteins in both plants and animals (River Science, 2005; Stamatis *et al.*, 2011). Nitrates move through the ecosystem via the nitrogen cycle. The nitrogen cycle contains the following interactions, as outlined by River Science, (2005):

Nitrogen is recycled many times in an estuary before it is flushed out to the marine environment, or returned back to the atmosphere. Aquatic plants and algae take up inorganic nitrogen (ammonia and nitrate) and incorporate it into complex organic molecules such as proteins. Organic nitrogen is then transported though estuary food webs. Nitrogen is released from this organic component through excretion of metabolic waste products and decomposition of dead organisms. Decomposed organic matter that is not consumed by detritivores is broken down by bacterial and fungal action into simple compounds, including ammonia. Ammonia is an unwanted by-product of various metabolic processes in animals and is either excreted directly or converted to simple organic compounds such as urea and uric acid. If oxygen is present, bacterial action can convert ammonia to nitrate. This process is referred to as nitrification. The repeated movement of nitrogen through these pathways within the estuarine environment can sustain biological activity, even when external nitrogen concentrations are low. The nitrogen cycle is summarized below:

- Biological nitrogen fixing bacteria: these bacteria live in the roots of legume plants and they trap nitrogen from the air.
- Assimilation of fixed nitrogen: plants absorb nitrogen from the soil through their roots, and animals ingest nitrogen by eating plants.
- Ammonia is released: by plants and animals by a process known as ammonification.
- Reduction: reduction of nitrate to nitrogen oxides, and nitrogen is reduced to ammonium by bacteria.

This simple cycle allows for the conversion of nitrogen into many different compounds that allow the cycle to continue. It is important to note that nitrates themselves are not bad – where they occur and in what quantity is where the problem lies.

2.4.1 The Occurrence of Nitrates

Nitrates are derived from many different sources. Whilst they are naturally found in the environment, human activities such as agriculture and industrial development are major causes of nitrates entering our ecosystems. It was important to briefly discuss the nitrogen cycle to illustrate the various ways in which nitrates enter and leave an estuary. As a result, it is possible to ascertain how human activities are affecting this, particularly *via* agriculture. There are various ways in which nitrates can enter or leach out of soil, however the largest amount of nitrates are being lost due to agriculture (Chapin et al., 2004). Naturally, nitrates can enter an area due to nitrogen fixing bacteria (explained above in the nitrogen cycle), and by lightening. Anthropogenic activities also introduce nitrates to a system by the use of nitrogen fertilizers; by discharging sewage effluent into a water body; as well as industrial pollution (Bouvy *et al.*, 2010). Nitrates leave a system by the biological conversion of nitrates into nitrogen (denitrification), and they can also simply leach out of the soil into surface waters and aquifers.

Farming in general and the use of nitrate fertilizers plays a major role in creating the problem of excess nitrates entering water systems, and is one of the main sources of nitrate pollution (Beckert et al., 2011; Prasad and Ramanathan, 2009). Farmers have been using fertilizers rich in nitrates and phosphates in order to increase crop production. The problem arises when more nitrate is added to the fertilizers than that used in plant growth, which results in the excess nitrates being leached from the soil and carried away in runoff (Dudley, 1990). Not only is the use of fertilizers a problem, but even ploughing of crops is an issue, because it releases nitrates that may have been stored in the roots (Dudley, 1990). Other sources of nitrate pollution are the discharge of treated or untreated sewage (a major problem in KwaZulu-Natal); livestock manure runoff from feedlots; runoff from streets, lawns and construction in general; runoff from erosion due to poor land use; and of course natural runoff from the atmosphere and soil. The sources of nutrients in general, are summarized by Dallas and Day (2004) adapted in Table 2.2 below.

Table 2.2: Major Potential Sources Of Nutrients

Sources		
Climatic	Weathering of rocks & soil Erosion Rainfall Variability of runoff	
Catchment Characteristics	Surface geology Land form	
Anthropogenic	Point sources	Sewage effluent
		Industrial discharge
		Intensive animal enterprises
		Detergents
	Diffuse sources	Agricultural surface runoff
		Disturbance of soil mantle
		Addition of fertilizers
		Manure
	Atmospheric deposition	Urban runoff
		Gases released from agriculture
		Burning of fossil fuels

Another important source of nutrients to the estuarine environment is the marine environment. The adjacent ocean supplies a considerable amount of nutrients to the estuarine environment, regulating nutrient dynamics (Alvarex-Salgado *et al*., 1996; Prasad and Ramanathan, 2009).

2.4.2 The Impact of Nutrient Over-Enrichment in Estuaries

Estuaries are commonly subjected to intensive anthropogenic stress due to pollutant loading from urbanized areas (McQuatters-Gollop *et al*., 2009). Nitrogen and nitrates (as well as phosphorus) are implicated as being the main nutrients responsible in the over-enrichment of nutrients in estuaries. Nutrient enrichment in a body of water is referred to as eutrophication. Eutrophication in estuarine and coastal waters is widely recognized as a major worldwide threat (Duarte & Vieira, 2009; Holstein and Wirtz, 2009; McQuatters-Gollop *et al*., 2009). Eutrophication causes algal populations to explode, the water becoming clogged with algae, which in turn results in the depletion of dissolved oxygen (Dudley, 1990; McQuatters-Gollop *et al*., 2009). The World Health Organization (WHO) defines eutrophication (see Figure 2.10) as "an accelerated growth of algae on higher forms of plant life caused by the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus and inducing an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned" (WHO, 2002, p5).

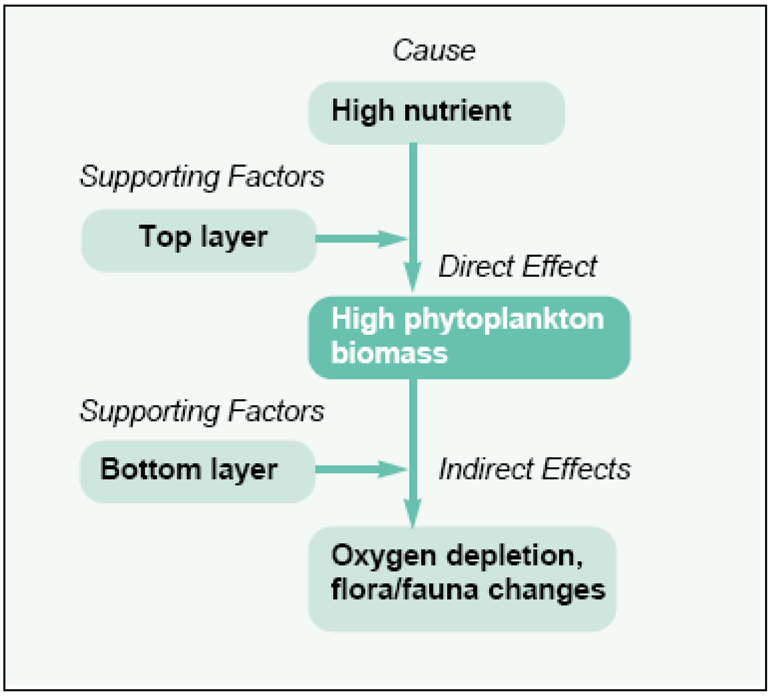


Figure 2.10: Diagram illustrating the process of eutrophication (WHO, 2002).

Figure 2.10 above shows that the direct consequence of eutrophication is the depletion of oxygen near the bottom of a water body.

It is important to remember that nitrates are naturally found in the environment, so it is to be expected for there to be nitrates in estuarine water. In fact, nitrates in small amounts stimulate plant growth, so it is vital that estuarine water contains some nitrates. However developments and agriculture have resulted in excess nitrates entering our water systems and estuaries (Roselli et al., 2009). When there are excess nitrates in estuaries, the first organisms to respond to this change are the algae, particularly the green algae (Dudley, 1990). These green algae respond the quickest to over-enrichment, and they go through a population explosion. If one were to see water that is covered by algae (blue-green or green algae) over a couple of days, it can immediately be assumed that the water is over-enriched and contaminated. When the algae becomes a very thick layer on the water's surface, it prevents light from penetrating the water (CERM, 2009). Aquatic plants therefore cannot photosynthesize effectively, and as a result, they die. The bacteria that live in estuaries will begin to decompose the dead organic matter, and this processes of decomposition utilizes dissolved oxygen. Furthermore, oxygen contained in sulphates will be utilized, resulting in the release of sulphur, which captures any oxygen in the upper layers of the water body (WHO, 2002). The water body will lose all its oxygen, and life will suffocate. In addition to the depletion of oxygen, the WHO (2002) states that other changes that will occur in a water body due to eutrophication include:

- Changes in algal population: during eutrophication, there is usually a population explosion of macroalgae, phytoplankton (diatoms, dinoflagellates, and cholorophytes), and cyanobacteria. These organisms depend on nutrients, water movement, temperature, and light. These organisms may be dangerous with respect to human health, as many of them release toxins into the water.

- Changes in zooplankton, fish, and shellfish population: this is the first group to display changes when eutrophication occurs. These species are heavily dependent on oxygen availability, and they will usually show the first signs of distress and mortality.

Ultimately, increased nitrates in river systems and especially estuaries will result in the complete disruption of the ecosystem (Roselli et al., 2009). Due to the fact that excessive eutrophication causes many organisms to die, the sensitive food web that was discussed earlier in this chapter will be disrupted. An increase in industrial activity, development, as well as agriculture causes an over-enrichment of nutrients in the water body, resulting in eutrophication. Unfortunately, this will become a bigger problem in our estuaries, as development along estuaries becomes more popular. Careful and thorough management of these activities is therefore crucial to ensure the productivity of estuaries is maintained.

2.4.3 Material Transport in Estuaries

An important factor that must be considered with regard to material and nutrient transport in estuaries (and ultimately estuarine-marine exchange) is hydrodynamics. Hydrodynamics is a vital component of the functioning of estuaries as flushing time affects the transport and permanence of water, as well as the materials and nutrients suspended in the water, within estuaries (Duarte & Vieira, 2009). The residence time of water within estuaries has a high spatial and temporal variability, which is accentuated by estuarine-marine exchange due to turbulence at the mouth.

The transportation of materials and nutrients to the estuarine environment is dependent on the velocity of river discharge, which in turn is directly dependant on rainfall.

2.5 Conclusion

Estuaries and estuarine processes are incredibly sensitive to change, especially change in water quality. Any activity that occurs upstream of an estuary or surrounding an estuary, will result in negative impacts on the estuarine environment. Estuaries support many different types of species and most of them are reliant on some aspect of estuaries for their survival – whether it is a permanently open mouth condition to allow for fish migration, or the establishment of indigenous estuarine vegetation that provides food as well as shelter. Important estuarine processes are changing due to anthropogenic activities, especially the addition of nutrients such as nitrates in the water, resulting in eutrophication and the increased occurrence of invasive alien plants. It is these kinds of changes that result in the elimination of fish and indigenous vegetation species, resulting in habitat loss, as well as decreased water quality and quantity.

CHAPTER 3: REGIONAL SETTING

3.1 Introduction

"The characteristics of estuaries are dependent on where they are, and therefore on the climate of the region" (Allanson and Baird, 1999, p29). Important climate factors that influence estuarine processes include precipitation (rainfall), wind, waves, radiation and finally evaporation (Allanson and Baird, 1999). These important variables will briefly be discussed below.

This study focused on three dominantly opened estuaries on the east coast of KwaZulu-Natal, namely the Tongati estuary, the Mgeni estuary, and the Isipingo estuary (see Figure 3.1). According to Preston-Whyte and Tyson (2000), the climate of the KwaZulu-Natal coastline is subtropical, and has a mean annual rainfall of 900 to 1000 mm. Eighty percent of this rain falls in the summer months, with hardly any rainfall occurring in the winter months. This means that KwaZulu-Natal has a highly seasonal climate with a relatively high occurrence of floods, and therefore, high sediment loads in rivers on the coast. Rainfall is important as it influences the discharge as well as the flow of the rivers along the KwaZulu-Natal coastline (Garden and Garland, 2005). Allanson and Baird (1999) state that the flow of South Africa's rivers is low compared to other global examples due to South Africa's erratic rainfall patterns.

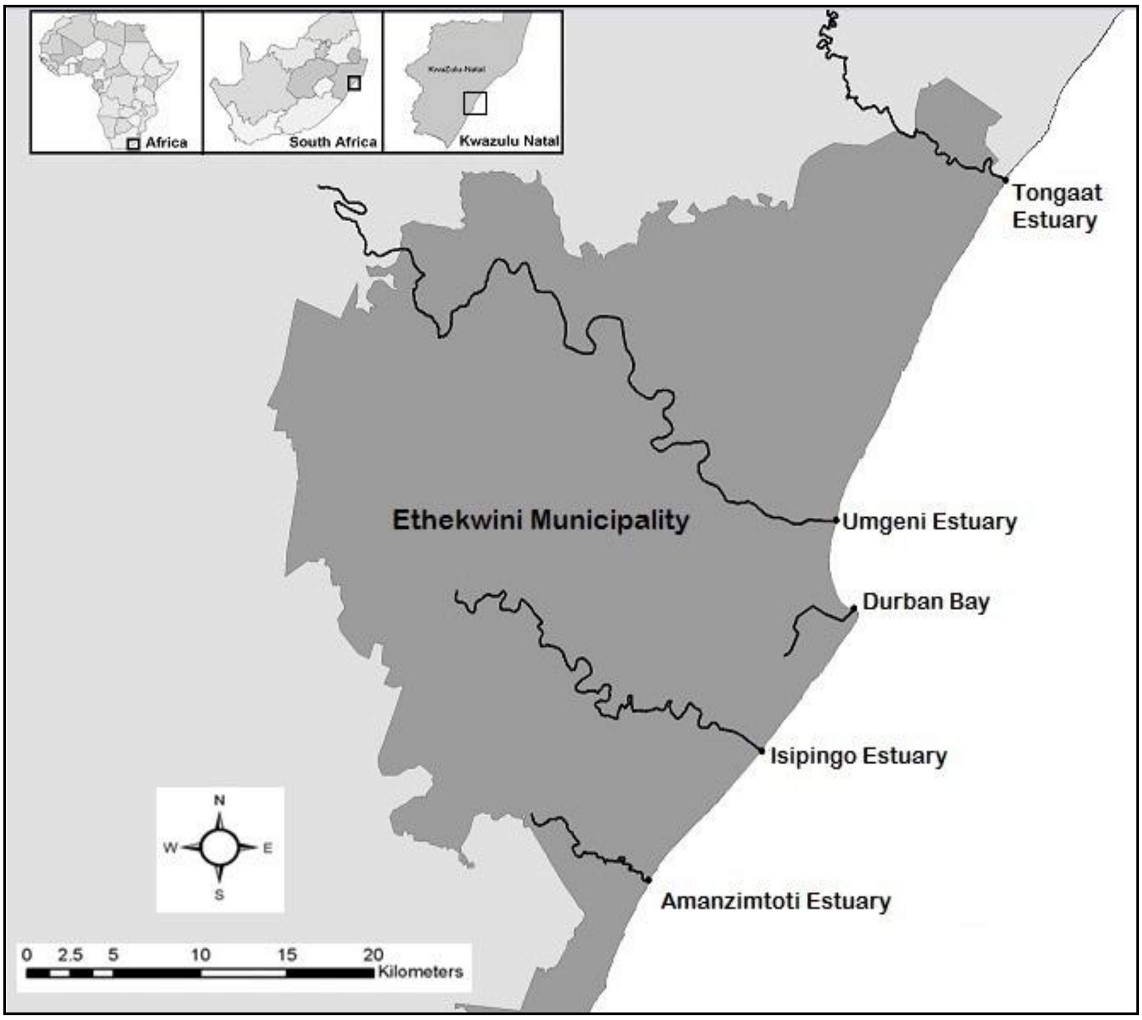


Figure 3. 1: Map showing the locations of the Mgeni, Isipingo, and Tongati estuaries within the eThekwini Municipality (Sukdeo, P., 2010).

Wind conditions experienced along the KwaZulu-Natal coastline vary seasonally. This is due to the fact that there is a high pressure belt that circles the southern hemisphere at 30 ° South Latitude (Preston-Whyte and Tyson, 2000). The result is that the KwaZulu-Natal coast is bombarded with frontal systems which move offshore along the coast, particularly in the summer, bringing with it easterly winds. Sometimes, the coastline is influenced by coastal lows, which result in a preceding warm, offshore Berg wind, followed by strong westerly winds (Preston-Whyte and Tyson, 2000). Generally, the KwaZulu-Natal coast experiences its strongest winds in October and November, while its calmest period is experienced in June (Allanson and Baird, 1999).

Waves are an important driver of coastal processes that shape our coasts (Haslett, 2000). Waves originate from the east along the KwaZulu-Natal coast. The coast is vulnerable to very high waves formed by frontal systems in the summer, while more calm conditions are experienced in winter. Waves are formed and influenced by wind, and so wind conditions and wave conditions go hand in hand – the stronger the wind, the higher and more destructive the wave.

Solar radiation is an important variable regarding estuaries, as it directly affects air and water temperatures. In addition, cloud cover is important, as it reflects solar radiation, so this factor cannot be ignored. The KwaZulu-Natal coast has a reasonable amount of cloud cover (especially in the summer in the afternoons), and so receives the most diffuse sky radiation and not as much surface radiation due to reflection. Evaporation results in water loss from estuaries, and this may be an important factor when considering the hydrology budget for South African estuaries (Allanson and Baird, 1999). Evaporation is high in hot, dry areas, which implies that high evaporation is not correlated with high rainfall. The KwaZulu-Natal coast is very humid, and so evaporation is not as pressing an issue as other areas of South Africa, such as the Western Cape, where evaporation can actually be higher than freshwater inflow from rivers.

3.2 Choice of Estuaries

The Mgeni, Isipingo, and Tongati estuaries were chosen as case studies for this study due to the fact that they remain open to the sea for most of the year. An open mouth condition was vitally important for this study, as it facilitated in capturing the exchange of nitrates between the estuarine and marine environment. Estuaries such as the Mdloti and Mhlanga estuaries are closed for most of the year, and would therefore not be appropriate for this study.

3.3 Mgeni Estuary

The Mgeni estuary is located approximately five kilometers north of Durban's city center (see Figure 3.2) and the co-ordinates of the estuary's location are 29°48'35''S; 31°02'27''E. The eThekwini Municipality (2009) classifies the Mgeni as a modified permanently open estuary. The Mgeni catchment comprises of an area of 4400 square kilometers (Garland and Moleko, 2000; WRC, 2002), and the length of the Mgeni river is between 230 kilometers to 235 kilometers, while mean annual runoff is approximately 707 x $10^6 m^3$ (Begg, 1978).

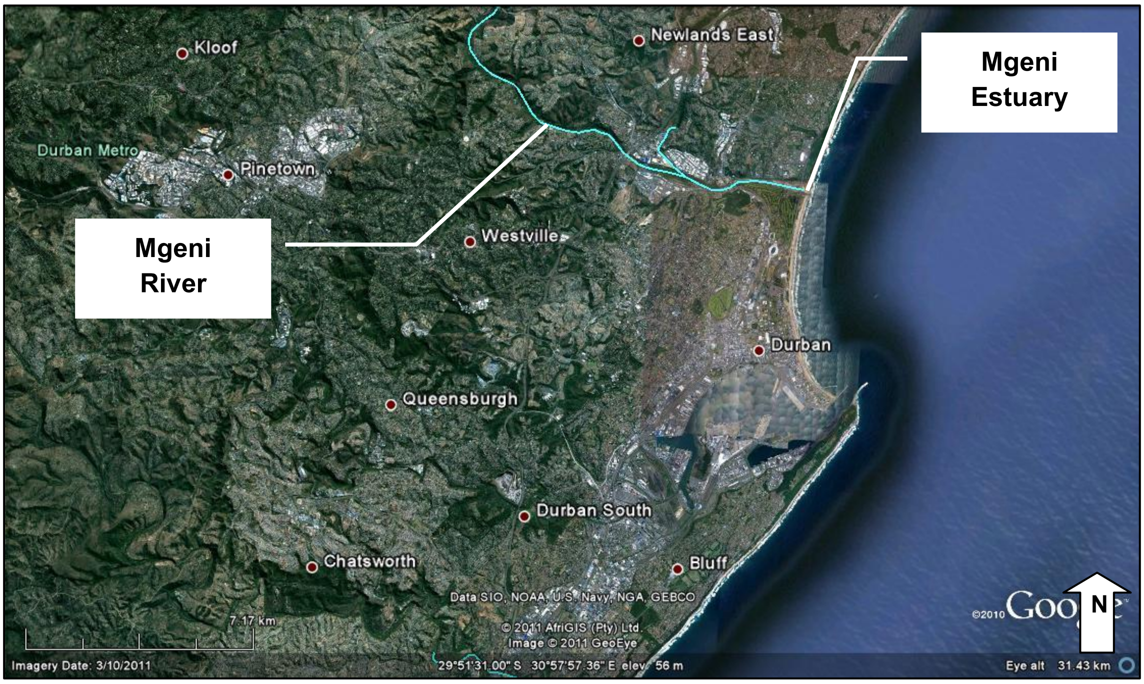


Figure 3.2: Satellite image showing the location of the Mgeni Estuary (©Google Earth Satellite Imagery, Imagery Date: 17/07/2010).

The discharge of the Mgeni River has been recorded at a maximum of 532m^3/sec and at a minimum of 4.5m^3/sec. The flow of the river varies seasonally, for example it has been recorded that the mean summer discharge was 18.4m^3/sec, and the mean winter discharge was 6.5m^3/sec (Begg, 1978). These recordings were taken during the period 1958 to 1961 (before the Inanda dam was constructed). Flow readings of over 500m^3/sec have been recorded when the river was in flood after many days of prolonged rainfall (Begg, 1978). The construction of the Inanda dam has impacted discharge of the Mgeni River – it has decreased from 323 million m^3 to 309 million m^3 (Garland and Moleko, 2000). The water level in the estuary itself does fluctuate, and a tidal range of 0.4 to 1.1 meters has been recorded. During times of flood however, the water level of the estuary can rise by up to six meters (Begg, 1978).

There are five dams that have been constructed within the Mgeni river catchment and they include the Henley Dam, the Nagle Dam, the Midmar Dam, the Albert Falls dam and finally the Inanda Dam (see Figure 3.3). Soil erosion within the catchment is severe and the Mgeni River carries an enormous amount of silt. It has been recorded that during the period 1958 to 1961, the silt load carried by the Mgeni river was approximately 70 000 tons per year (Begg, 1978).

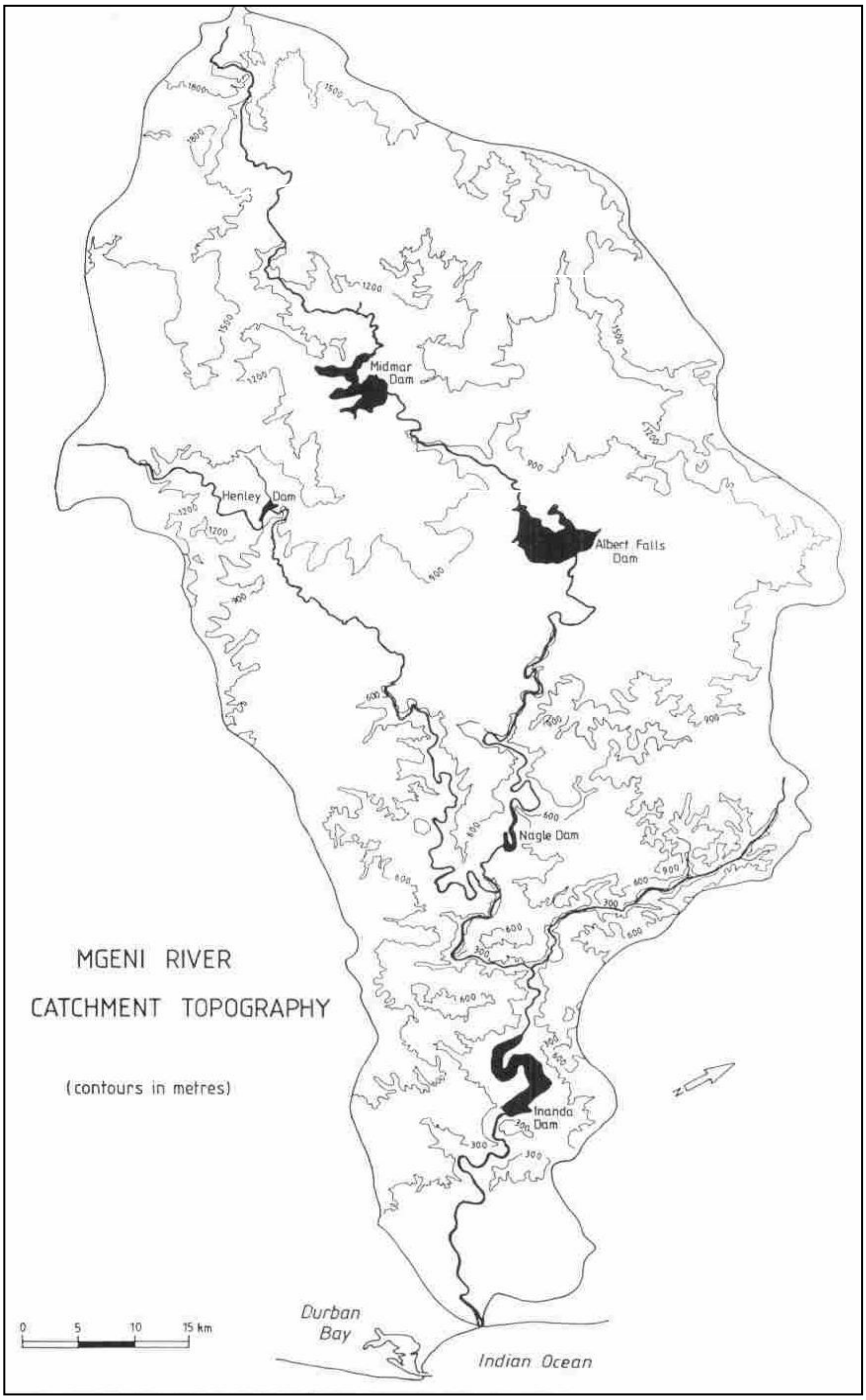


Figure 3.3: Map showing the location of dams located in the Mgeni Catchment (Cooper, 1993).

The total extent of the Mgeni estuary, including Beachwood, on a spring tide is 230 hectares (Forbes & Demetriades, 2008). The axial length of the estuary is 2.5 kilometers, and the maximum width at spring tide can reach up to 600 meters near the river mouth. The river channel is usually 100 meters wide, and the floodplain can be over a kilometer wide in places (Begg, 1978). During spring tides, the depth of the estuary can reach two and a half meters, and on an ebbing neap tide, depths can vary from 75 centimeters to two meters (calculated in this study). The Beachwood creek runs in a northerly direction at right angles to the Mgeni River (Begg, 1978).

As is the case with most estuaries, the Mgeni has a sandbar. This sandbar is a spit that extends in a southerly direction; however, under certain conditions such as an onshore swell, the spit can grow in a northerly direction (Begg, 1978). The estuary has been described by Cooper (1993) as being river-dominated, and the mouth is permanently stabilized by a groyne, which keeps the mouth permanently open unless river discharge is exceptionally low. The estuary also contains tidal deltas, bars and sandbanks at the mouth. Of interest, is that Begg (1978) suggests that there is historical evidence that shows that the Mgeni River used to flow behind a sand barrier into the bay, and that the mouth was actually located 4.8 kilometers south from the position it is today. If there were concerns such as flooding and malaria risks, the bar would be artificially breached at the position of the current mouth position (Begg, 1978). At present, it is ensured that the river mouth remains open all year round.

There are many different types of land use within the Mgeni catchment (see Figure 3.4). One can see by the land-cover map that the estuary is heavily developed (urban). As a result of this intense urbanization, there has been a dramatic loss of estuarine habitat – much of the estuarine vegetation and floodplains have been replaced with impermeable structures (eThekwini Municipality, 2009). Agriculture in the catchment area consists of sugar farming, fodder crops, tropical fruits, beef and dairy cattle raising (Begg, 1978). The industrial area called the Springfield Flats is situated upstream of the estuary. There is a golf course as well as a model yacht pond, restaurant and other entertainment facilities located on the southern bank of the estuary (Begg, 1978). The northern bank of the estuary has not been as extensively developed and near the river mouth, the Beachwood tidal creek has been declared a nature reserve, where boardwalks have been constructed through the mangroves. Garland and Moleko (2000) state that the estuary's sediment is an important resource, as not only does it replenish the beaches with sediment, but also it is the raw material used for construction.

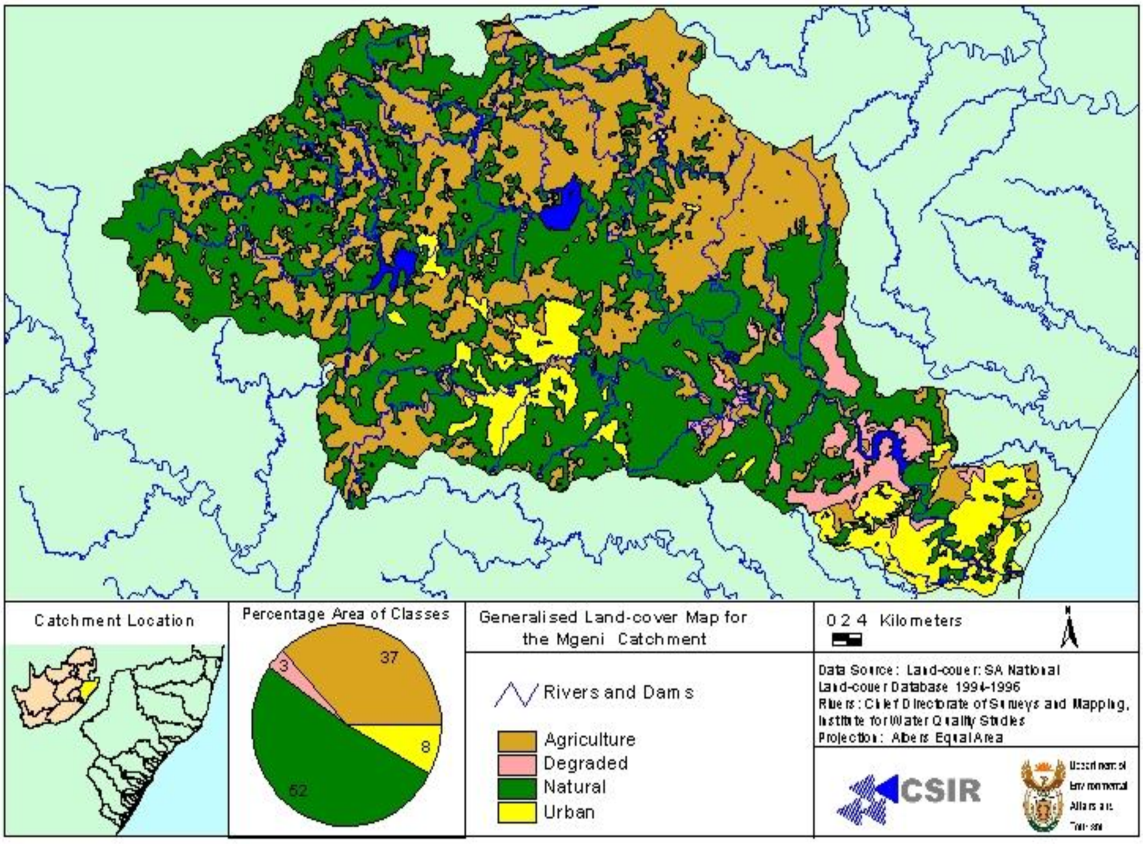


Figure 3.4: Map showing the various types of land use within the Mgeni Catchment (DEAT, 1994-1996).

The Mgeni River is a popular site for recreational activities, such as fishing, bait collecting and water sports events for example the annual Duzi canoe marathon. In addition, the Beachwood nature reserve contains a scientific and educational facility for the public as well as nature trails. Unfortunately, the Mgeni River also serves as a disposal site for effluent and storm-water.

There are many studies focused on the Mgeni estuary. This could be due to the fact that it is in close proximity to Durban and its research centers, as well as the fact that the Beachwood area has become so important with regard to conservation. The major impacts that have affected the estuary according to Forbes and Demetriades (2008) include:

- Habitat loss as a consequence of intense urbinisation;
- Sedimentation;
- Freshwater deprivation due to the construction of dams in the catchment; and
- Chemical and organic pollution.

Due to the abovementioned impacts, the Mgeni estuary has been classified as highly degraded (Forbes and Demetriades, 2008).

3.4 Tongati Estuary

The Tongati estuary is located approximately 35 kilometers north of Durban on the east coast of South Africa (see Figure 3.5) at 29°34'21''S; 31°11'07''E (Demetriades, 2007). It is classified as a temporarily open/closed estuary (Demetraides *et al*., 2007; eThekwini Municipality, 2009) and access to the estuary is via a few footpaths from the freeway bridge which crosses the estuary approximately 100 meters from the mouth (Begg, 1978).

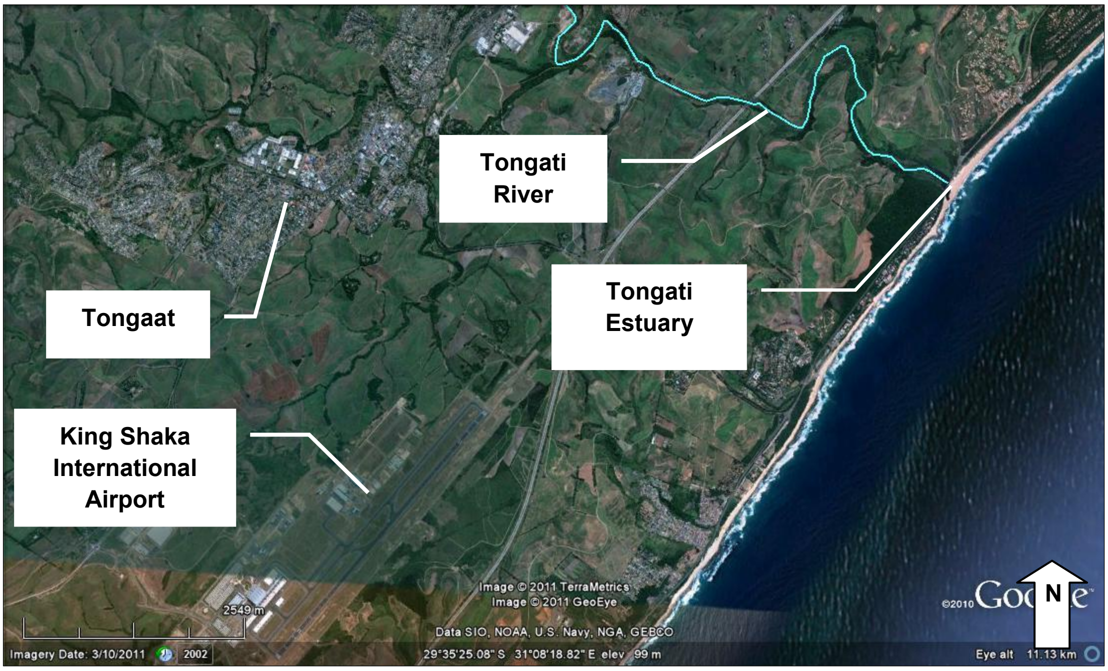


Figure 3.5: Satellite image showing the location of the Tongati Estuary (©Google Earth Satellite Imagery, Imagery Date: 17/12/2009).

The Tongati River is approximately 50 kilometers long (Demetriades *et al*., 2007) and has a mean annual runoff ranging from 84.8 x $10^6 m^3$ to 92.7 x $10^6 m^3$ (Begg, 1984). The Tongati catchment in its entirety covers an area of approximately 400 square kilometers (Demetriades *et* al., 2007). The discharge of the Tongati differs seasonally. On average, annual discharge is 2.18m^3/s, with higher readings during summer of more than 2.4m^3/s and lower readings during winter of less than 1.2m^3/s (Begg, 1978). There are no dams along the river's course.

The Tongati estuary covers an area of 9.5 hectares (eThekwini Municipality, 2009), has an axial length of 2 kilometers and the depth can range from 0.65 meters to 2.70 meters (Begg, 1978). The width of the estuary can reach a maximum of 150 meters, while the estuary's channel under normal conditions has a depth of approximately 10 meters (Begg, 1978).

Like the Mgeni estuary, the Tongati estuary has a sandbar that extends in a southerly direction, and is 150 meters long (Begg, 1978). The width of the sandbar ranges between 30 meters and 70 meters, and in some areas can rise up to 5 meters above mean sea level. The mouth is usually open across a rocky outcrop on the southern bank, while a sand bank enters the estuary on the northern bank (Begg, 1978). It has been suggested that the effects of the tides in the estuary are diminished due to the fact that there is too little tidal scouring and too much sediment transportation caused by littoral drift (Begg, 1978). The mouth of the Tongati is rarely closed, and therefore breaching of the mouth is usually unnecessary. This means that the flow of the river is adequate enough to keep the mouth in an open state for much of the year (Begg, 1978). In addition, as mentioned above, the mouth opens across a rocky outcrop, which ensures that if scouring does occur, sediment that is accumulating in the channel is removed effectively, maintaining an open mouth state.

Most of the land surrounding the Tongati estuary is owned by the Tongaat Group, and is therefore used for the cultivation of sugar cane (Begg, 1984). Approximately 10 kilometers upstream is the town of Tongaat, as well as a major sugar mill and sewage works, which pose a threat regarding aquatic pollution (Begg, 1978; Durban Local Agenda 21, 1999). With regard to land use, much of the catchment is used for sugar cane cultivation. The Tongati estuary has not been well researched thus there is a poor understanding of the entire system.

The major impacts that have affected the estuary according to Forbes and Demetriades (2008) include:

- Habitat loss due to excessive sedimentation and eutrophication.

Due to the abovementioned impacts, the Tongati estuary has been classified as highly degraded.

3.5 Isipingo Estuary

The Isipingo estuary is located 21 kilometers south west from Durban on the east coast of KwaZulu-Natal (see Figure 3.6) at 30°00'S; 30°57'E (Begg, 1984). There are two main bridges crossing the estuary – a small bridge leading to the Isipingo Island Hotel on the southern limb, and a major bridge (the N2) at the head of the estuary.

Figure 3.6: Satellite image showing the location of the Isipingo estuary (©Google Earth Satellite Imagery, Imagery Date: 17/07/2010).

The Isipingo catchment comprises a total area of approximately 47 km^2, while the Isipingo River has a length of 27 kilometers, with a mean annual run-off of 3.34 x 10^{6}m^3 (Begg, 1978; Kalicharran and Diab, 1993). Due to the construction of the now old Durban International Airport as well as the Prospecton industrial area, the Isipingo and Mlazi rivers, which fed the Isipingo estuary, were diverted. This resulted in a decreased flow, ranging from 0.28m^3/s to 2.8m^3/s (Begg, 1978), and a reduction in mean annual run-off from 102 x 10^{6}m^3/yr to 3.34 x 10^{6}m^3/yr (Kalicharran and Diab, 1993). Before the rivers were diverted, the amount of freshwater from the Mlazi and Isipingo Rivers entering the estuary was adequate to keep the mouth permanently open. This is no longer the case – there is not enough freshwater input from the Isipingo River to the estuary to maintain an open mouth condition. When the estuary closed as a result of the diversion of the rivers, all contaminants entering the estuary via the Isipingo River were trapped in the estuary. To prevent the estuary from becoming too polluted, two concrete pipes were laid in 1961 to allow the estuary to be permanently opened (Begg, 1978; Hatton, 1990; Kalicharran and Diab, 1993). This is important in the sense that it ensures connectivity between the estuary and the marine environment throughout the year.

The estuary covers an area of 6.8 hectares, and has an axial length of 1.25 kilometers along the northern arm (Begg, 1978). The estuary can reach a maximum width of 100 meters along the southern arm and the depth can vary between 0.15 meters and over one meter near the mouth as calculated in this study.

As is the case with both the Mgeni and Tongati estuaries, the Isipingo estuary has a sandbar, which extends in a southerly direction and was formerly 250 meters long (Begg, 1984). The mouth was situated against the southern bank; however, after the diversion of the Isipingo and Mlazi rivers, the mouth has become permanently closed to the sea. Two concrete pipes now represent the “new” mouth, which ensures that the estuary remains open, allowing tidal exchange to occur (see Figures 3.7 and 3.8).

Figure 3.7: Photograph showing the mouth of the Isipingo estuary, upstream of the sandbar (Author, 2008).

Figure 3. 8: Photograph showing the mouth of the Isipingo estuary, downstream of the sandbar (Author, 2008).

The major land uses upstream of the estuary are the industrial areas of Prospecton and Isipingo Rail. There is also sugar cane cultivation around the head of the estuary (Kalicharran and Diab, 1993). The Isipingo River has been canalized along the stretch of river that runs through Prospecton. On the southern bank of the estuary there is the Isipingo Island Hotel and an informal settlement. The estuary used to be a popular angling and boating site; however, this is no longer the case due to pollution. The development of Prospecton has resulted in the degradation of the Isipingo estuary to such an extent that there are no uses for the estuary today. The beach still however attracts large numbers of fishermen, however the estuary itself is not used for recreation.

The Isipingo estuary used to be one of the finest estuarine and mangrove habitats in KwaZulu-Natal, however it has been regarded as one of the most severely degraded estuaries along the KwaZulu-Natal coastline (Hatton, 1990; Kallicharran and Diab, 1993).

The major impacts affecting the Isipingo estuary according to Forbes and Demetriades (2008) include:

- Habitat loss due to intense urbanisation and inappropriate urban planning;
- Sedimentation;

- Freshwater deprivation as a result of diversion to the uMlazi canal and Mbokodweni rivers; and
- Chemical and organic pollution.

Due to the abovementioned impacts, the Isipingo estuary is classified as highly degraded. The Isipingo estuary continues to experience severe water quality problems, and events such as fish deaths due to low levels of dissolved oxygen as a result of excess pollutants in the estuary are not rare. A rehabilitation and management program has been proposed to increase water flow, improve water quality and to decrease the continuous degradation of the system (Kallicharran and Diab, 1993).

3.6 Conclusion

The Mgeni, Tongati, and Isipingo estuaries were chosen for this study, as they remain open to the sea for the majority of the year (the Isipingo remains open to the sea via two concrete pipes) – an important factor when studying the flux and estuarine-ocean exchange. The Mgeni, Isipingo, and Tongati estuaries are all located within the eThekwini Municipality. All three estuaries are impacted by anthropogenic activities: the Tongati estuary is impacted by intensive sugar cane cultivation; the Isipingo estuary is heavily impacted by industry; and the Mgeni estuary is impacted by industry and intense urbanisation. These estuaries have all experienced water quality problems. They continue to experience water quality problems, such as organic and industrial pollution, due to activities occurring upstream and surrounding the estuaries themselves.

CHAPTER 4: METHODOLOGY

4.1 Introduction

This chapter highlights the different methods which were used to achieve the objectives of this study. The methodology applied in this study included quantitative fieldwork, observation and mathematical assessment of fluxes. Each estuary and its corresponding methodology will be discussed separately.

4.2 Estuary Selection

Five river catchments lie within the eThekweni Municipality. These are the Tongati on the northern border, and successively south, the Mdloti; Mhlanga; Isipingo and Amanzimtoti. There are two other minor catchments that have rivers that flow directly into the Durban Harbour embayment. Of the five, only the Tongati, Mgeni and Isipingo have inlets (the Isipingo has two pipes that act as an inlet, which allows for permanent connectivity between the estuarine and marine environment) that are open for protracted periods of the year and have been considered for this study.

4.3 Field Surveys

As stated in the introduction to this chapter, the methodology applied in each estuary will be discussed separately, however the field survey methods for this assessment for all three estuaries were based on the same principles that are discussed in this section. According to Fan *et* al., (2008); Frick *et al*., (2007); Gordon *et* al., (1992); and Pillay (1988), the calculation of instantaneous material fluxes (F), in river systems, where flow is unidirectional, is given by:

$$F = Qc \qquad \text{(Eq. 1)}$$

Where Q is the discharge (m/s) and c is the mean material concentration (mg/L). The discharge is obtained as a product of the cross sectional area, (A), of the channel and the mean flow velocity of water (V).

In tidal systems however, the situation changes in that:

- Flow is bi-directional. Water is forced into the estuary on the rising tide (flood flow) and leaves the estuary on the falling tide (ebb flow);
- The velocity of flow and the volume of water entering or leaving the system changes constantly on either tide;
- The duration of flooding or ebbing may not be the same (tidal asymmetry);
- The extent of flooding and ebbing varies with tidal variations (spring and neap tides).

The formula used to obtain net transport in this way was sourced from Pillay (1988):

$F = I/T \int_{O}^{T} A(t)\ c(t)\ u(t)\ dt$ where: (E.q. 1.1)

- F is the net flux (kg)
- a(t) is the time varying cross sectional area in m^2
- c(t) is the mean concentration of nitrates (mg/L) that varies with time
- u(t) is the mean velocity (m/s) that varies over time
- dt is the duration of the tidal cycle

Therefore, in tidal systems, there should be continuous monitoring of the parameters throughout the tidal cycle. Since this is not always possible, the process is discreticised and instantaneous fluxes are calculated in much the same way as for the unidirectionally flowing river, but the process is repeated at fixed time intervals throughout the tidal cycle. The results of these instantaneous fluxes are then integrated over the tidal cycle. The tidal cycle may be divided into its flood and ebb components and the total flux for each component thus obtained. Subsequently, the net flux may be determined as a simple difference of the flood and ebb total fluxes.

To acquire a general understanding of whether the Isipingo, Mgeni and Tongati estuaries were effective at exporting or importing nitrates, it was essential that they were sampled all year round. The estuaries were sampled *in situ* over a spring and neap tide, during the summer, autumn, winter and spring seasons. Water samples were tested every two hours, between high and low tides, including the peak high and low tide if possible.

Measurements were taken every two hours in order to assess nitrate concentration changes with tidal change. In doing so, ebbing and flooding trends could be noted –

including whether there was tidal asymmetry or whether ebbing and flooding were of equal duration.

For this study, measurements were taken *in situ* with the YSI 6920 V2 Compact Multi-Parameter Sonde with the YSI 650 Multi-Parameter Display System water quality meter (see Figure 4.1). This instrument recorded the nitrate readings every second, and was held in place for 30 seconds, meaning that at each site, 30 sampling iterations were recorded.

In most studies of this nature, measurements are taken at three depths – near surface, near bottom and mid-depth. However, with the exception of the Mgeni system, water levels recorded were less than 1m. Thus, in order to keep sampling consistent at all sites, measurements were taken at mid-depth. Since the parameter measured for is a dissolved constituent, it was assumed that its concentration would be homogenously distributed across the channel.

The sonde was held in place under the water at approximately half the depth of the water at the mouth (Gordon *et* al., 1992; Pillay, 1988). The equipment used proved to be timesaving, as readings were saved *in situ*, therefore there was no need to collect water samples in bottles and analyse them in a laboratory at a later stage. Once the readings were saved, they were uploaded using the EcoWatch for Windows software. This information was then imported into Windows Excel for further analysis.

Figure 4.1: The YSI water quality meter (left) & the SonTek velocity meter (right) (SonTek/YSI, 2009).

4.4 Calibration

An accurate, multi-parameter environmental monitoring system and water quality meter, the YSI 6920 model, was made available for this study which reduced costs tremendously as readings could be taken *in situ* in the field.

The instrument is capable of monitoring 10 variables on a continuous basis or can be used in the laboratory to measure discrete samples taken in the field and brought back to the lab. The parameters measured are dissolved oxygen, conductivity, salinity, total dissolved solids, temperature, pH, turbidity, ammonia, chloride and nitrates.

Prior to each of the surveys, the instrument was calibrated for DO, Conductivity, TDS, pH, Turbidity, Ammonia, Chloride and Nitrates. The calibration procedures for each of these is outlined in the YSI manual of 2003 provided with the instrument. Only the procedure for nitrate calibration is given here.

The suggested values for calibrants *viz.* 1 and 100 mg/L of nitrate (NO_3) were used. The procedure required one portion of high concentration calibrant and two portions of the low concentration calibrant. One of the low concentration calibrants was cooled to 8˚C and the other two kept at ambient temperature. 100 mL of the high concentration calibrant was placed in the transport cup provided with the instrument and the probe end of the sonde was carefully immersed into the solution. The probe was left in the solution for a minute to allow for temperature equalization and thereafter calibration proceeded following the electronic procedure on the 650 display logger to which the sonde was coupled. The instrument is self-calibrating and does not produce a calibration graph. The procedure was repeated with the low concentration calibrant after emptying the transport cup and cleaning both cup and probes with deionised water. Finally, the procedure was again repeated with the chilled low concentration calibrant allowing for 5 minutes of temperature equalization.

4.5 Determination of Flow Velocity

In this study, the SonTek FlowTracker Handheld Acoustic Doppler Velocity Meter was used to determine mean velocity (See Figure 4.2). Acoustic Doppler velocity meters are useful for oceanography and estuarine research as they are well suited to saline water. Fluid in motion with a high conductivity creates a voltage that the meter can pick up. Saline water has a high conductivity, and therefore Acoustic Dopplers are well suited to measure velocity in oceans and estuaries (Gordon *et al.*, 1992). When measuring mean velocity, the standard depth where average velocity can be accurately measured is at four-tenths of the total depth measured upwards from the bed (Gordon *et al.*, 1992). Gordon *et al* (1992) indicates that the four-tenths method is used when the water depth is less than half a meter, or when a measurement must be taken quickly. The four-tenths method was the method employed for this study, as the depth in the estuaries rarely exceeded one meter. At each sample site, the velocity meter was held in place at four-tenths of the water depth, measured upwards from the bed. Following the procedure outline in the SonTek manual, the meter was held perpendicular to the flow. As was the case with the water quality meter, the velocity meter was also held for 30 seconds, where the meter immediately averaged all the readings after 30 seconds. This meter, therefore, proved to be very convenient and timesaving.

The final component needed to determine the net flux of nitrates in the estuaries, was the area of the channel or mouth. This was very simply measured by measuring the width of the mouth with a measuring tape, as well as measuring the depth of the water level also using a tape measure or measuring rod if needed. Once the width and the depth of the mouth were measured (in meters), area was obtained as a product of the two values.

As stated in the introduction, the Mgeni, Isipingo and Tongati estuaries were all morphologically different to each other and it was observed that conditions changed constantly through this study. Although the basic principles of the above-mentioned methodology were employed for this study, they had to be adapted to suit local physiographic estuarine characteristics.. The procedures adopted for each estuary will now be discussed.

4.6 Tongati Estuary

Regarding the Tongati estuary, water was sampled approximately 30 meters upstream of the mouth of the Tongati River (see Figure 4.2). The channel itself was narrow, rarely exceeding ten meters in width, and therefore only one sample was taken in the middle of the channel every two hours. It would have been ideal to sample the water right at the mouth, however at high tides, wave conditions were too rough to measure. Therefore, samples were tested just upstream of the mouth, where tidal exchange was still measurable.

The width of the channel was measured with a measuring tape, while the depth of the channel was measured with a measuring rod in the middle of the channel. The mouth of the Tongati was never consistently in one place. Sampling took place at approximately the same location on subsequent surveys.

Figure 4.2: Photograph showing the author sampling Tongati mouth (Author, 2008).

4.7 Isipingo Estuary

Of the three estuaries, the Isipingo estuary was the most unpleasant estuary to sample due to noxious odours, ritualistic practices, litter, and chemical odours. The mouth of the Isipingo estuary consists of two concrete pipes, each measuring one meter in diameter, which connect the estuary to the sea. These pipes are vital for the adequate functioning of the estuary – they allow tidal influence, which is vitally important for the existing mangroves. Measurements were taken at the estuary side of the pipes every two hours (refer to Figure 4.3). These included depth, velocity, and concentration measurements.

Figure 4.3: Photograph showing the author sampling the Isipingo mouth (Author, 2008).

4.8 Mgeni Estuary

Sampling of the Mgeni estuary could not take place at the mouth itself due to the danger aspect (the current is strong and unpredictable), therefore sampling took place approximately 170 meters upstream where tidal exchange was still very strong (refer to Figure 4.4).

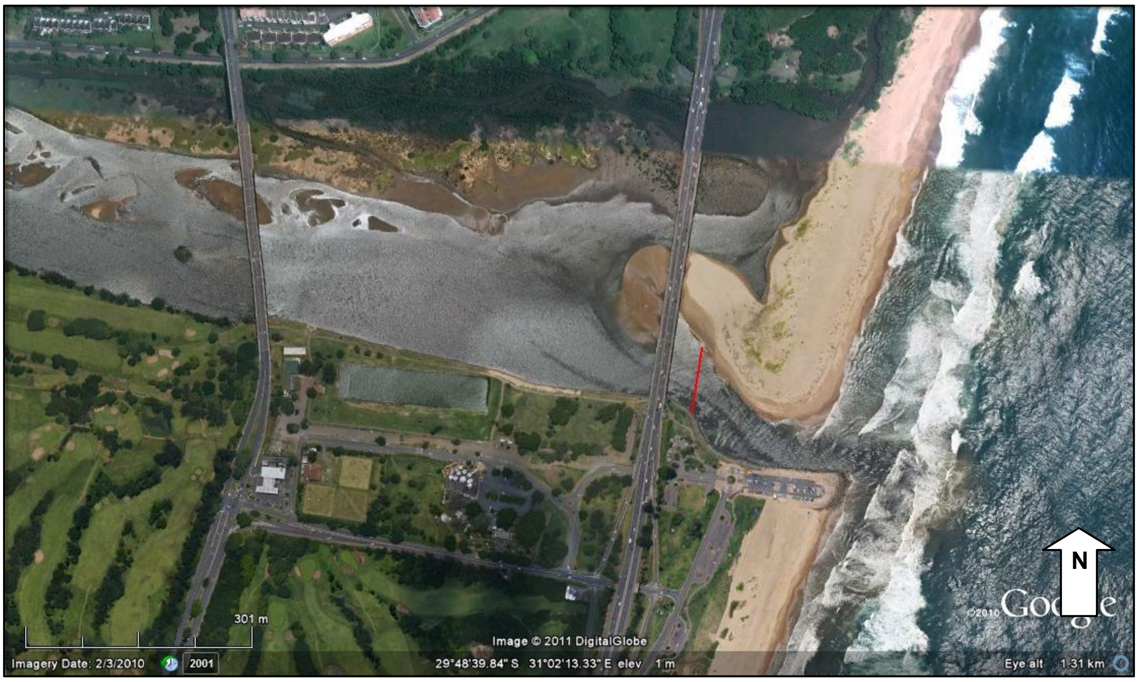


Figure 4.4: Satellite image showing the location of the sampling transect in red at the Mgeni estuary (©Google Earth Satellite Imagery, Imagery Date: 03/02/2010).

The methodology undertaken in the Mgeni estuary was the same as that of the Tongati and Isipingo estuaries. However, the location where sampling took place was much wider compared to that of the Tongati and Isipingo estuaries. Therefore a sample was taken along a transect every 15 meters to account for flow and concentration variations. The transect used was kept parallel to the Connaught Bridge for all sampling periods to ensure consistency.

4.9 Calculation of the Flux

All of the field data stored on the YSI Sonde was uploaded using the software provided with the instrument, Ecowatch for Windows. This software package incorporates summary statistics for rapid data analysis and also has graphical features. Mean nitrate concentrations were thus computed using the Ecowatch for windows. Other parameters required for flux determination (cross-sectional flow area and flow velocity) were measured in the field.

Before the net flux was calculated, the following conversions were made:

1. The mean concentration of nitrates was converted from mg/L to kg/m^3;
2. The flux of nitrates was then calculated by:
   Cross-sectional area of the mouth x average nitrate concentration (kg/m^3) x average flow velocity of water (m/s);
3. The flux value was multiplied by 7200, to attain the total flux over two hours of the tidal cycle (there are 7200 seconds in two hours);
4. The total flux of the ebb and flood component of the tide was determined;
5. The net flux was then computed as: Net flux of nitrates = Total flux of ebb flows – total flux of flood flows.

If the final net flux value was positive, it meant that nitrates were being lost from the estuaries and transported to the nearshore environment. If the final net flux value was negative, it meant that the estuaries were gaining nitrates into the system.

Finally, analysis of variance (ANOVA) was used to determine if significant differences existed in the seasonal mean nitrate fluxes of the three estuaries over neap and spring tides.

4.10 Observations, Photographs, and Satellite Images

Visual observations were crucial for this study. Changes in estuarine processes were observed and noted, such as changing mouth conditions, wave overwash, breaching, as well as the actual amount of time of ebbing and flooding. Rainfall and/or flooding events were also noted, as well as any visual water quality changes (especially in the Isipingo estuary). Photographs were taken to capture these events, as well as to capture any evidence of water quality issues, such as signs of eutrophication, fish deaths, etc. These visual observations and photographs were essential in explaining the characteristics of the different estuaries, and when attempting to explain the results attained for this study.

With the aid of Google Earth Satellite Imagery, satellite images were used to show the location of the estuaries as well as sewage outfalls located along the coastline. In addition, satellite images were important so as to be able to identify the different land uses surrounding the estuaries, as well as land used further upstream, so that the impacts of these land uses on the estuarine environment could be determined. Satellite images were also helpful in explaining the methodology regarding the Mgeni estuary, showing the location of the transect used for sampling, as well as for locating the pipes at the Isipingo estuary.

4.11 Conclusion

All three estuaries were sampled according to standard water quality procedures outlined by Gordon *et al.* (1992). The same equipment was used during the duration of this study to ensure accuracy and the sampling equipment was calibrated prior to each survey throughout the study. Sampling took place during the first year of this study, through summer, autumn, winter, and spring, during both spring and neap tides. The peak high and peak low tides were sampled. Sampling took place at the mouth, or as close to the mouth as possible.

CHAPTER 5: DATA PRESENTATION AND ANALYSIS

5.1 Introduction

This chapter deals with the results of the data that was collected for this study. The values of the average concentration of nitrates, average velocity as well as the net flux of nitrates in the Isipingo, Mgeni, and Tongati estuaries are presented in this chapter, in the following tables and graphs that encapsulate all data relating to the net flux of nitrates in the Isipingo, Mgeni, and Tongati estuaries. These data include:

- Tidal variation;
- The direction of water flow (ebb or flood);
- The cross-sectional area of the mouth;
- The mean flow velocity;
- The mean nitrate concentration, and
- The net flux.

The manner in which the samples were numbered needs elucidation for clarity. The first letter of the sample identifies the estuary, i.e. "T" for the Tongati, "I" for the Isipingo, and "U" for the Mgeni. The second letter represents the season, i.e. "SU" for summer, "A" for autumn, "W" for winter, and "S" for spring. The final letter identifies the tides i.e. "N" for neap tide, and "S" for spring tide. The numbers following the letters indicate the different sampling times. Finally, the table also contains the letters "H/T", which represents high tide, and L/T, which represents low tide. The raw data and calculations for this study are attached as Appendix A.

Since flow velocity reaches zero or near zero as the tide changes, minimal or no transport of material occurs at this time. Hence, in the presentation of data that follows, sampling carried out at times corresponding to low/no flow conditions have been omitted.

Table 5.1: Field data and calculated flux for the Tongati Estuary

Sample	Tide	Ebb/Flood	Area (m^2)	Mean Velocity (m/s)	Nitrate Conc. (kg/m^3)	Flux (kg/s)
TSUN 1	H/T	FLOOD	7.77	0.48	0.35	1.30
TSUN 2		EBB	7.77	0.76	0.38	2.27
TSUN 3		EBB	7.14	0.78	0.31	1.71
TSUN 4	L/T	EBB	6.93	0.74	0.24	1.22
TSUS 1	L/T	EBB	4.00	0.66	0.10	0.27
TSUS 2		EBB	3.20	0.70	0.14	0.32
TSUS 3		FLOOD	6.40	0.30	0.07	0.13
TSUS 4	H/T	FLOOD	12.00	0.07	0.03	0.03
TAN 1	H/T	EBB	3.00	0.61	0.03	0.05
TAN 2		EBB	3.04	0.69	0.03	0.06
TAN 3		EBB	3.04	0.67	0.03	0.06
TAN 4	L/T	EBB	3.04	0.60	0.03	0.06
TAS 1	L/T	EBB	3.40	1.21	0.02	0.10
TAS 2		EBB	2.94	0.77	0.02	0.06
TAS 3		EBB	3.60	0.54	0.03	0.06
TAS 4	H/T	FLOOD	3.11	0.61	0.02	0.03
TWN 1	H/T	EBB	1.98	0.49	0.02	0.02
TWN 2		EBB	1.73	0.52	0.02	0.02
TWN 3		EBB	1.89	0.58	0.02	0.02
TWN 4	L/T	EBB	2.07	0.54	0.02	0.02
TWS 1	L/T	EBB	2.27	0.82	0.02	0.03
TWS 2		EBB	2.15	0.99	0.02	0.03
TWS 3		FLOOD	2.40	0.11	0.02	0.00
TWS 4	H/T	FLOOD	5.00	0.10	0.01	0.01
TSN 1	TO H/T	EBB	3.52	0.86	0.13	0.40
TSN 2	TO H/T	EBB	2.85	0.89	0.09	0.23
TSN 3	H/T	FLOOD	4.28	0.53	0.12	0.26
TSN 4	TO L/T	FLOOD	5.32	0.54	0.07	0.21
TSS 1	L/T	EBB	1.44	0.55	0.04	0.03
TSS 2		EBB	1.44	0.54	0.02	0.02
TSS 3		FLOOD	1.44	0.12	0.02	0.00
TSS 4	H/T	FLOOD	7.50	0.06	0.02	0.01

Table 5. 2: Field data and calculated flux for the Isipingo Estuary

Sample	Tide	Ebb/Flood	Area (m^2)	Nitrate Conc. (kg/m^3)	Mean Velocity (m/s)	Flux (kg/s)
ISUN 1	H/T	FLOOD	0.52	0.05	0.39	0.01
ISUN 2		EBB	0.40	0.07	0.56	0.02
ISUN 3		EBB	0.40	0.09	0.62	0.02
ISUN 4	L/T	EBB	0.40	0.11	0.85	0.04
ISUS 1	L/T	EBB	0.64	0.03	0.68	0.01
ISUS 2		EBB	0.60	0.04	0.38	0.01
ISUS 3		FLOOD	0.60	0.06	0.47	0.02
ISUS 4	H/T	FLOOD	1.00	0.03	0.56	0.02
IAN 1	H/T	EBB	0.46	0.02	0.87	0.01
IAN 2		EBB	0.42	0.02	0.84	0.01
IAN 3		EBB	0.46	0.02	0.87	0.01
IAN 4	L/T	EBB	0.42	0.02	0.92	0.01
IAS 1	H/T	FLOOD	0.80	0.02	1.57	0.02
IAS 2		FLOOD	1.20	0.01	0.95	0.02
IAS 3		EBB	1.34	0.02	0.56	0.01
IAS 4	L/T	EBB	1.40	0.01	0.52	0.01
IWN 1	H/T	FLOOD	0.64	0.02	0.43	0.00
IWN 2		EBB	0.54	0.02	0.34	0.00
IWN 3		EBB	0.60	0.02	0.25	0.00
IWN 4	L/T	EBB	0.70	0.02	0.28	0.00
IWS 1	L/T	EBB	0.72	0.02	0.76	0.01
IWS 2		EBB	0.76	0.02	0.63	0.01
IWS 3		EBB	0.80	0.01	0.68	0.01
IWS 4	H/T	FLOOD	1.62	0.01	0.55	0.01
ISN 1	H/T	FLOOD	1.08	0.02	0.13	0.00
ISN 2		EBB	0.76	0.02	0.32	0.01
ISN 3		EBB	0.96	0.02	0.53	0.01
ISN 4	L/T	EBB	0.96	0.02	0.61	0.01
ISS 1	L/T	EBB	0.56	0.04	0.38	0.01
ISS 2		EBB	0.56	0.04	0.33	0.01
ISS 3		EBB	0.80	0.04	0.24	0.01
ISS 4	H/T	FLOOD	1.20	0.02	1.68	0.04

The tables for the results of the Mgeni sampling are split into sections, each representing samples taken at specific points along the transect. For example, samples that are numbered 1 are samples that were taken from the first sampling point along the transect. Samples that are numbered 2 are samples that were taken from second sampling point along the transect, and so on. As stated in the methodology chapter, there were at least three samples taken for each transect. These samples were given the letters A, B, C etc. Therefore, sample 1A would be the very first sample taken during the first transect. The mean for nitrate concentration, velocity as well as net flux were calculated for the entire transect and is included in the tables in the row labeled “T MEAN”.

Table 5.3: Field data and calculated flux for the Mgeni Estuary

Sample	Tide	Ebb/Flood	Area (m^2)	Nitrate Conc. (kg/m^3)	Mean Velocity (m/s)	Flux (kg/s)
USUN1A			8.70	0.14	0.26	
USUN1B			11.70	0.14	0.25	
USUN1C			9.00	0.15	0.29	
T MEAN	H/T	FLOOD	**9.80**	**0.14**	**0.27**	**0.37**
USUN2A			5.10	0.08	0.25	
USUN2B			6.90	0.12	0.40	
USUN2C			9.44	0.11	0.39	
T MEAN		EBB	**7.15**	**0.10**	**0.35**	**0.26**
USUN3A			2.10	0.05	0.15	
USUN3B			15.00	0.16	0.78	
USUN3C			8.70	0.16	0.64	
T MEAN		EBB	**8.60**	**0.12**	**0.52**	**0.55**
USUN4A			13.80	0.13	0.64	
USUN4B			6.00	0.16	0.69	
USUN4C			8.40	0.16	0.66	
T MEAN	L/T	EBB	**9.40**	**0.15**	**0.66**	**0.93**
USUS1A			10.80	0.04	0.51	
USUS1B			4.80	0.04	0.25	
USUS1C			14.40	0.04	0.88	
USUS1D			11.50	0.04	1.02	
T MEAN	TO L/T	EBB	**10.38**	**0.04**	**0.67**	**0.27**
USUS2A			9.30	0.05	0.57	
USUS2B			2.40	0.09	0.29	
USUS2C			8.10	0.10	0.39	
USUS2D			15.60	0.12	0.83	
T MEAN	TO H/T	EBB	**8.85**	**0.09**	**0.52**	**0.42**
USUS3A			12.45	0.09	0.12	
USUS3B			6.30	0.11	0.11	
USUS3C			17.40	0.12	0.22	
T MEAN	TO H/T	FLOOD	**12.05**	**0.11**	**0.15**	**0.19**
USUS4A			6.30	0.01	0.13	
USUS4B			8.10	0.02	0.12	
USUS4C			22.50	0.02	0.21	
T MEAN	TO H/T	FLOOD	**12.30**	**0.01**	**0.15**	**0.03**

Table 5.3: Field data and calculated flux for the Mgeni Estuary (continued…)

Sample	Tide	Ebb/Flood	Area (m^2)	Nitrate Conc. (kg/m^3)	Mean Velocity (m/s)	Flux (kg/s)
UAN1A			4.50	0.01	0.51	
UAN1B			10.50	0.01	0.56	
UAN1C			13.20	0.01	0.53	
UAN1D			17.25	0.01	0.53	
T MEAN	H/T	FLOOD	**11.36**	**0.01**	**0.53**	**0.09**
UAN2A			6.00	0.01	0.51	
UAN2B			9.75	0.02	0.50	
UAN2C			10.50	0.01	0.52	
UAN2D			15.00	0.01	0.56	
UAN2E			12.00	0.02	0.50	
T MEAN		FLOOD	**10.65**	**0.02**	**0.52**	**0.09**
UAN3A			3.00	0.02	0.50	
UAN3B			7.50	0.02	0.53	
UAN3C			11.40	0.02	0.61	
UAN3D			13.50	0.02	0.72	
UAN3E			4.40	0.02	0.53	
T MEAN		EBB	**7.96**	**0.02**	**0.58**	**0.08**
UAN4A			1.50	0.02	0.50	
UAN4B			4.50	0.02	0.56	
UAN4C			6.30	0.02	0.54	
UAN4D			11.70	0.02	0.60	
UAN4E			15.75	0.02	0.71	
T MEAN	L/T	EBB	**7.95**	**0.02**	**0.58**	**0.08**
UAS1A			3.75	0.01	0.50	
UAS1B			9.75	0.02	0.57	
UAS1C			10.50	0.02	0.58	
UAS1D			5.22	0.02	0.58	
T MEAN	L/T	EBB	**7.31**	**0.02**	**0.56**	**0.07**
UAS2A			1.50	0.01	0.53	
UAS2B			7.50	0.02	0.53	
UAS2C			8.25	0.02	0.55	
UAS2D			4.50	0.02	0.76	
UAS2E			1.50	0.02	0.53	
T MEAN		EBB	**4.65**	**0.02**	**0.58**	**0.05**
UAS3A			4.50	0.01	0.68	
UAS3B			11.25	0.01	0.51	
UAS3C			12.00	0.01	0.51	
T MEAN		FLOOD	**9.25**	**0.01**	**0.57**	**0.07**
UAS4A			4.50	0.01	0.52	
UAS4B			12.00	0.01	0.53	
UAS4C			18.00	0.01	0.83	
T MEAN	H/T	FLOOD	**11.50**	**0.01**	**0.63**	**0.09**

Table 5.3: Field data and calculated flux for the Mgeni Estuary (continued…)

Sample	Tide	Ebb/Flood	Area (m^2)	Nitrate Conc. (kg/m^3)	Avg. Velocity (m/s)	Flux (kg/s)
UWN1A			4.50	0.02	0.52	
UWN1B			12.75	0.02	0.58	
UWN1C			13.80	0.02	0.51	
UWN1D			15.75	0.02	0.60	
UWN1E			17.25	0.02	0.50	
UWN1F			9.20	0.02	0.51	
AVG.	H/T	FLOOD	**12.21**	**0.02**	**0.53**	**0.11**
UWN2A			2.70	0.02	0.55	
UWN2B			10.50	0.02	0.52	
UWN2C			12.75	0.02	0.52	
UWN2D			11.70	0.02	0.55	
UWN2E			13.50	0.02	0.90	
AVG.		EBB	**10.23**	**0.02**	**0.61**	**0.11**
UWN3A			7.80	0.01	0.52	
UWN3B			9.30	0.01	0.61	
UWN3C			7.35	0.02	0.51	
UWN3D			9.30	0.01	0.57	
AVG.		EBB	**8.44**	**0.01**	**0.55**	**0.07**
UWN4A			4.50	0.01	0.50	
UWN4B			6.75	0.02	0.56	
UWN4C			5.25	0.02	0.57	
UWN4D			7.95	0.02	0.66	
UWN4E			6.30	0.02	0.62	
AVG.	L/T	EBB	**6.15**	**0.02**	**0.58**	**0.06**
UWS1A			3.00	0.01	0.59	
UWS1B			8.70	0.02	0.56	
UWS1C			12.45	0.02	0.52	
UWS1D			9.75	0.02	0.58	
UWS1E			14.70	0.02	0.65	
AVG.	L/T	EBB	**9.72**	**0.02**	**0.58**	**0.09**
UWS2A			5.70	0.02	0.56	
UWS2B			6.75	0.02	0.53	
UWS2C			9.75	0.02	0.68	
UWS2D			6.30	0.02	0.63	
UWS2E			4.00	0.02	0.62	
AVG.		EBB	**6.50**	**0.02**	**0.60**	**0.06**
UWS3A			6.00	0.01	0.51	
UWS3B			10.50	0.02	0.55	
UWS3C			7.50	0.02	0.56	
UWS3D			7.80	0.01	0.54	
UWS3E			9.30	0.01	0.60	
AVG.		FLOOD	**8.22**	**0.01**	**0.55**	**0.06**
UWS4A			3.75	0.01	0.51	
UWS4B			10.50	0.01	0.56	
UWS4C			15.00	0.01	0.67	
UWS4D			9.75	0.01	0.66	
AVG.	H/T	FLOOD	**9.75**	**0.01**	**0.60**	**0.08**

Table 5.3: Field data and calculated flux for the Mgeni Estuary (continued…)

Sample	Tide	Ebb/Flood	Area (m^2)	Nitrate Conc. (kg/m^3)	Avg. Velocity (m/s)	Flux (kg/s)
USN1A			11.10	0.03	0.26	
USN1B			9.00	0.04	0.23	
USN1C			3.00	0.04	0.28	
AVG.	L/T	EBB	**7.70**	**0.04**	**0.26**	**0.07**
USN2A			1.50	0.02	0.01	
USN2B			1.50	0.03	0.08	
USN2C			12.90	0.02	0.33	
USN2D			13.50	0.02	0.45	
USN2E			7.60	0.02	0.23	
AVG.		EBB	**7.40**	**0.02**	**0.22**	**0.04**
USN3A			6.90	0.02	0.11	
USN3B			3.00	0.02	0.21	
USN3C			6.00	0.02	0.28	
USN3D			18.00	0.02	0.30	
AVG.		EBB	**8.48**	**0.02**	**0.23**	**0.04**
USN4A			10.50	0.02	0.02	
USN4B			7.80	0.02	0.01	
USN4C			9.30	0.02	0.07	
USN4D			22.50	0.02	0.23	
AVG.	H/T	FLOOD	**12.53**	**0.02**	**0.08**	**0.02**
USS1A			3.90	0.02	0.02	
USS1B			2.40	0.03	0.25	
USS1C			12.90	0.03	0.72	
AVG.	TO L/T	EBB	**6.40**	**0.02**	**0.33**	**0.05**
USS2A			2.10	0.02	0.02	
USS2B			9.60	0.02	0.62	
USS2C			6.90	0.02	0.55	
USS2D			12.90	0.02	0.54	
AVG.	L/T	EBB	**7.88**	**0.02**	**0.43**	**0.07**
USS3A			9.30	0.02	0.03	
USS3B			6.30	0.03	0.06	
USS3C			5.00	0.03	0.07	
AVG.	TO H/T	EBB	**6.87**	**0.03**	**0.05**	**0.01**
USS4A			5.40	0.02	0.03	
USS4B			3.60	0.02	0.08	
USS4C			4.80	0.02	0.24	
USS4D			17.70	0.02	0.35	
AVG.	TO H/T	FLOOD	**7.88**	**0.02**	**0.17**	**0.03**

5.2 Determining the Net Flux of Nitrates Over a Tidal Cycle

The flux of nitrates presented in the foregoing tables represent the rate of nitrate transfer (in kg/s) at a point in time or the instantaneous flux rate. Instantaneous fluxes thus calculated were integrated over the complete tidal cycle (flood and ebb components). The product of the mean of successive instantaneous flux rates (F_1 and F_2) and the time duration between these (T_1 and T_2) yields the net flux (in kg) for this period. The sum of all such net fluxes for each component of the tidal cycle (flood and ebb) yields the total flux, TF, for the tidal component.

$$TF = \sum \{(F_1 + F_2)/2 * (T_2 - T_1)\} \qquad \text{(eg. 2)}$$

$$TF_{tc} = \sum_{TF=1}^{n} TF \qquad \text{(eq. 2.2)}$$

If $TF_{EBB} > TF_{FLOOD}$, the value will be positive, meaning that overall, nitrates in the system are being lost from the land to the sea. If $TF_{FLOOD} > TF_{EBB}$, the value will be negative, implying that the system is gaining nitrates from the sea. The results of the above calculation are presented as follows:

Table 5.4: Results of the net flux determinations over complete tidal cycles: Tongati

Sample	Tide	Ebb/Flood	Flux (kg/s)	Flux f(t) (kg)	Net Flux (kg)
TSUN 1	H/T	FLOOD	1.30	9353.48	
TSUN 2		EBB	2.27	16343.07	
TSUN 3		EBB	1.71	12298.73	
TSUN 4	L/T	EBB	1.22	8803.26	28092
TSUS 1	L/T	EBB	0.27	1933.79	
TSUS 2		EBB	0.32	2294.53	
TSUS 3		FLOOD	0.13	917.63	
TSUS 4	H/T	FLOOD	0.03	193.92	3117
TAN 1	H/T	EBB	0.05	345.04	
TAN 2		EBB	0.06	437.68	
TAN 3		EBB	0.06	426.79	
TAN 4	L/T	EBB	0.06	443.41	1653
TAS 1	L/T	EBB	0.10	724.21	
TAS 2		EBB	0.06	403.95	
TAS 3		EBB	0.06	450.70	
TAS 4	H/T	FLOOD	0.03	246.13	1333
TWN 1	H/T	EBB	0.02	139.79	
TWN 2		EBB	0.02	116.31	
TWN 3		EBB	0.02	131.84	
TWN 4	L/T	EBB	0.02	141.87	530
TWS 1	L/T	EBB	0.03	230.05	
TWS 2		EBB	0.03	250.95	
TWS 3		FLOOD	0.00	32.66	
TWS 4	H/T	FLOOD	0.01	43.92	404
TSN 1	TO H/T	EBB	0.40	2854.19	
TSN 2	TO H/T	EBB	0.23	1690.59	
TSN 3	H/T	FLOOD	0.26	1867.88	
TSN 4	TO L/T	FLOOD	0.21	1494.04	1183
TSS 1	L/T	EBB	0.03	231.40	
TSS 2		EBB	0.02	110.99	
TSS 3		FLOOD	0.00	28.34	
TSS 4	H/T	FLOOD	0.01	49.09	265

The Tongati estuary is characterized by tidal asymmetry during neap tides with the exception of the spring season. As this is a perched estuary, ebb flows tend to be strong and dominant, hence the system exports nitrates and other material throughout the year. A seasonal variation in net flux is evident as fluvial flows that enhance ebbing are greater in summer and diminishes through autumn and winter and only begins to increase again in late spring.

Table 5.5: Results of net flux determinations over complete tidal cycles: Isipingo

Sample	Tide	Ebb/Flood	Flux (kg/s)	Flux f(t) (kg)	Net Flux (kg)
ISUN 1	H/T	FLOOD	0.01	70.85	
ISUN 2		EBB	0.02	108.52	
ISUN 3		EBB	0.02	167.44	
ISUN 4	L/T	EBB	0.04	271.17	476
ISUS 1	L/T	EBB	0.01	105.94	
ISUS 2		EBB	0.01	61.69	
ISUS 3		FLOOD	0.02	114.49	
ISUS 4	H/T	FLOOD	0.02	109.99	-57
IAN 1	H/T	EBB	0.01	71.40	
IAN 2		EBB	0.01	54.11	
IAN 3		EBB	0.01	62.15	
IAN 4	L/T	EBB	0.01	69.19	257
IAS 1	H/T	FLOOD	0.02	158.91	
IAS 2		FLOOD	0.02	119.18	
IAS 3		EBB	0.01	91.47	
IAS 4	L/T	EBB	0.01	66.61	-120
IWN 1	H/T	FLOOD	0.00	30.64	
IWN 2		EBB	0.00	22.53	
IWN 3		EBB	0.00	18.44	
IWN 4	L/T	EBB	0.00	22.13	32
IWS 1	L/T	EBB	0.01	64.23	
IWS 2		EBB	0.01	52.14	
IWS 3		EBB	0.01	57.89	
IWS 4	H/T	FLOOD	0.01	91.60	83
ISN 1	H/T	FLOOD	0.00	18.35	
ISN 2		EBB	0.01	40.86	
ISN 3		EBB	0.01	71.27	
ISN 4	L/T	EBB	0.01	75.51	169
ISS 1	L/T	EBB	0.01	61.80	
ISS 2		EBB	0.01	53.89	
ISS 3		EBB	0.01	55.27	
ISS 4	H/T	FLOOD	0.04	287.32	-116

The Isipingo estuary is a unique system in that tidal exchange is maintained continuously *via* twin pipes connecting the estuary with the nearshore environment. Tidal asymmetry is a common feature throughout the year except when strong spring tides prevail as was the case in summer and autumn of this study. During these times, nitrates were imported from the marine environment and into the estuary. The spring tide of the spring season also recorded nitrate import. At all other times, the ebb tide was dominant, resulting in a seaward flux of nitrates.

Table 5.6: Results of net flux determinations over complete tidal cycles: Mgeni

Site	Tide	Ebb/Flood	Flux (kg/s)	Flux f(t) (kg)	Net Flux (kg)
USUN T1	H/T	FLOOD	0.37	2676.34	
USUN T2		EBB	0.26	1838.97	
USUN T3		EBB	0.55	3994.45	
USUN T4	L/T	EBB	0.93	6696.73	9854
USUS T1	TO L/T	EBB	0.27	1959.95	
USUS T2	TO H/T	EBB	0.42	2992.30	
USUS T3	TO H/T	FLOOD	0.19	1333.86	
USUS T4	TO H/T	FLOOD	0.03	201.60	3417
UAN T1	H/T	FLOOD	0.09	615.04	
UAN T2		FLOOD	0.09	622.81	
UAN T3		EBB	0.08	588.31	
UANT4	L/T	EBB	0.08	552.07	-97
UAS T1	L/T	EBB	0.07	489.17	
UAS T2		EBB	0.05	342.08	
UAS T3		FLOOD	0.07	472.99	
UAS T4	H/T	FLOOD	0.09	625.63	-267
UWN T1	H/T	FLOOD	0.11	813.09	
UWN T2		EBB	0.11	794.14	
UWN T3		EBB	0.07	473.67	
UWN T4	L/T	EBB	0.06	406.72	861
UWS T1	L/T	EBB	0.09	653.22	
UWS T2		EBB	0.06	442.62	
UWS T3		FLOOD	0.06	462.07	
UWS T4	H/T	FLOOD	0.08	560.25	74
USN T1	L/T	EBB	0.07	529.17	
USN T2		EBB	0.04	282.28	
USNT3		EBB	0.04	301.18	
USN T4	H/T	FLOOD	0.02	144.17	968
USS T1	TO L/T	EBB	0.05	375.93	
USS T2	L/T	EBB	0.07	526.63	
USS T3	TO H/T	EBB	0.01	69.81	
USS T4	TO H/T	FLOOD	0.03	189.51	783

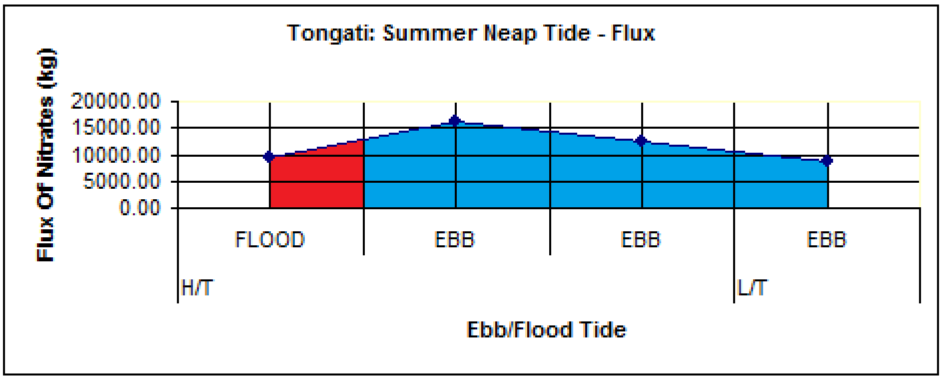
The Mgeni system is the largest of the three estuaries studied and demonstrated some tidal asymmetry, particularly during neap tides. With the exception of the autumn season, when nitrates were imported on both the spring and neap tides, the system was export oriented. The largest amounts of nitrates exported coincided with summer when fluvial flows and ebbing were the greatest. In a similar study, Pato *et al*., (2008) determined that the flux of mercury between an impacted coastal lagoon and the Atlantic Ocean similarly varied with seasonality and tidal regime.

5.3 Flux of Nitrates Over the Tidal Cycle

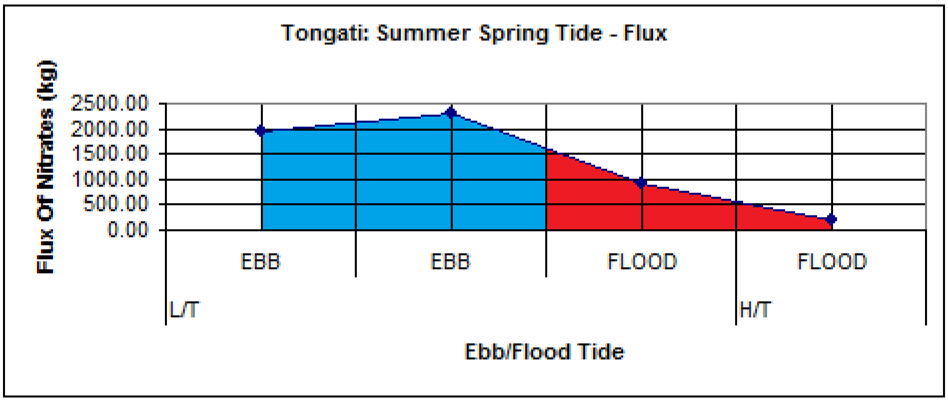
The flux of nitrates over complete tidal cycles are presented in the following series of graphs which provides a visual impression of the amount of nitrates transported into or out of the three systems studied. Where appropriate, brief explanations of the graphs are given, however the reasons and implications for the results below will be discussed in more detail in the following chapter.

TONGATI

Summer: Neap Tide

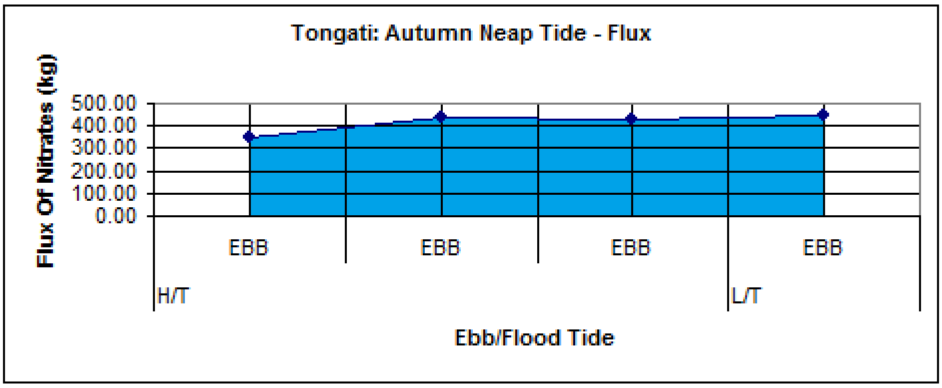


Summer: Spring Tide

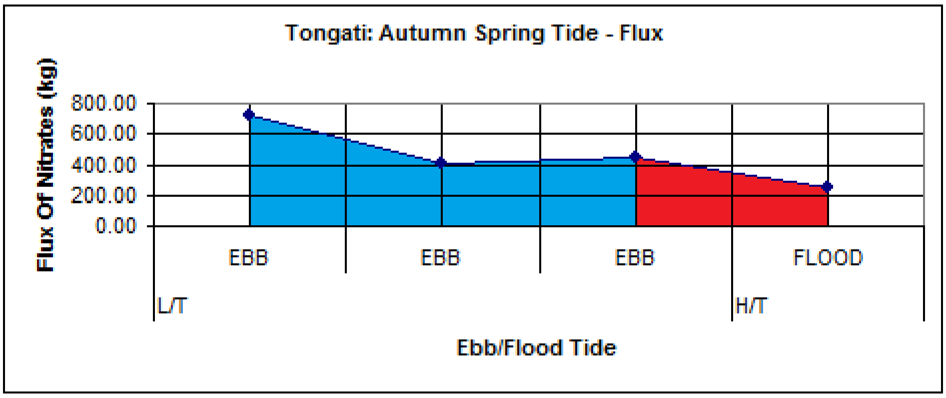


The graphs above show the results for the flux of nitrates in the Tongati estuary in summer. During neap tide, the Tongati displayed a longer period of ebbing of six hours, and only two hours of flooding. On the neap tide, the estuary transports more nitrates to the nearshore environment than what is being transported into the estuary on the flood tide. Tidal symmetry characterizes the spring tide and similar nitrates export occurs.

Autumn: Neap Tide

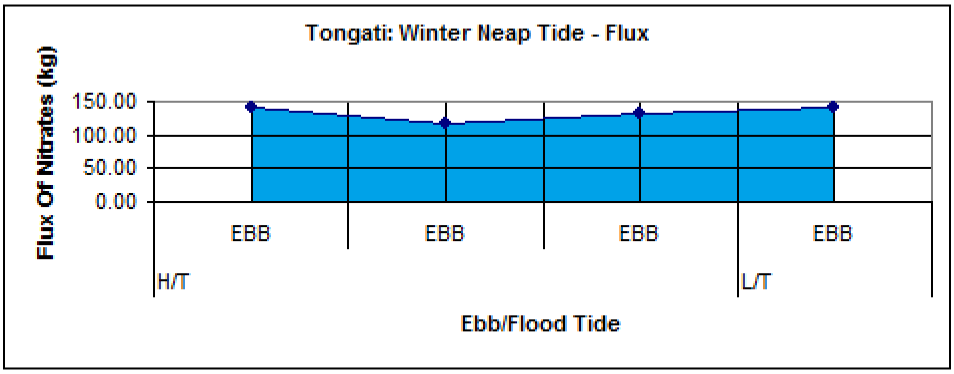


Autumn: Spring Tide

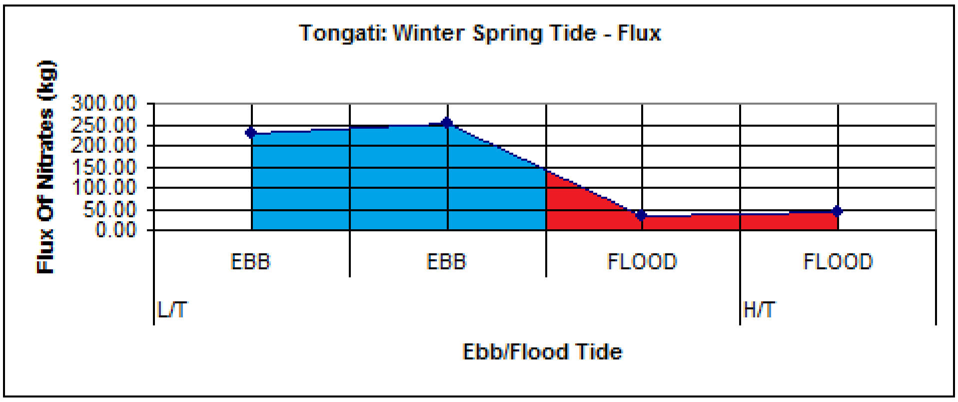


The Tongati estuary is dominantly ebb flow in autumn with limited import occurring for a short duration of the spring tide.

Winter: Neap Tide

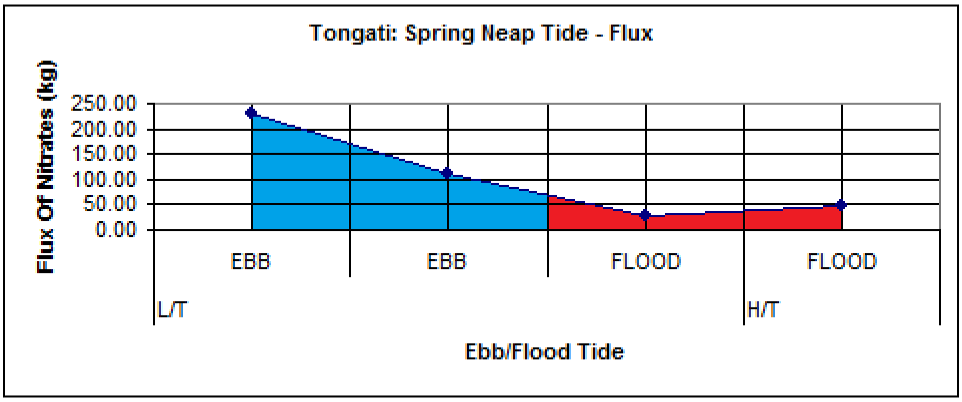


Winter: Spring Tide

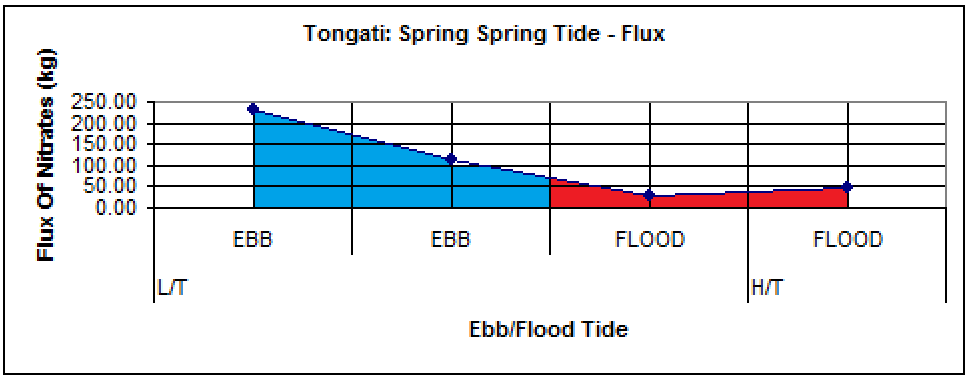


During the winter, the Tongati was still strongly ebb dominated despite tidal symmetry being achieved during the spring tide.

Spring: Neap Tide



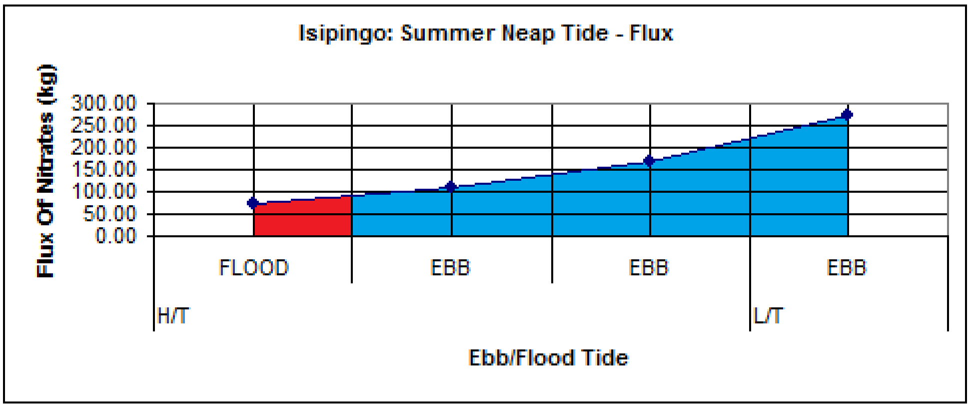
Spring: Spring Tide



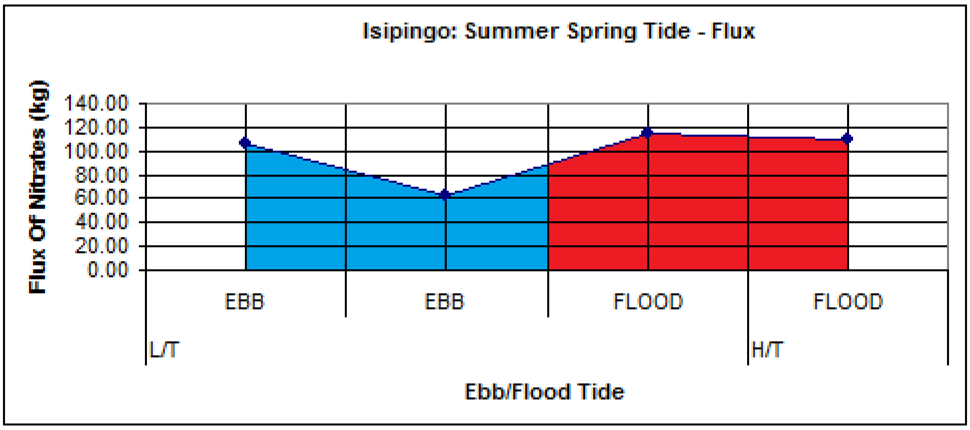
Tidal symmetry was maintained during both neap and spring tides of the spring season. However, the net transport was in the seaward direction due to the higher volumes achieved on the ebb tide.

ISIPINGO

Summer: Neap Tide

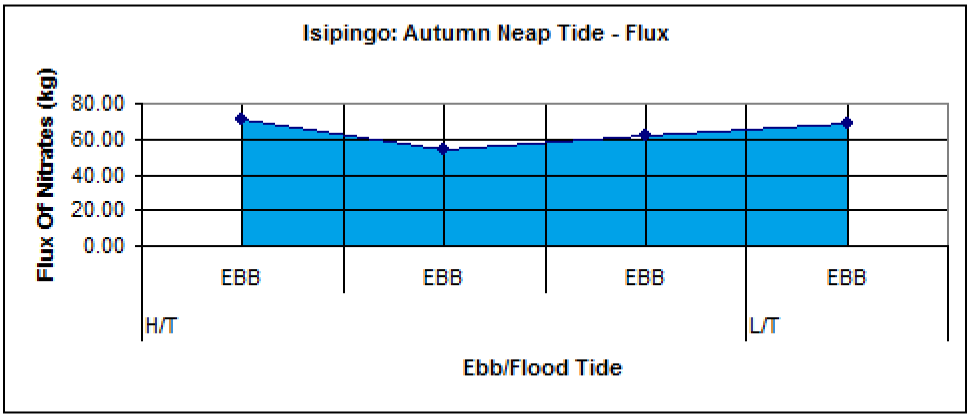


Summer: Spring Tide

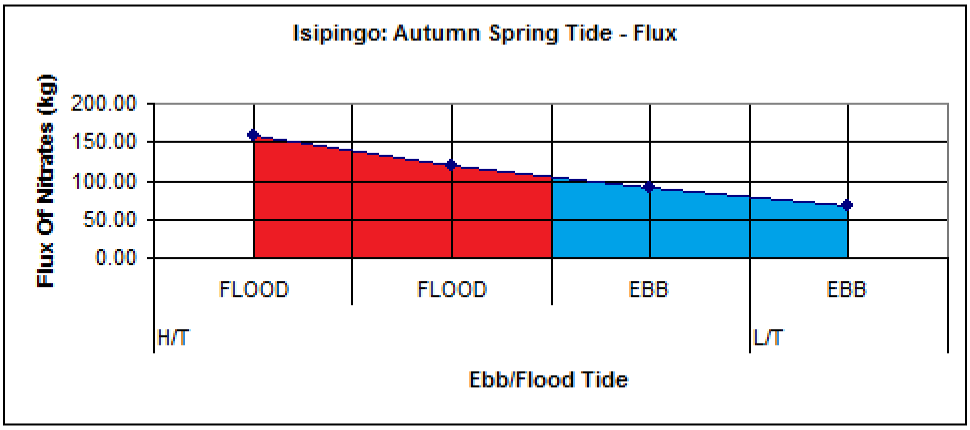


The Isipingo system is ebb dominated during the neap tide but assumes tidal symmetry upon flooding. Flooding on the spring tide surprisingly brought in large amounts of nitrates. These results are explained further in the next chapter.

Autumn: Neap Tide

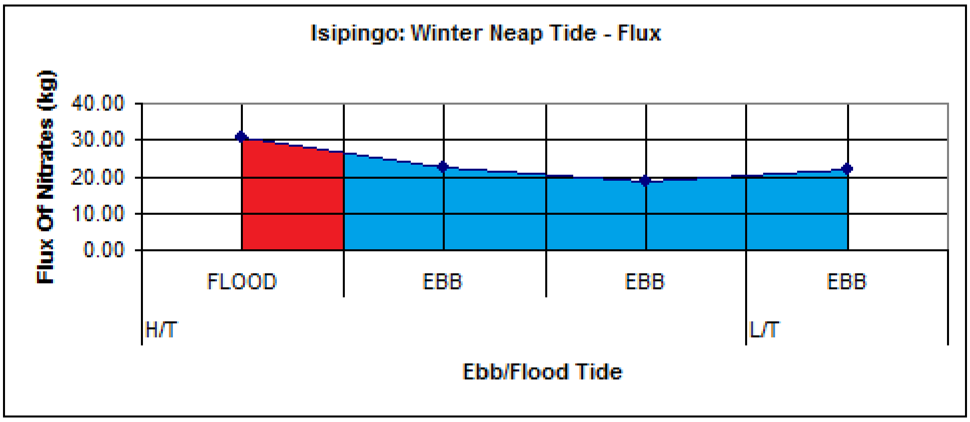


Autumn: Spring Tide

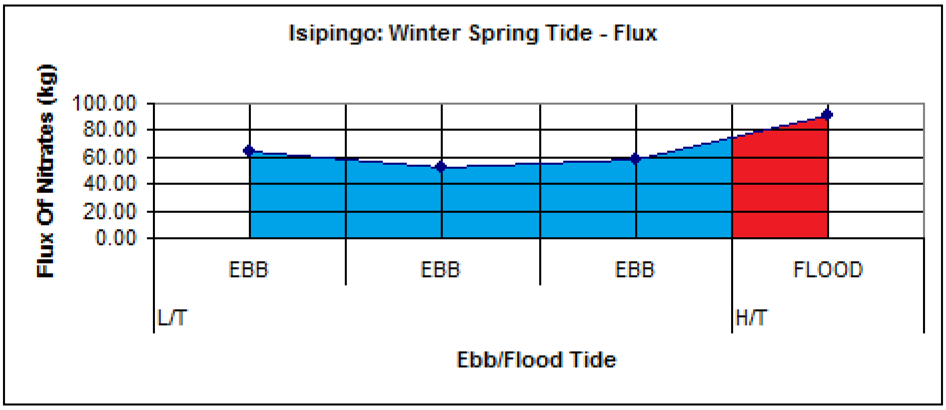


The Isipingo is strongly ebb dominated during the autumn neap episode. On the autumn spring tide, considerably more nitrates are brought into the system than is exported.

Winter: Neap Tide

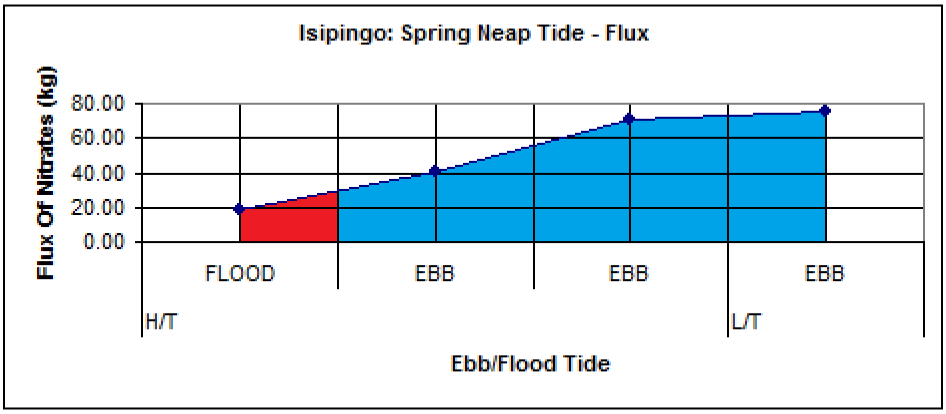


Winter: Spring Tide

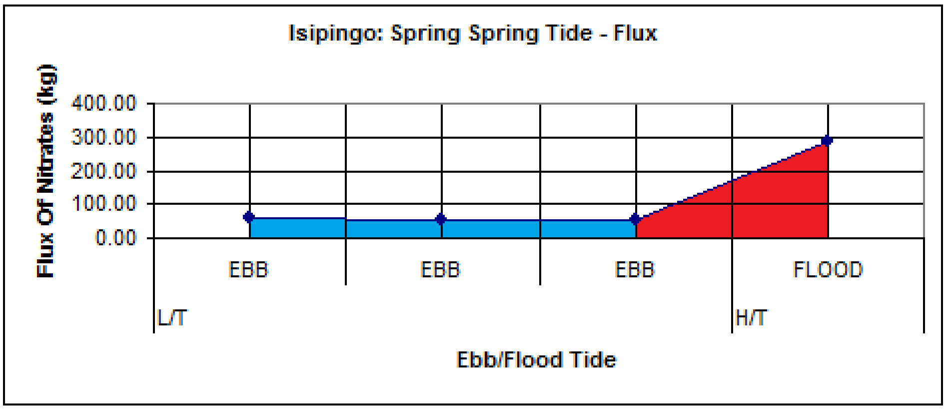


Ebb dominance is common in both spring and neap tides in winter for the Isipingo. Although there is protracted ebbing, larger quantities of nitrates enter the system during flooding.

Spring: Neap Tide



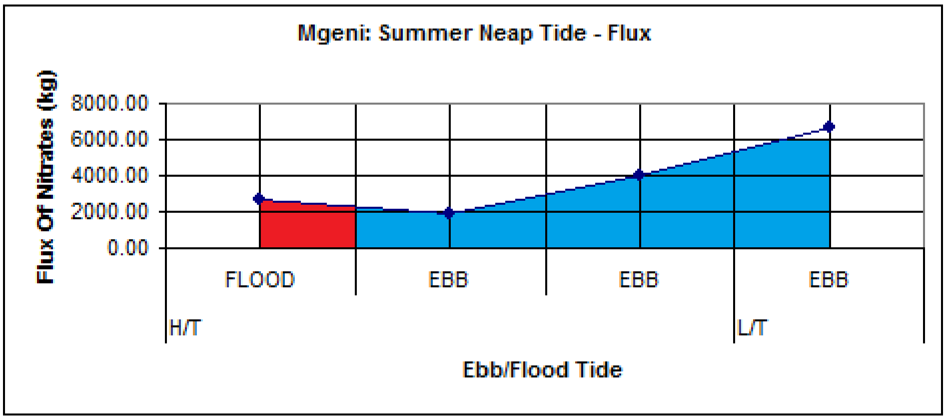
Spring: Spring Tide



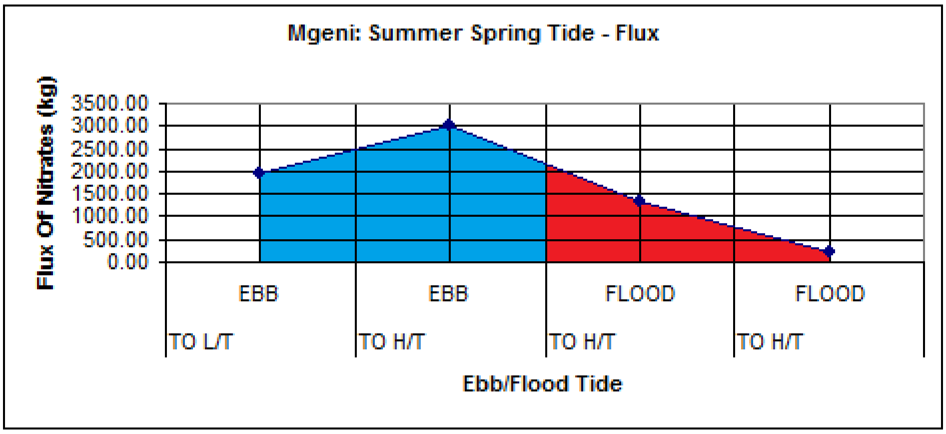
During neap tide, dominant ebbing occurred, with more nitrates being exported to the nearshore environment than what was being brought in the estuary on the flood tide from the marine environment. Dominant ebbing also occurred during the spring tide. However it is clear that there was a higher concentration of nitrates entering the estuary on the flood tide.

MGENI

Summer: Neap Tide

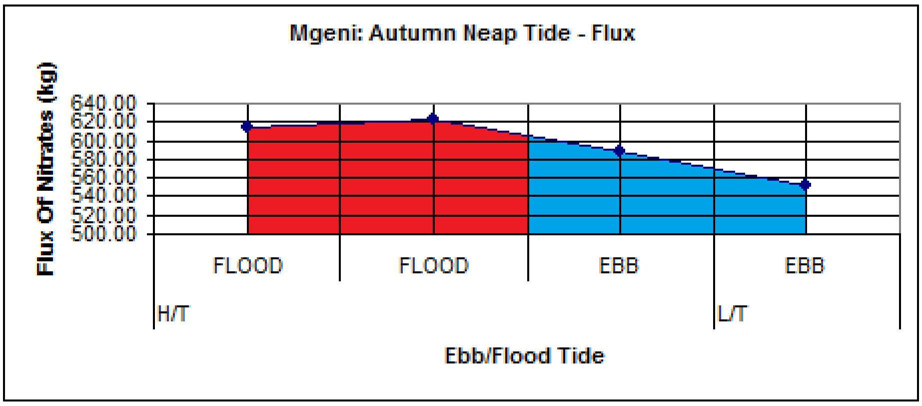


Summer: Spring Tide

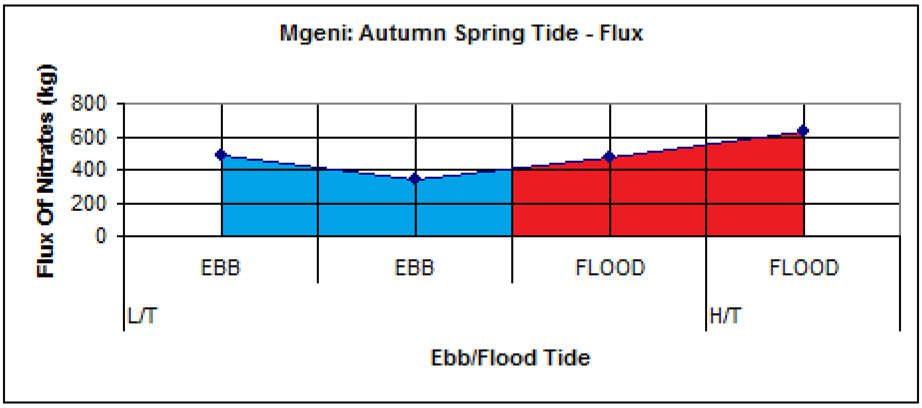


The graphs above show the results for the flux of nitrates in the Mgeni estuary for summer. The Mgeni displayed dominant ebbing (six out of eight hours), and exported a higher concentration of nitrates to the nearshore environment during this time. During the spring tide, there were equal periods of ebbing and flooding (four hours of each), and again the estuary exported more nitrates to the nearshore environment.

Autumn: Neap Tide

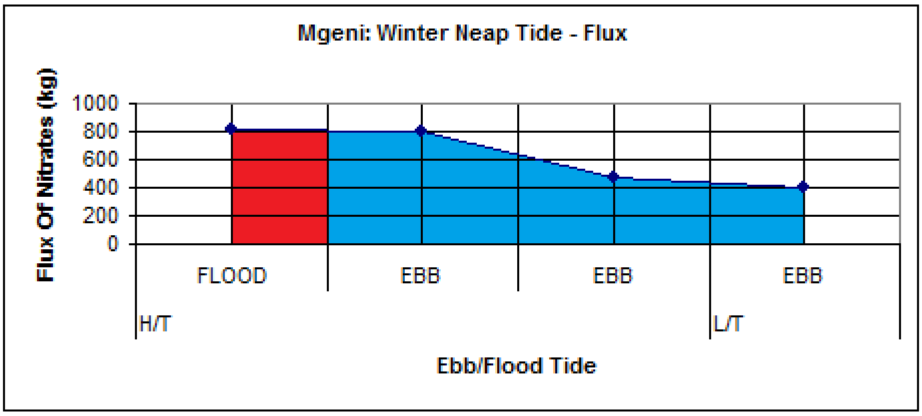


Autumn: Spring Tide

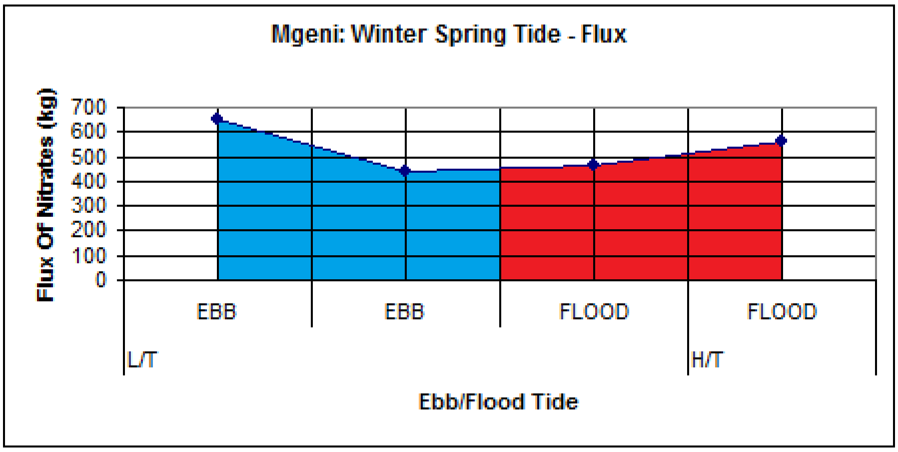


Tidal symmetry was preserved for both spring and neap tides of the autumn sampling. For both tides, import exceeded export of nitrates.

Winter: Neap Tide

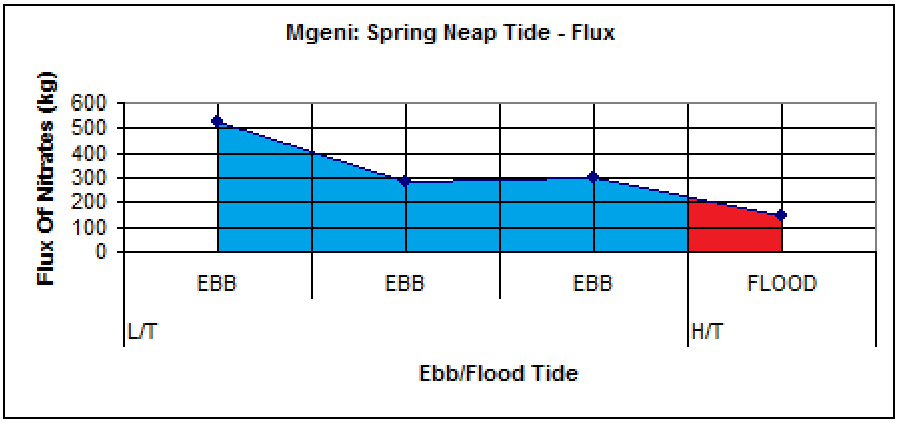


Winter: Spring Tide

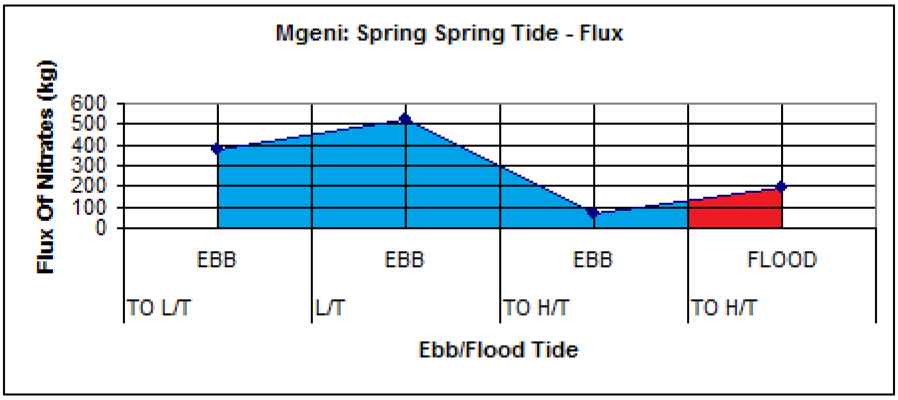


The winter season was characterized by ebb dominance on the neap tide. With the exception of the flood flow of the neap tide, export of nitrates to the nearshore environment was dominant for the remaining duration of the tides.

Spring: Neap Tide



Spring: Spring Tide



Finally, for the spring results, the system displayed strong ebbing and export of nitrates.

5.4 Seasonal neap and spring tide net flux variation

Figure 5.1 graphs the seasonal neap and spring tide net flux variation for the sampling times at the three estuaries. Figure 5.1A-C illustrates the flux dominance of neap tides in summer for all measurements with a pronounced increase late in the tidal cycle. The high fluxes for summer have been mentioned above and are attributed to high fluvial flows and primary productivity in the catchments. Increased nitrate concentrations measured late in the tidal cycle are thought to be due to greater resuspension of bed material as flow velocities and turbidity increases late in the ebb cycle. Over spring tides a similar pattern is evident for the Tongati and Mgeni estuaries. Figure 5.1F (Isipingo estuary) shows the effect of nitrate importation into the system from the marine environment early in the flood cycle during the spring season.

Figure 5.2 A-C shows the net nitrate flux for all neap tidal cycles sampled. Neap tides for each of the estuaries recorded highest nitrate concentrations in summer. The Tongati and Mgeni estuaries demonstrated consistently lower nitrate content in all other seasons. The Isipingo estuary showed a more varied pattern of concentrations reflective of the greater anthropogenic impact from its intensely utilized catchment. Over spring tides (Figure 5.2 D-F) some variation to this pattern occurs. The Tongati estuary recorded its highest nitrate output during the spring season as a consequence of the leaching of newly fertilized agricultural lands. The Mgeni system neap and spring tides are similar except for larger quantities of nitrates transported during neap tides. A good deal of variability occurs in the Isipingo system during spring tides (Figure 5.2F). Of interest is the large import of nitrates during the spring season.

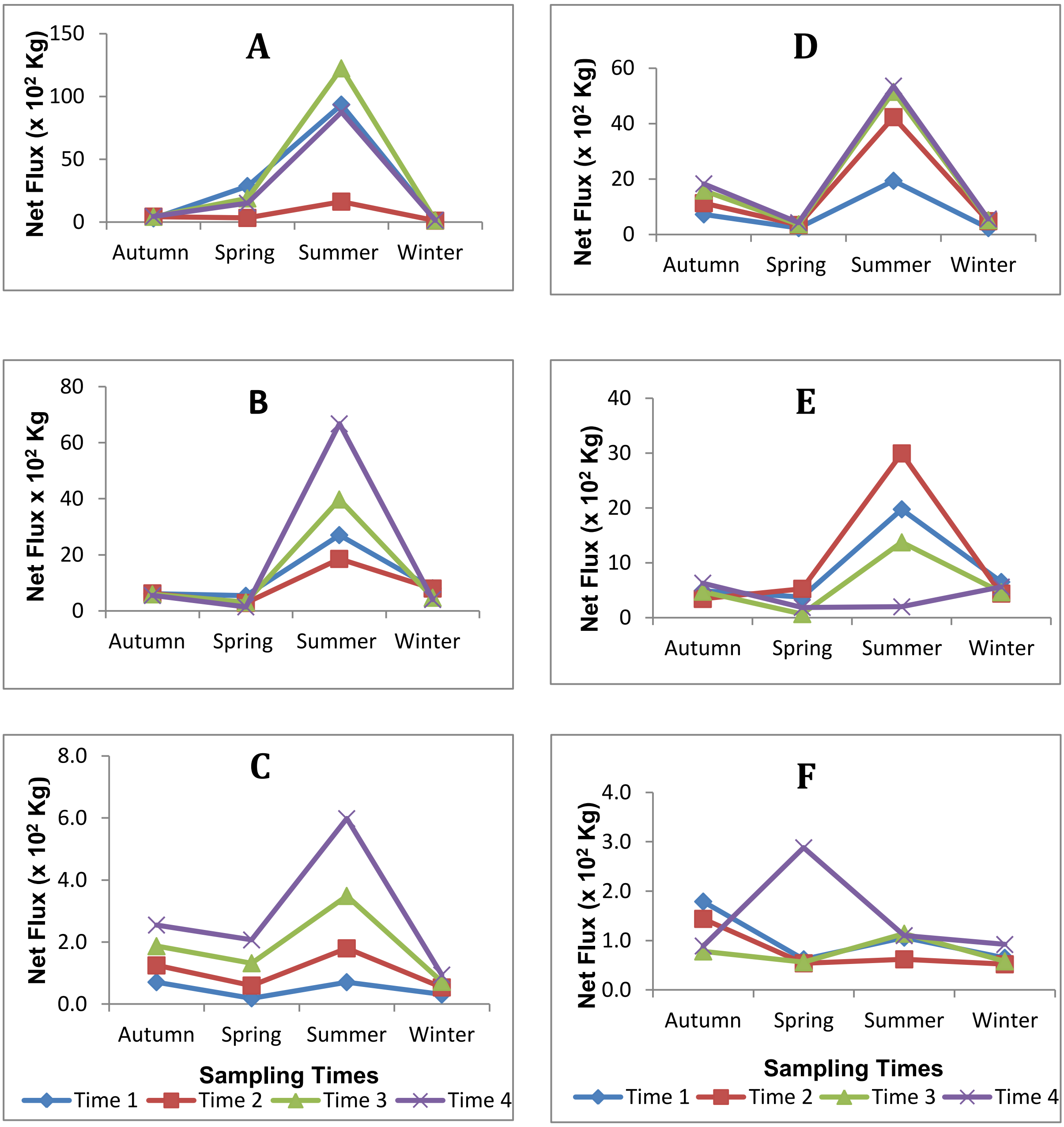


Figure 5.1: Seasonal neap tide nitrate flux of the (A) Tongati; (B) Mgeni and (C) Isipingo estuaries, and seasonal spring tide nitrate flux of the (D) Tongati; (E) Mgeni and (F) Isipingo.

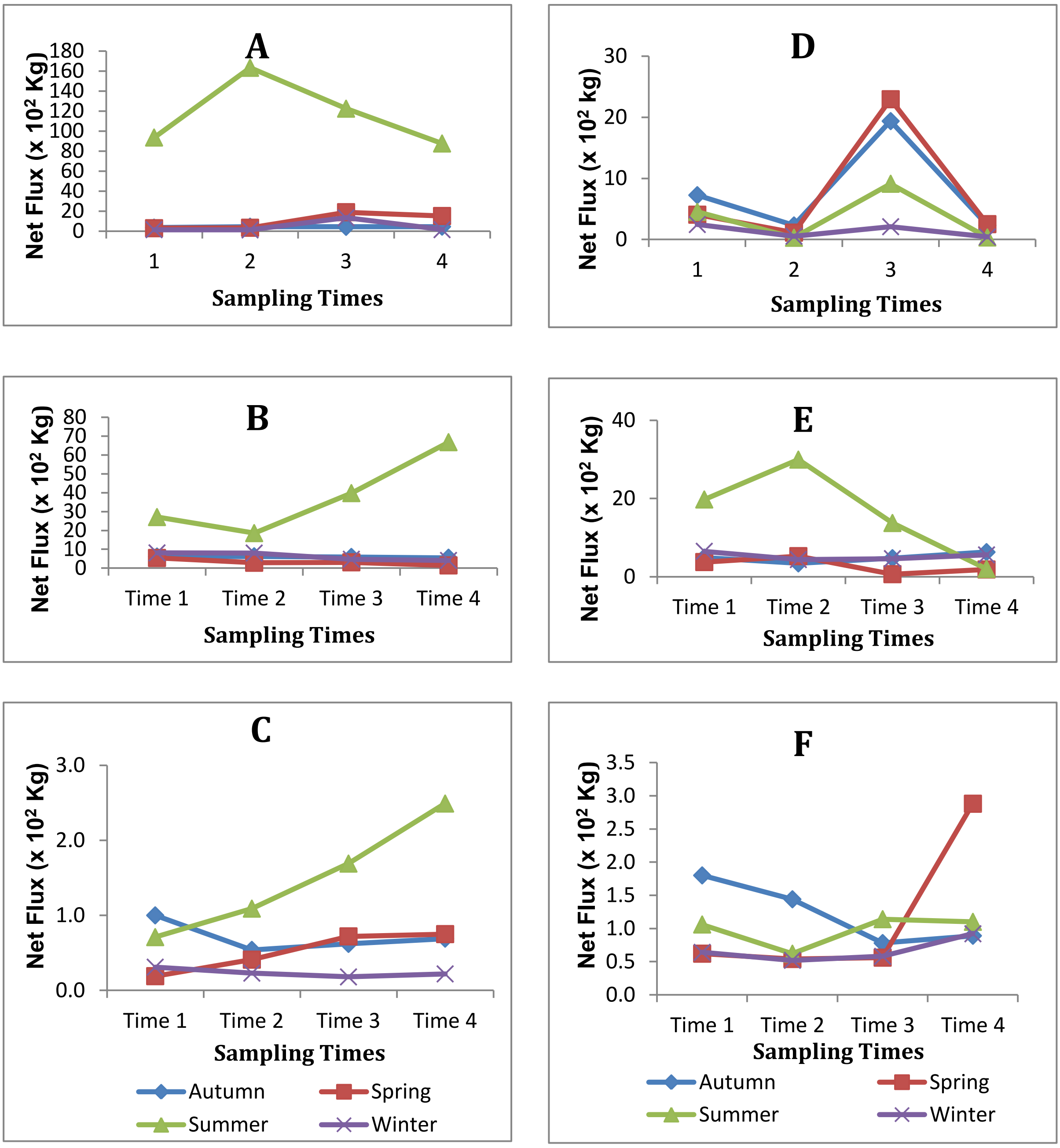


Figure 5.2: Temporal neap tide net flux of the (A) Tongati; (B) Mgeni and (C) Isipingo estuaries through seasonal tidal cycles, and the temporal spring tide net flux of the (D) Tongati; (E) Mgeni and (F) Isipingo estuaries through seasonal tidal cycles.

5.5 Analysis of Variance of Seasonal Net Flux

Results of the analysis of variance (ANOVA) of seasonal net flux over neap and spring tides are presented in Table 5.7. Comparing mean nitrate fluxes over tides (neap/spring) for all three estuaries yields no significant differences (tidal $F_{T,}$ F_M, F_I < F_{Crit}) whilst significant variation in seasonal fluxes occurred in the Tongati and Mgeni estuaries. Nitrate fluxes for the Isipingo estuary yielded no significant seasonal variation. These results are consistent with the interpretation extrapolated from the graphs. ANOVA results also showed greater flux variance for neap tides than spring tides and in summer months for the Tongati and Mgeni estuaries. For the Isipingo estuary, greater variance occurred during spring tides and the spring season. All of these results are consistent with the interpretation extrapolated from the graphs above.

Table 5.7: **Results of ANOVA of Nitrate Fluxes for Tide Type (Neap/Spring) and Seasonality**

Source of Variation	df	MS_T	F_T	MS_M	F_M	MS_I	F_I	F_{Crit}
Tides	7	1.1E+7	1.25	9.08+5	0.91	3.7E+3	1.16	2.49
Seasons	3	7.3E+7	8.38	1.02E+8	10.27	8.4E+3	2.61	3.07

MS = Mean Squares; T = Tongati; M = Mgeni; I = Isipingo

5.6 Conclusion

Data from the field surveys were collated and used to calculate the net flux of nitrates for the three estuaries. These results were then presented in the tables and graphs as shown previously. A more summarized version of the results are given in the tables below.

The aim of this study was to determine whether the Isipingo, Tongati, and Mgeni estuaries were efficiently exporting nitrates to the nearshore environment. The results indicate that this is indeed the case. Although in some cases there were more nitrates entering the estuary at peak high tide than were being exported out the estuary at peak low tide, overall the NET flux of nitrates suggests that the estuary is overall losing nitrates to the nearshore environment. Table 5.8 below shows that exceptions to the general trend occurred during the spring tides of the summer, autumn and spring seasons in the Isipingo estuary and for both the tides of the autumn season at the Mgeni estuary. The Tongati displayed export of nitrates throughout the survey period.

Table 5.8: Summarized Results For The Tongati Estuary

Season	Tide	Nitrates Exported
Summer	Neap	Yes
	Spring	Yes
Autumn	Neap	Yes
	Spring	Yes
Winter	Neap	Yes
	Spring	Yes
Spring	Neap	Yes
	Spring	Yes

Table 5.9: Summarized Results For The Isipingo Estuary

Season	Tide	Nitrates Exported
Summer	Neap	Yes
	Spring	No
Autumn	Neap	Yes
	Spring	No
Winter	Neap	Yes
	Spring	Yes
Spring	Neap	Yes
	Spring	No

Table 5.10: Summarized Results For The Mgeni Estuary

Season	Tide	Nitrates Exported
Summer	Neap	Yes
	Spring	Yes
Autumn	Neap	No
	Spring	No
Winter	Neap	Yes
	Spring	Yes
Spring	Neap	Yes
	Spring	Yes

CHAPTER 6: DISCUSSION

6.1 Introduction

This chapter provides an interpretation of the results which were presented in the previous chapter. This chapter will:

- Identify the various land uses that occur around the estuaries using satellite images;
- Attempt to determine the sources of nitrates found in the Tongati, Isipingo, and Mgeni estuaries;
- Analyse the flux of nitrates through changing tidal conditions in the Tongati, Isipingo, and Mgeni estuaries; and
- Discuss the net flux of nitrates in the Tongati, Isipingo, and Mgeni estuaries over full tidal cycles.

6.2 Source of Nitrates

In order to determine the source of nitrates in the Tongati, Isipingo, and Mgeni estuaries, it is necessary to identify the land uses surrounding the estuaries and rivers. Whilst nitrates occur naturally in the environment, the increasing occurrence of nitrates and nutrients due to anthropogenic influences is becoming problematic (Dallas and Day, 2004). Any activity that occurs in the vicinity of an estuary, upstream of an estuary and in the catchment as a whole, will have an impact on the estuary. Using photographic images (Google Earth, 2009), the various land uses that surround the estuaries were identified providing valuable insight into the possible sources of the measured concentrations of nitrates.

6.2.1 Tongati Estuary

The results clearly show that the Tongati estuary is an efficient export system. This follows as a consequence of its morphodynamic characteristics. The estuary is a perched, ebb dominated system with some spring tidal intrusion. The results also indicate that the Tongati system is the least impacted of the three estuaries studied. Figure 6.1 shows that the main land use surrounding the estuary is agriculture, more specifically, sugar cane cultivation. A development is currently under construction

(Zimbali Housing Estate) north of the estuary, however the impacts of this development are yet to be seen.

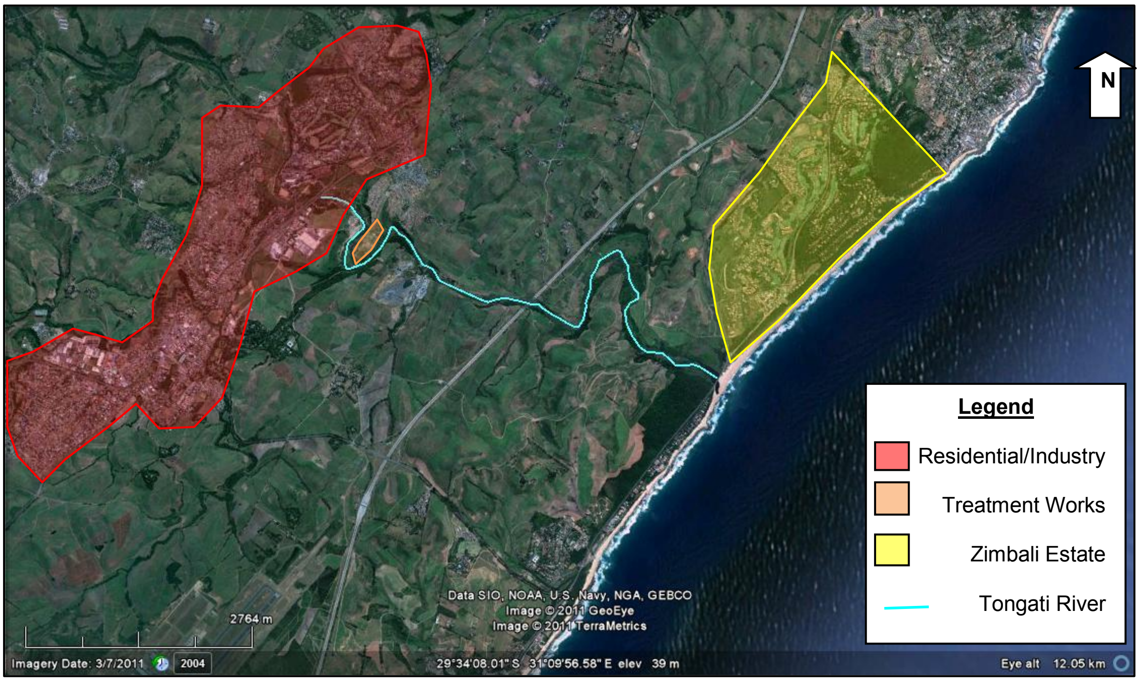


Figure 6.1: Satellite image showing the surrounding land use of the Tongati estuary (©Google Satellite Imagery, Imagery Date: 17/12/2009).

Except for a narrow strip of natural coastal forest, the area surrounding the estuary is intensively cultivated and this activity would be the major source of nitrates to the estuary.

Although the Tongati estuary and catchment is one of the smaller systems in KwaZulu-Natal, it yields extremely high amounts of nitrates to the sea, especially during summer and autumn. The reasons for this can be attributed to the fact that the catchment is mostly used for commercial sugarcane agriculture. The fields are generally fertilized prior to the summer rainfall season. Leaching of nitrates from these fields following summer rainfall causes strong fluvial flows and ebbing at the estuary mouth. This can result in massive amounts of dissolved material being exported to sea as was evident in the summer neap tide sampled (over 28 tonnes of nitrates moved from the estuary to the sea (refer to Table 5.4). Similar high nitrate exports from estuaries have also been attributed to leaching from agricultural lands by a host of researchers (Falco *et al.*, 2010; Sa'ncchez-Carrilloa *et al*., 2009; Mishima *et al*., 2011; and Wang *et al*.; 2011).

Instances of such over fertilization are mentioned by Loehr (1997) in studies conducted in the United States. Snow and Taljaard (2007) cite higher nitrate and phosphorus concentrations in river systems and estuaries bordered by agricultural activities than other human activities. Further, these authors report increasing volumes of these nutrients in the water body following high rainfall seasons. This is consistent with the results obtained in this study, particularly with the Tongati estuary.

Once nutrients from farmlands enter the river, they are diluted to a concentration dependant on the river discharge. However, the total volume of nutrients increases downstream as nutrient contributions increase cumulatively, compounding high nutrient concentrations in the estuary.

Further upstream is the town of Tongaat, which contains the Tongaat South and Central Sewage Works, Whitehead Textiles, as well as the Tongaat sugar mill (Maidstone), all of which result in return flow to the Tongati river (Durban Local Agenda 21, 1999). Return flow is defined as water that is used by wastewater treatment works which is then returned to the river after use. It is known that the return flow contains contaminants, with generally high nitrate concentrations leading to the contamination of the Tongati River from the sewage works. Any nitrates entering the Tongati River from the town of Tongaat, will eventually be transported to the Tongati estuary.

Another source of excess nitrates and nutrients to the Tongati estuary would be from the formal, informal and rural settlements upstream. Poor sanitation and sewage facilities in rural and informal settlements are known to cause significant increases in nitrate concentration in fluvial systems (Moodley, *et al*., submitted). Monitoring of effluent originating from these areas is essential to ensure proper management of this issue. Other sources in these areas include faecal pollution from livestock, as well as from detergents.

Nitrate overenrichment can be ascertained by eutrophication of aquatic bodies (explained in chapter 4). Although there were no obvious algal blooms observed in the estuary during the time of study, the reed *Phragmites* is ubiquitous along the banks of the river. The presence of *Phragmites may* be an indicator of nutrient overenrichment, (Achtzehn, 1991; McCormick *et al*., 2010). Another observation of nutrient enrichment of the estuary was the occurrence of water hyacinth. They were particularly abundant after periods of rainfall, where the Tongati River would wash them downstream onto the beach (see Figure 6.2). Like the *Phragmites*, water hyacinth is an indicator species of nutrient enrichment in water bodies (Carignan and Neiff*,* 1992; Charudattan *et al.,* 1995; Spaulding, 2010; Toft *et al.,* 2003).

Figure 6.2: Photograph showing evidence of Water Hyacinth in the Tongati estuary (Author, 2008).

The Tongati estuary is the least impacted estuary in this study due to its size and largely agriculturalized catchment. As far as the Tongati system is concerned, this study confirms signs of nutrient enrichment in the system, as the Tongati River is choked with *Phragmites*, and an abundance of water hyacinth upstream.

6.2.2 Mgeni Estuary

The Mgeni estuary also dominantly exports nitrates, except on a few occasions when import occurred. In the case of the Mgeni, conditions favoring import of nitrates into the estuary occurred in autumn. During this time, nitrate concentrations recorded for the flood flows for both the neap and spring tides were greater than those of the ebb flows. This indicates higher nitrate concentrations in the nearshore environment possibly as a consequence of upwelling or increased biomass degradation and /or longshore transport of nitrates derived from sewage outfall located to the south of the Mgeni being forced into the estuary on the flood flow.

The difference in land use between the Tongati estuary and the Mgeni estuary is astonishing. One can see immediately from Figure 6.3 that the Mgeni estuary and river are heavily impacted by anthropogenic activities. The Mgeni River and estuary are flanked by heavy industry and development, which implies a high likelihood of nutrient contamination of the estuary. The river has been periodically heavily polluted with organic nutrients. Much of this pollution emanates from upstream sewage pollution as the river traverses through dense rural and informal settlements that lack sewage treatment facilities. This is a serious problem as every year during the Duzi canoe marathon, participants suffer from what is referred to as the “Duzi Gut” - participants suffer from nausea and diarrhoea when water is accidentally ingested (Denny-Dimitriou, 2008; Oliver, 2011).

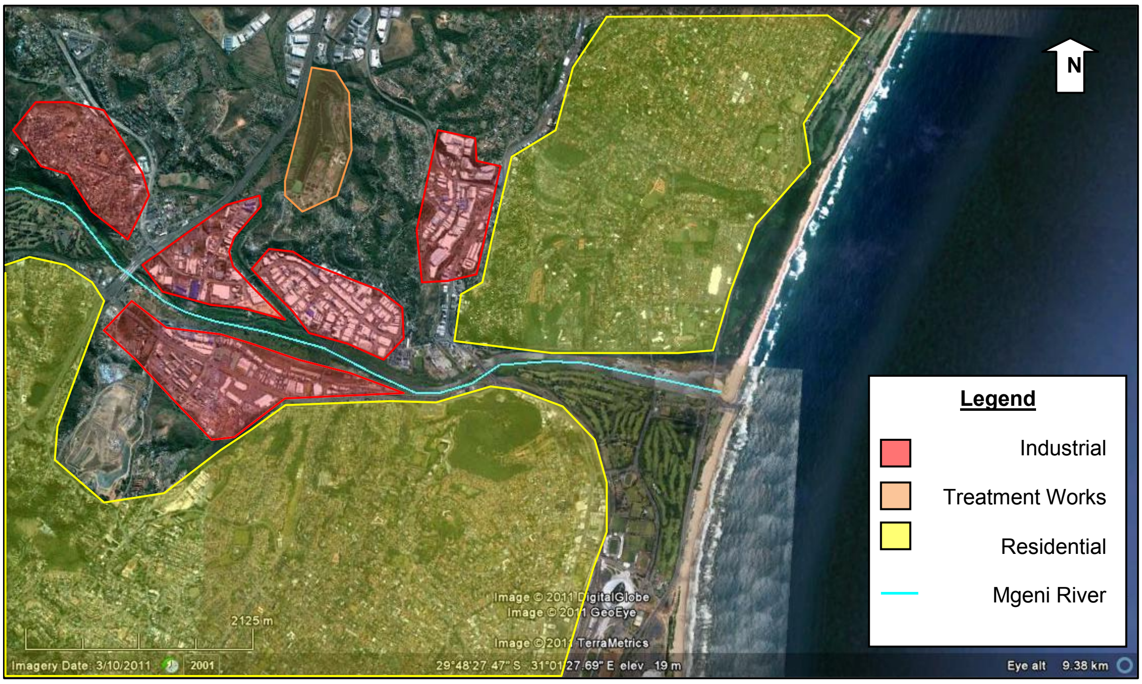


Figure 6. 3: Satellite image showing the surrounding land use of the Mgeni estuary (©Google Satellite Imagery, Imagery Date: 14/07/2010).

Other potential sources of nitrates would emanate from the industrial areas as industrial effluent as well as in wastewater from the wastewater treatment works. Sewage pollution may originate from the Northern Sewage Works in New Germany, and as stated in chapter 2, sewage contains a high concentration of nitrates which would find their way into the estuary. Sewage works aim to ensure the reduction in nutrient enrichment, however, if not managed correctly, it would definitely cause enrichment. Similar to the Tongati estuary, there is evidence of nutrient overenrichment in the Mgeni River and estuary, as there is a heavy presence of *Phragmites* along the riverbanks, as well as water hyacinth washed down into estuary after periods of rainfall (see Figure 6.4).

Figure 6.4: Photograph showing evidence of Water Hyacinth in the Mgeni Estuary (Author, 2008).

The spit that extends across the estuary was completely covered with litter during most of this study. The litter problem is so serious that Ezemvelo KZN Wildlife has constructed a net that extends along the width of Beachwood Creek as it enters the estuary, to prevent the litter from entering the creek and settling in the mangroves.

The Mgeni estuary is heavily impacted by industry and development in the catchment. Sources of nitrates for this estuary include effluent discharge from industry and wastewater treatment plants, and organic enrichment from the sewage works and informal settlements upstream.

Informal and rural settlements upstream of the estuary where no formal sanitation facilities exist, utilize pit latrines. Leachate from these together with faecal pollution from livestock are potential sources of nitrates to the Mgeni system.

6.2.3 Isipingo Estuary

The Isipingo estuary experienced import of nitrates on the spring tide for all seasons except winter. In the latter case, the longer duration of the ebb flow coupled with a reduced flow velocity of the flood ensured that there was no net import of material. On the other hand, for the spring tide of the spring season, although flood duration was significantly lower than that of ebb, nitrates were imported into the system due to the much higher mean flood velocity (flood velocity = 1.68 ms^{-1}; ebb velocity =0.32 ms^{-1}). Nitrate sources in the nearshore environment would also likely be derived from local upwelling or northerly longshore transport from sewage outfalls at the town of Amanzimtoti located to the south of Isipingo or from biomass decomposition.

The main land use surrounding the Isipingo estuary is industry (see Figure 6.5), and is possibly one of the most degraded estuaries in the eThekwini municipality. The first indication that this estuary is in a bad state is the strong chemical odour arising from the estuary. The second indication of degradation is the colour of the water which was most of the time, dark brown to black. According to Demetriades (2009, *pers. comm.),* this dark colour is caused by algal blooms on the bed of the estuary, indicating eutrophic conditions.

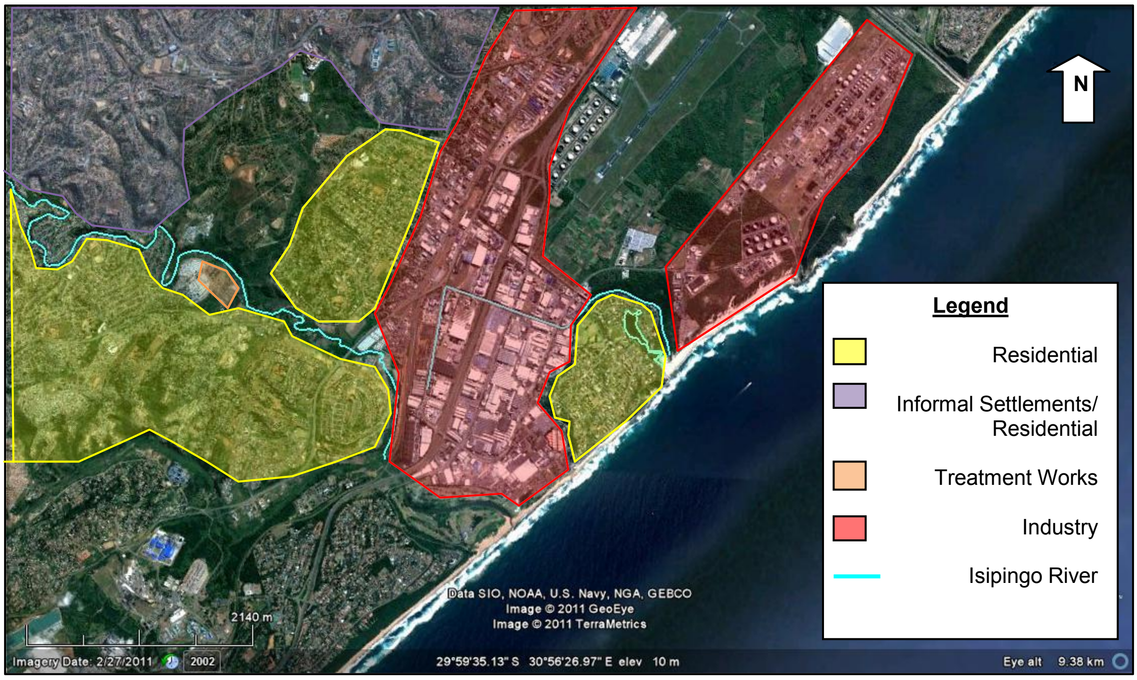


Figure 6.5: Satellite image showing the surrounding land use of the Isipingo estuary (©Google Satellite Imagery, Imagery Date: 17/07/2010).

Prior to the era of industrial development, the Isipingo estuary used to be in pristine condition, with the Isipingo and Umlazi Rivers both draining into the Isipingo River, allowing for the mouth to be permanently open to the sea. The presence of mangroves in the estuary are indicative of this. The problems regarding the estuary began when the Louis Botha Airport (located approximately 2 km north-east of the estuary) and the Prospecton Industrial Area (extending from the upper estuary) were built. In order for construction to take place, it was necessary for the Umlazi River to be diverted, resulting in flow reduction and the mouth at the Isipingo estuary to be closed. Mouth closure resulted in contaminant concentration in the estuary, and to combat this, two concrete pipes were laid to act as a conduit, in order to connect the estuary to the sea on a more continual basis (Begg, 1978). This should seem to be an effective solution, however, there are still major water quality problems that persist in this estuary.

Sources of nitrates in this estuary would include effluent discharge from the Prospecton industrial area including enrichment from sewage effluent from the Umlazi Wastewater Treatment Plant located in the upper catchment. Over the years there has been a major problem with raw sewage contamination of the Isipingo estuary. During power load shedding of 2008, it was reported in the media that several tons of raw sewage were pumped directly into the Isipingo River, resulting in severe pollution of the estuary. These sewage spills have devastating results including fish mortalities. On two occasions during this study, dead fish were observed in the estuary and along the estuary banks (see Figure 6.6). There are people who live on the banks of the estuary (further upstream) with no access to utility services. Accordingly, they produce a considerable amount of litter, were observed to be washing clothing directly in the river and, with no adequate sanitation, pose a threat of sewage pollution of the estuary.

Figure 6.6: Photograph showing a fish death at the Isipingo estuary (Author, 2008).

The Isipingo estuary is highly degraded, and continues to experience severe problems with water quality. This estuary has been completely neglected, and this is apparent by the litter on the estuary banks and amongst the mangroves. The estuary has obvious signs of nitrate enrichment – during the survey period algal blooms on the estuary bed were observed and, in addition, the upper reaches of the estuary are completely choked with water hyacinth.

6.3 The Fate of Nitrates

The question that remains is what happens to these nitrates? Are they stored in the estuary or are they exported out of the estuary? The following are suggested:

- Nitrates emanating from their different sources (industry, agriculture, detergents, livestock etc.) enter the rivers and are diluted to a concentration dependant on the river's discharge. The concentration of nitrates and nutrients in general, would therefore increase downstream. Therefore it is expected that estuaries will contain high concentrations of nutrients, and nitrates specifically.

- The rivers transport the nitrates to the estuaries where they could reside for a length of time, as estuaries act as sediment and nutrient traps (Beckert *et al*., 2011; Chapin et al., 2004). Furthermore, some of the nitrates may be adsorbed onto fine sediment, particularly clays, which settle out in the relative calm of the estuarine embayment. These may be flushed out during spring high tides or during fluvial floods. Hence nutrient enrichment in estuaries is common making them highly productive systems.

Tides are a vitally important component for the transportation of nitrates. The volume of nitrates transported into and out of the estuary depends on the tidal prism, tide duration and nitrate concentration of the tidal waters. The duration of flooding and ebbing may not be the same; this is called tidal asymmetry. This would influence the volume of nitrates transported in and out of the estuaries. Perched estuaries typically function more as river mouths with dominant ebbing and occasional flooding during spring tides. Export of nitrates is common under these conditions.

6.4 Flux of Nitrates

This study has shown that the flux of nitrates in the Tongati, Mgeni, and Isipingo estuaries does not follow an obvious pattern. One would assume that if the estuaries were efficient, during low tide when ebb flows are strong, there would be more nitrates leaving the estuaries than nitrates entering the estuary at high tide. This was indeed largely the case with all three estuaries. However, at certain times during the year, this pattern would change. It is important to note that in this study, it is in the author's opinion that the estuaries are referred to as being efficient when the nitrates are exported to the nearshore environment. It would be desirable for the estuaries to export excess nitrates, which could otherwise result in eutrophic conditions in the estuary.

6.4.1 Tongati Estuary

It was found that the Tongati estuary was totally efficient at exporting nitrates to the nearshore environment during all seasons. One of the reasons that this could be the case is that the estuary is perched and has a high berm, making it difficult for seawater to penetrate the estuary during high tides, even during spring high tides. The mouth of this system is maintained in an open state mainly due to the discharge of the Tongati river.

During the site visits, it was observed that there was little or no seawater entering the estuary at high tide, and the results show this. Results from tidal measurements indicate a strong tidal asymmetry (see table 6.1). Table 6.1 below confirms that the Tongati estuary was characterized by significant ebbing.

Table 6.1: Tidal Measurements In The Tongati Estuary

Season	Tide	Ebbing (%)	Flooding (%)
Summer	Neap	75	25
	Spring	50	50
Autumn	Neap	100	0
	Spring	75	25
Winter	Neap	100	0
	Spring	50	50
Spring	Neap	50	50
	Spring	50	50

The table above shows that the Tongati estuary displayed tidal symmetry (equal hours of ebbing and flooding) during the following spring tides of the summer, winter and spring seasons and the neap tide of the spring season.

It was noted that seawater would only penetrate the estuary during the high tides when sea conditions were very rough and when there were strong onshore winds. Despite these conditions, the tidal prism was insufficient to maintain strong flooding. It is these rough conditions that are associated with KwaZulu-Natal's climatic conditions in spring (characterized by strong winds) and summer (characterized by storms), and therefore tidal symmetry was more likely to occur.

Rough sea conditions during high tides resulted in the tidal channel doubling in width, as well as creating wave overwash into the channel (see Figure 6.7). The channel and the mouth itself would change position constantly - each site visit was characterized by a different mouth position (see Figures 6.8 and 6.9). The beach is known for its high-energy waves and combined longshore drift, which resulted in the constant shifting of the mouth.

Table 6.1 shows that the Tongati estuary was characterized by longer periods of ebbing during the neap tides of summer, autumn and winter, including the autumn spring tide.

It is interesting to note that the estuary experienced only ebbing during the autumn neap and winter neap tide visits. This would imply that during these periods, there would be a net material transport in one direction – seaward. During the above site visits the Tongati estuary took on the characteristics of a river mouth. Snow and Taljaard (2007) noted that nitrate concentrations measured in estuaries display an inverse relation with salinity. The largely fresh water status of the Tongati therefore allows for considerable nitrate transport.

Figure 6.7: Photograph showing wave overwash into the Tongati tidal channel (Author, 2008).

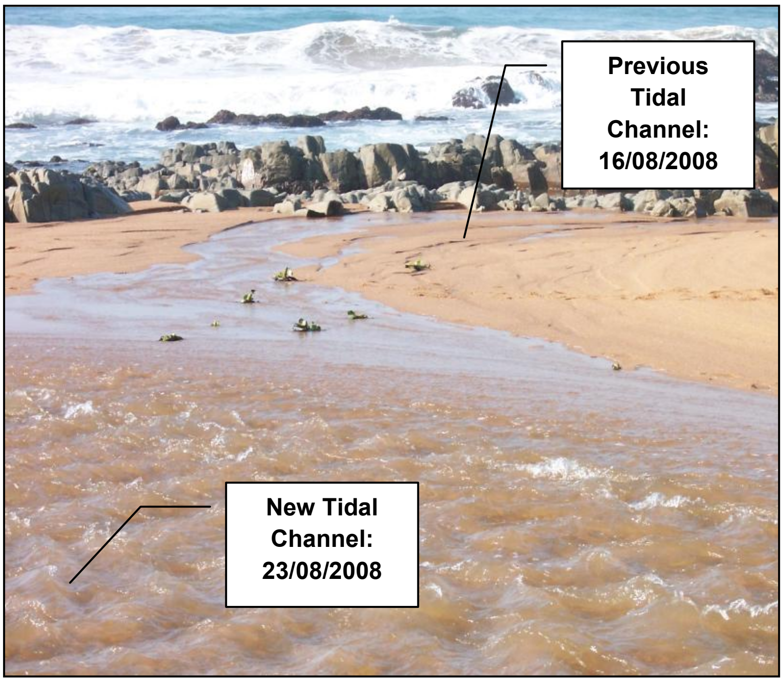


Figure 6.8: Photograph showing changing mouth position at the Tongati estuary from a southerly direction to a northerly direction (Author, 2008).

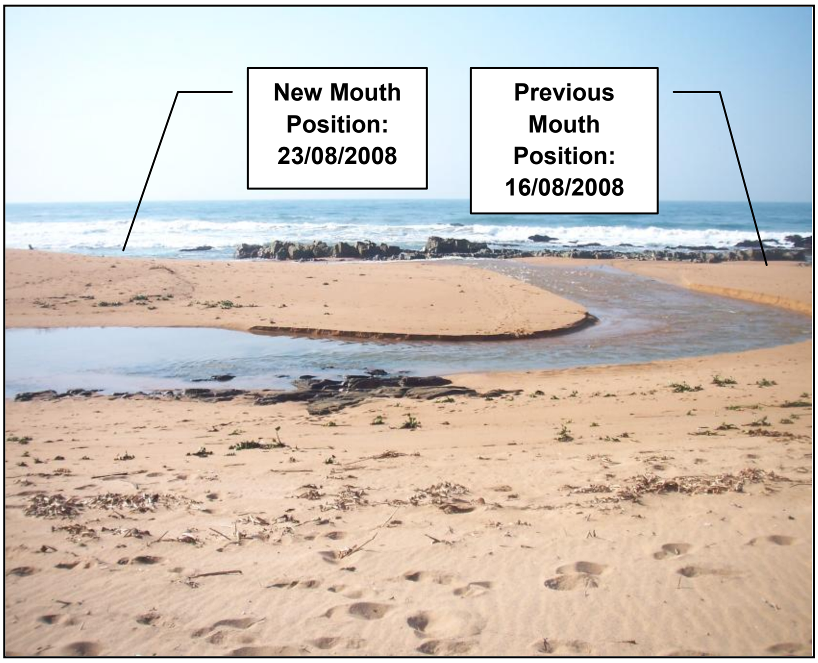


Figure 6.9: Photograph showing changing mouth position at the Tongati estuary from a southerly to a northerly direction (Author, 2008).

Interestingly, the Tongati estuary contained higher concentrations of nitrates, particularly in summer, compared to the Isipingo and Tongati estuaries. This could be due to the fact that the estuary is surrounded by sugar cane farms, where fertilizers rich in nitrates and phosphates are utilized. The highest quantity of nitrates (0.03-0.35kg/m^3) were recorded in summer, due to the increased rainfall KwaZulu-Natal receives in the summer months. When it rains, nitrates as well as other nutrients that adhere to soil particles, are washed into rivers which are ultimately transported to the estuaries. In winter, when KwaZulu-Natal receives little or no rain, the lowest amounts of nitrates (0.01-0.02kg/m3) were recorded. Research on nutrient status of South African estuaries (Allanson, 2001) support the view that higher precipitation in agricultural lands yield greater leaching of nutrients that are eventually transported to the estuaries.

Although the Tongati estuary receives more nitrates from the surrounding land than the Isipingo and Mgeni estuaries, it is a successful exporter of nitrates to the nearshore environment. This is due to the fact that tidal asymmetry allows for prolonged ebbing as the estuary itself is perched.

6.4.2 Isipingo Estuary

The results of this study show that for approximately 63% of the time the Isipingo estuary receives a higher flux of nitrates from the sea during high tide than it exports out to sea from landward drainage during low tide. Unlike the Tongati estuary, seawater does enter the Isipingo estuary during high tide due to the pipes that permanently connect the estuary with the sea (see Figure 6.10). However, a lot less seawater is able to enter the estuary during flood flows on neap tides, and the results show this – nitrates were successfully exported to the nearshore environment during most of the site visits during neap tides, except for winter.

Figure 6.10: Satellite image showing the pipes connecting the Isipingo Estuary to the sea (©Google Earth Satellite Imagery, Imagery Date: 17/07/2010).

However, the case was completely different during spring tides. Due to the higher sea level and rough conditions experienced during spring tides, more seawater was able to penetrate through the pipes and into the estuary during high tides, compared to the neap high tides (see Figures 6.11 and 6.12). Figures 6.11 and 6.12 show the difference between the water level in the estuary at neap high tides and spring high tides.

Figure 6.11: Photograph showing a neap high tide at the Isipingo Estuary (Author, 2008).

Figure 6.12: Photograph showing a spring high tide at the Isipingo Estuary (Author, 2008).

The Isipingo estuary, like the Tongati, is generally characterized by a dominant ebb flow (see table 6.2 below).

Table 6.2: Tidal Measurements In The Isipingo Estuary

Season	Tide	Ebbing (%)	Flooding (%)
Summer	Neap	75	25
	Spring	50	50
Autumn	Neap	100	0
	Spring	50	50
Winter	Neap	75	25
	Spring	75	25
Spring	Neap	75	25
	Spring	75	25

Table 6.2 above shows that while tidal symmetry was experienced during the summer and autumn spring tides, tidal asymmetry occurred for the remainder of the sampling surveys.

The information presented in the graphs in chapter 5 suggest an increase in the flux of nitrates entering the estuary at high tide. The trend suggests that on many occasions more nitrates were entering the estuary during high tide. This would imply enrichment of the nearshore region of the Isipingo coastline. No known source of such enrichment could be identified in the vicinity, hence nitrates emanating from another source along the coast were thought to be responsible. One possible source is from nearshore coastal upwelling causing recirculation of bottom nutrients as suggested by Snow and Taljaard (2007). Further, keeping in mind that sewage (treated or untreated) contains high concentrations of nitrates, the researcher sought to identify sewage outfalls along this stretch of coastline as well as nearshore and longshore drift current characteristics.

Two major sewage outfalls (refer to Figure 6.13) were identified along the coastline between Stanger (approximately 60km north of Durban) and Amanzimtoti (located on the coastline 35 km south of Durban) (Westland, C., 2009, *pers. comm.*). It is important to note the Amanzimtoti River continuously experiences sewage pollution which is pumped out to sea and is therefore counted as a “sewage outfall” (Durban Local Agenda 21, 1999).

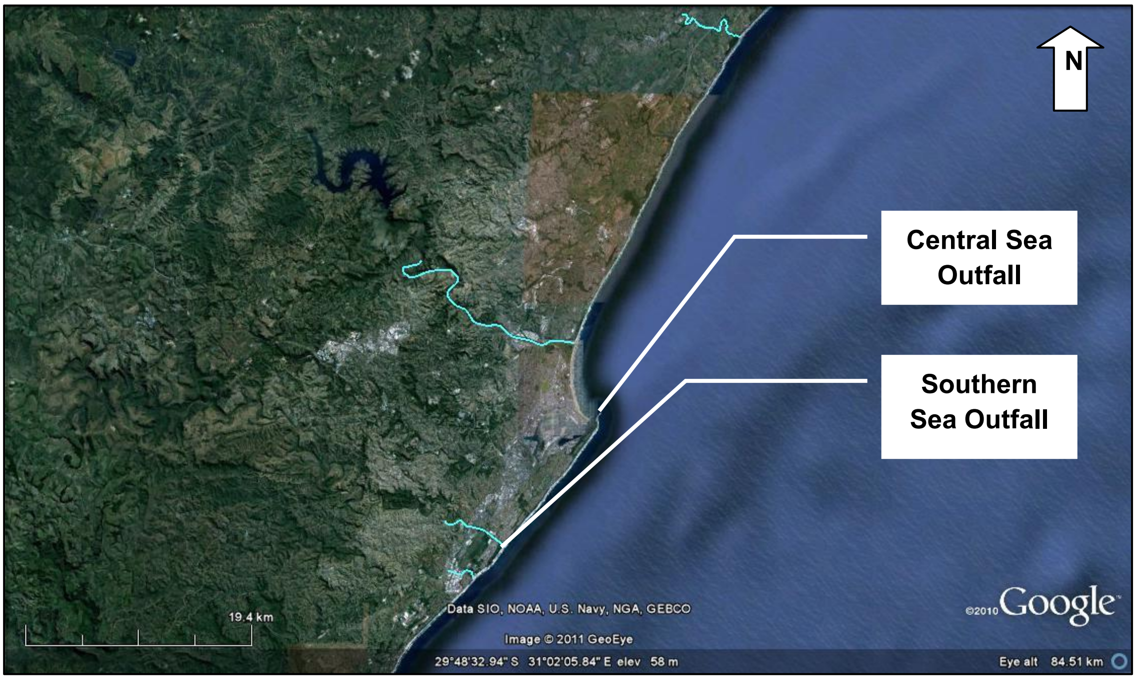


Figure 6.14: Satellite image showing the location of the sewage outfalls (©Google Earth Satellite Imagery).

The two main sewage outfalls located between Stanger and Amanzimtoti are the Central Sea Outfall in the Durban harbour, and the Southern Sea Outfall located in close proximity to the Umlazi canal (approximately 5km north of the Isipingo estuary). The Amanzimtoti outfall is also shown on Figure 6.13 and effluents from such outfall contains high concentrations in nitrate-rich compounds which begin to degrade in the highly oxygenated seawater.

The dominant longshore drift along this coastline is in a northerly direction i.e. from south to north (Bosman *et al.*, 2007). Materials supplied to the coast are continuously moved along the shore in a northerly direction by the drift current. Due to the close proximity of the Amanzimtoti outfall to the Isipingo estuary, it is possible that some of this nitrate rich water would enter the Isipingo estuary on the spring high tide. This would explain the nitrate flux increase during these periods in the estuary. It is important to note that nitrate transfers, due to the northerly flowing longshore drift, was inferred and not quantified, as this was not an objective of this study. Futher research into this aspect would serve to confirm or negate this inference. The other possible source arises from upwelling in the nearshore environment or from biomass decomposition (Allanson, 2001; Eyre, 1998).

Looking at the quantities of nitrates themselves, the Isipingo estuary portrayed a seasonal variation in nitrate quantities – it received higher quantities of nitrates during summer, similar to the Tongati estuary. In the summer, nitrate quantities ranged between 0.03kg/m^3 – 0.11kg/m^3, whilst during winter, nitrate quantities ranged between 0.01kg/m^3 – 0.02kg/m^3. Possible explanations for this difference are seasonal industrial production variations and greater leaching from surface sources due to higher summer rainfall.

This study has shown that the Isipingo estuary is effective at exporting nitrates to the nearshore environment during neap tides. At these times, as very little or no estuarine-ocean exchange occurs , seawater is not able to enter the estuary, During spring high tides, seawater is able to enter the estuary through the pipes bringing in with it a significant amount of nitrates. Therefore, whilst the Isipingo estuary is effective at exporting nitrates during neap tides, significant import may occur on the spring high tides.

6.4.3 Mgeni Estuary

The results of this study have shown that during the site visits, the Mgeni estuary was 62.5% effective at exporting nitrates to the nearshore environment. The estuary did display periods of tidal asymmetry and dominant ebbing (see table 6.3).

Table 6.3: Tidal Measurements In The Mgeni Estuary

Season	Tide	Ebbing (%)	Flooding (%)
Summer	Neap	75	25
	Spring	50	50
Autumn	Neap	50	50
	Spring	50	50
Winter	Neap	75	25
	Spring	50	50
Spring	Neap	75	25
	Spring	75	25

Table 6.3 above shows that tidal symmetry (equal hours and ebbing and flooding) did occur in the Mgeni estuary during the spring tides of summer, autumn and winter as well as the autumn neap tide.

With regards to the Mgeni estuary, tidal symmetry would be expected, due to its morphology. It has a short, wide tidal channel, allowing for efficient ocean-estuarine exchange. Seawater enters the estuary at high tide, no matter what the conditions – there are no barriers to exchange such as a high berm, pipes, and the estuary itself is not perched. The Mgeni estuary did however experience some tidal asymmetry, characterized by greater ebbing than flooding, during the neap tides of summer, winter and spring, as well as the spring season neap tide.

Heavy rainfall prior to the summer neap, spring neap, and spring spring tide site visits resulted in bankfull conditions with dominant ebbing. It was during these occasions that the estuary behaved like a river mouth which resulted in the net movement of materials seaward.

Regarding the flux of nitrates, as was the case with the Isipingo estuary, there were also occasions in the Mgeni estuary where it was found that during high tide, nitrates were entering the estuary during flooding. On these occasions, tidal symmetry was preserved except during the winter neap tide. The source of nitrates in this case is thought to originate from the sewage outfall located at the Durban harbour – the Central Sea Outfall, which pumps effluent out to sea. The northward flowing longshore drift would then transport some of this nutrient enriched water past the Mgeni estuary, and a proportion may then enter the estuary under favourable flood tide conditions. The validity of this explanation is enhanced by the fact that despite tidal symmetry during autumn sampling, the amount of nitrates entering the system was less than that of the winter neap tide where only two hours of flooding occurred.

As was the case with the Tongati and Isipingo estuaries, the Mgeni estuary displayed a seasonal variation in nitrate quantities. Sampling during summer recorded significantly higher quantities of nitrates than in winter: In summer, the quantities of nitrates ranged between 0.01kg/m^3 – 0.16kg/m^3, and in winter quantities ranged between 0.01kg/m^3 – 0.02kg/m^3. Again, this would be due to the fact that more nitrates are transported into the estuary from the hinterland during summer as KwaZulu-Natal experiences summer rainfall.

With regard to the flux of nitrates in the Mgeni estuary, these were successfully exported to the nearshore environment during approximately 63% of the site visits due to dominant tidal asymmetry. Hence, the study demonstrated that the Mgeni estuary was effective at exporting nitrates to the nearshore environment most of the time, except during autumn when there were equal amounts of ebbing and flooding and during winter neap tide, where it was likely that the nearshore environment was enriched with nitrates.

6.5 Net Flux of Nitrates

Looking at the three systems, it is clear that the Tongati estuary is ebb dominated and a strong exporter of nitrates to the nearshore.

The Isipingo estuary, on the other hand, demonstrated a gain of nitrates from the ocean on three occasions.

Finally, regarding the Mgeni estuary, there were only two occasions when nitrates entered the estuary from the ocean, and that was during the autumn season. It was found that the Mgeni was characterized by a longer ebbing time for a significant proportion of the site visits, allowing effective nitrates export. However, during autumn, tidal symmetry was experienced, allowing more time for nitrates to enter the estuary during flooding. Additionally, the longshore drift transport of nutrient enriched seawater and its subsequent entry into the estuary on the high tide allowed for greater import of nitrates.

6.6 Associated Impacts

On the occasions where it was found that nitrates were entering the estuary from the sea, the main impact would be increased contamination of the estuary leading to possible eutrophication of the system. As stated before, all three estuaries showed signs of eutrophication, whether it occurred in the estuary itself or further upstream. All the estuaries contained water hyacinth, the reed *phragmites*, or in the case of the Isipingo estuary, algal blooms. Eutrophication is evident and added nitrates into the system will only worsen the problem. Estuaries are known as “nutrient traps” therefore any nutrients entering the estuary via the sea will reside in the estuary for a period of time.

Whilst nitrates were, most of the time, exported out of the three estuaries, the possibility of longshore transport and re-entry into neighbouring systems on the high tide is a cause for concern. This is a problem in that any estuary gaining added nitrates and other nutrients into the system would experience eutrophication and other water quality problems.

However, as is the case for almost all human intervention in natural systems, there are often unforeseen repercussions. Clearly this is an impact that municipal authorities need to be aware of and needs addressing by relevant authorities.

6.7 Total Net Flux of Nitrates From the eThekwini Municipality

Table 6.4 below shows the total net flux of nitrates from the eThekwini Municipality region estuaries (comprising the three estuaries of this study) that maintain continuous open interchange with the sea. Net export of nitrates was obtained for all seasons and tidal cycles measured. A clear seasonal influence is evident in this summer rainfall region. High fluvial flows from catchment hinterlands drive the export of nitrates, especially on the summer neap tide. There is a rapid drop in total nitrates delivered to the nearshore environment of the eThekwini Municipality from the summer high of over 38421.66kgs (neap tide) to a winter low of 560.60kgs (spring tide). Due to the lower flooding characteristic of neap tides, they yield greater export values for all seasons. Accordingly, greater amounts of nitrates enter into the estuaries on spring tide flood flows. The net flux (difference between ebb and flood flows) of spring tides is therefore generally smaller.

Table 6.4: Total net nitrate flux for the eThekwini Municipality

SEASON/TIDE	TONGATI NET FLUX (Kg)	ISIPINGO NET FLUX (Kg)	MGENI NET FLUX (Kg)	TOTAL NET FLUX (Kg)
Summer Neap tide	28091.58	476.27	9853.81	38421.66
Summer Spring tide	3116.77	**-56.85**	3416.79	6476.71
Autumn Neap tide	**1652.91**	**256.85**	**-97.47**	1812.29
Autumn Spring tide	1332.73	**-120.02**	**-267.38**	945.33
Winter Neap tide	**529.80**	32.46	861.44	1423.7

SEASON/TIDE	TONGATI NET FLUX (Kg)	ISIPINGO NET FLUX (Kg)	MGENI NET FLUX (Kg)	TOTAL NET FLUX (Kg)
Winter Spring tide	404.42	82.67	73.51	560.60
Spring Neap tide	1182.86	169.29	968.46	2320.61
Spring Spring tide	264.96	**-116.36**	782.85	931.45

6.8 Conclusion

The source of nitrates to these estuaries were identified; the individual flux of nitrates for the estuaries over the whole sampling period were analysed; and finally the net flux of nitrates for the estuaries were determined. In conclusion, it has been determined that:

- The Tongati estuary consistently transports nitrates to the nearshore environment due to the fact that the estuary is perched and experiences ebb dominance;

- A significant amount of nitrates entered the Isipingo estuary during spring high tides with the exception of winter. This was due to:

    1. Seawater being able to enter the estuary through the pipes during spring high tides, whereas during neap tides, this was not always the case; and

    2. Sewage effluent originating from the Amanzimtoti outfall causing nutrient enrichment of nearshore waters that were transported north by the longshore drift and entered the estuary on the spring high tides.

- Nitrates enter the Mgeni estuary in autumn which is due to:

    1. Increased time of flooding (tidal symmetry), allowing for more nutrient-rich seawater to enter the estuary; and

2. Sewage effluent originating from the Central Sea Outfall in the Durban Harbour being transported north by the longshore drift and a portion of this nutrient enriched water entering the Mgeni estuary on the high tide.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This chapter presents the conclusions and recommendations of this study. Additionally, it will show whether the research objectives were achieved, and the limitations during this study will also be outlined.

7.2 Conclusions

The aim of this study was to determine the net flux of nitrates between the Tongati, Isipingo and Mgeni estuaries, and their adjacent nearshore environments, i.e., to determine whether the estuaries were efficiently exporting nitrates to the sea. These estuaries were chosen for this study as it was necessary for the estuaries to remain open to the sea for most of the year, in order to measure tidal exchange. The Tongati, Isipingo, and Mgeni estuaries all fit this requirement.

The estuaries were sampled throughout the first year of this study. The sampling was seasonal, meaning that the estuaries were sampled during summer, autumn, winter and spring. Sampling took place during one neap and one spring tide per season, resulting in a total of 24 sampling days.

In order to calculate the net flux of nitrates, three components were required: the cross-sectional area of the mouth, the average flow velocity of water in the cross-section (including the direction of flow), and the average concentration of nitrates. The average concentration of nitrates was attained by the use of a YSI Multi-Parameter Water Quality Meter was held in the water at half-depth. The average flow velocity of water in the cross-section was determined by the use of a SonTek Velocity Meter.

Unlike the determination of nutrient transport in fluvial systems where flow is unidirectional, flux determinations in tidal systems are more complex, incorporating constantly changing flow directions, velocity and volumes. For this reason, no prior study of material transport in the study had previously been attempted.

Results from this study demonstrates that significant amounts of nitrates and likely other dissolved substances are transferred on a continual basis between the estuarine and marine environments through tidal cycling. Whilst estuaries may serve as a temporary storage for much of the material received from their catchments as a consequence of natural and anthropogenic processes and activities, a significant proportion of these are exported to the marine environment.

Prior assumptions have always concurred with the belief that estuarine systems simply export material to the adjacent sea. However this study also determined that estuarine morphodynamics, together with chemical loading and nearshore processes, determines whether material such as nitrates would be imported into estuaries. For instance, the Isipingo and Mgeni estuaries were both found to import significant quantities of nitrates into the system from the marine environment under favourable conditions. This finding is particularly important for management of the systems and must be considered in investigations aimed at identifying pollution sources.

One of the objectives of the study was to determine the impact to the estuarine environment, should the estuaries be found to be efficient or inefficient at exporting nitrates to the nearshore environment. It was concluded that it is a good result that the estuaries are efficient at exporting nitrates most of the time, as they do receive large quantities of nitrates via agriculture, industry, sewage outfall, and biotic decomposition. However, as mentioned above, due to nearshore processes such as longshore drift, nitrates that are deposited into the sea may be transported back into the estuaries, putting the estuaries at a higher risk of further pollution.

The total net flux of nitrates from the eThekwini Municipality region estuaries shows that a net export of nitrates was obtained for all seasons and tidal cycles measured notwithstanding isolated cases of nitrate import from the sea. A clear seasonal influence was detected with summer high exports driven by high fluvial flows from catchment hinterlands. Calculations reveal a rapid drop in total nitrates delivered to the nearshore environment of the Municipality from the summer high of over 38 421.66kgs (neap tide) to a winter low of 560.60kgs (spring tide). Finally, due to the lower flooding characteristic of neap tides, they yield greater export values for all seasons as they aid in the removal of accumulated nitrates in the estuaries.

7.3 Recommendations

A study of this nature has not previously been undertaken along the KwaZulu-Natal coastline. It has clearly shown that:

- Nutrient enrichment is occurring in highly productive yet very ecologically sensitive estuaries;
- Whilst much of this material is exchanged with the nearshore environment, further assessment as to residence time within estuaries and associated impacts need attention;
- Not all estuaries export material to the nearshore environment all of the time, and that the estuaries may serve as sinks of marine derived material;
- This marine derived material may well be the consequence of poorly planned or unforeseen disposal methods of treated and/or untreated sewage, and other waste.

The eThekwini Municipality needs to address the potential problems derived from the points above, and should conduct surveys, studies and research to fully understand the fate of sewage outfalls and their wastewater disposal systems. It is also recommended that farmers constantly monitor and test their soil to ascertain which nutrient, such as phosphorous or nitrates, are deficient, and should only add this nutrient to the soil to reduce over-fertilization. However, this would prove challenging to rural and subsistence farmers, who do not have the facilities and means to test the soil. Perhaps municipalities could assist in providing the facilities to these farmers in order to prevent them from over-fertilizing. Finally, the lack of proper sanitation is a problem and needs to be resolved.

In a local and global context, the results of this study highlights the dynamic nature of estuarine environments, and that they display varying functional characteristics that make them unique.

7.4 Limitations

Limitations to sampling were encountered during periods of heavy rainfall. This was particularly a problem in the Mgeni estuary. Flood conditions following persistent precipitation made it dangerous to wade into the estuary, making flow velocity measurements particularly difficult.

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APPENDIX A: RAW DATA & CALCULATIONS

TONGATI ESTUARY: RAW DATA

Summer: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TSUN 1	H/T	FLOOD	7.77	0.48	348.32	0.35	1.30	9353.48
TSUN 2		EBB	7.77	0.76	383.88	0.38	2.27	16343.07
TSUN 3		EBB	7.14	0.78	305.15	0.31	1.71	12298.73
TSUN 4	L/T	EBB	6.93	0.74	237.14	0.24	1.22	8803.26

Summer: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TSUS 1	L/T	EBB	4.00	0.66	101.89	0.10	0.27	1933.79
TSUS 2		EBB	3.20	0.70	142.27	0.14	0.32	2294.53
TSUS 3		FLOOD	6.40	0.30	65.94	0.07	0.13	917.63
TSUS 4	H/T	FLOOD	12.00	0.07	34.53	0.03	0.03	193.92

Autumn: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TAN 1	H/T	EBB	3.00	0.61	26.36	0.03	0.05	345.04
TAN 2		EBB	3.04	0.69	28.98	0.03	0.06	437.68
TAN 3		EBB	3.04	0.67	28.93	0.03	0.06	426.79
TAN 4	L/T	EBB	3.04	0.60	33.82	0.03	0.06	443.41

Autumn: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TAS 1	L/T	EBB	3.40	1.21	24.49	0.02	0.10	724.21
TAS 2		EBB	2.94	0.77	24.88	0.02	0.06	403.95
TAS 3		EBB	3.60	0.54	32.26	0.03	0.06	450.70
TAS 4	H/T	FLOOD	3.11	0.61	17.92	0.02	0.03	246.13

Winter: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TWN 1	H/T	EBB	1.98	0.49	19.93	0.02	0.02	139.79
TWN 2		EBB	1.73	0.52	17.84	0.02	0.02	116.31
TWN 3		EBB	1.89	0.58	16.82	0.02	0.02	131.84
TWN 4	L/T	EBB	2.07	0.54	17.62	0.02	0.02	141.87

Winter: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TWS 1	L/T	EBB	2.27	0.82	17.15	0.02	0.03	230.05
TWS 2		EBB	2.15	0.99	16.39	0.02	0.03	250.95
TWS 3		FLOOD	2.40	0.11	17.18	0.02	0.00	32.66
TWS 4	H/T	FLOOD	5.00	0.10	12.08	0.01	0.01	43.92

Spring: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TSN 1	TO H/T	EBB	3.52	0.86	131.75	0.13	0.40	2854.19
TSN 2	TO H/T	EBB	2.85	0.89	92.57	0.09	0.23	1690.59
TSN 3	H/T	FLOOD	4.28	0.53	115.59	0.12	0.26	1867.88
TSN 4	TO L/T	FLOOD	5.32	0.54	72.77	0.07	0.21	1494.04

Spring: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Avg. Velocity (m/s)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Flux (kg/s)	Flux f(t) (kg)
TSS 1	L/T	EBB	1.44	0.55	40.36	0.04	0.03	231.40
TSS 2		EBB	1.44	0.54	20.01	0.02	0.02	110.99
TSS 3		FLOOD	1.44	0.12	22.59	0.02	0.00	28.34
TSS 4	H/T	FLOOD	7.50	0.06	16.53	0.02	0.01	49.09

TONGATI – NET FLUX CALCULATION

Summer: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
37445.06	9353.48	28091.58

Summer: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
4228.32	1111.55	3116.77

Autumn: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
1652.92	0	1652.92

Autumn: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
1578.86	246.13	1332.73

Winter: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
529.80	0	529.80

Winter: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
480.99	76.58	404.42

Spring: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
4544.77	3361.91	1182.86

Spring: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
342.40	77.43	264.96

ISIPINGO – RAW DATA

Summer: Neap Tide

Sample	Tide	Flood/Ebb	Area	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
ISUN 1	H/T	FLOOD	0.52	48.65	0.05	0.39	0.01	70.85
ISUN 2		EBB	0.40	67.89	0.07	0.56	0.02	108.52
ISUN 3		EBB	0.40	94.38	0.09	0.62	0.02	167.44
ISUN 4	L/T	EBB	0.40	110.51	0.11	0.85	0.04	271.17

Summer: Spring Tide

Sample	Tide	Flood/Ebb	Area	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
ISUS 1	L/T	EBB	0.64	33.71	0.03	0.68	0.01	105.94
ISUS 2		EBB	0.60	37.78	0.04	0.38	0.01	61.69
ISUS 3		FLOOD	0.60	56.27	0.06	0.47	0.02	114.49
ISUS 4	H/T	FLOOD	1.00	27.28	0.03	0.56	0.02	109.99

Autumn: Neap Tide

Sample	Tide	Flood/Ebb	Area	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
IAN 1	H/T	EBB	0.46	24.75	0.02	0.87	0.01	71.40
IAN 2		EBB	0.42	21.20	0.02	0.84	0.01	54.11
IAN 3		EBB	0.46	21.62	0.02	0.87	0.01	62.15
IAN 4	L/T	EBB	0.42	24.79	0.02	0.92	0.01	69.19

Autumn: Spring Tide

Sample	Tide	Flood/Ebb	Area	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
IAS 1	H/T	FLOOD	0.80	17.55	0.02	1.57	0.02	158.91
IAS 2		FLOOD	1.20	14.49	0.01	0.95	0.02	119.18
IAS 3		EBB	1.34	16.96	0.02	0.56	0.01	91.47
IAS 4	L/T	EBB	1.40	12.61	0.01	0.52	0.01	66.61

Winter: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
IWN 1	H/T	FLOOD	0.64	15.50	0.02	0.43	0.00	30.64
IWN 2		EBB	0.54	17.25	0.02	0.34	0.00	22.53
IWN 3		EBB	0.60	16.87	0.02	0.25	0.00	18.44
IWN 4	L/T	EBB	0.70	15.85	0.02	0.28	0.00	22.13

Winter: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
IWS 1	L/T	EBB	0.72	16.39	0.02	0.76	0.01	64.23
IWS 2		EBB	0.76	15.15	0.02	0.63	0.01	52.14
IWS 3		EBB	0.80	14.89	0.01	0.68	0.01	57.89
IWS 4	H/T	FLOOD	1.62	14.33	0.01	0.55	0.01	91.60

Spring: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
ISN 1	H/T	FLOOD	1.08	18.73	0.02	0.13	0.00	18.35
ISN 2		EBB	0.76	23.19	0.02	0.32	0.01	40.86
ISN 3		EBB	0.96	19.64	0.02	0.53	0.01	71.27
ISN 4	L/T	EBB	0.96	17.88	0.02	0.61	0.01	75.51

Spring: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
ISS 1	L/T	EBB	0.56	40.55	0.04	0.38	0.01	61.80
ISS 2		EBB	0.56	40.50	0.04	0.33	0.01	53.89
ISS 3		EBB	0.80	40.49	0.04	0.24	0.01	55.27
ISS 4	H/T	FLOOD	1.20	19.83	0.02	1.68	0.04	287.32

ISIPINGO – NET FLUX CALCULATION

Summer: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
547.12	70.85	476.27

Summer: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
167.63	224.49	-56.85

Autumn: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
256.85	0	256.85

Autumn: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
158.07	278.09	-120.02

Winter: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
63.10	30.64	32.46

Winter: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
174.27	91.60	82.67

Spring: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
187.64	18.35	169.29

Spring: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
170.96	287.32	-116.36

MGENI – RAW DATA

Summer: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
USUN1A	H/T		8.70	136.56	0.14	0.26		
USUN1B	H/T		11.70	143.06	0.14	0.25		
USUN1C	H/T		9.00	146.56	0.15	0.29		
AVG.	H/T	FLOOD	**9.80**	**142.06**	**0.14**	**0.27**	**0.37**	**2676.34**
USUN2A			5.10	80.09	0.08	0.25		
USUN2B			6.90	119.34	0.12	0.40		
USUN2C			9.44	109.55	0.11	0.39		
AVG.		EBB	**7.15**	**102.99**	**0.10**	**0.35**	**0.26**	**1838.97**
USUN3A			2.10	54.04	0.05	0.15		
USUN3B			15.00	157.02	0.16	0.78		
USUN3C			8.70	159.45	0.16	0.64		
AVG.		EBB	**8.60**	**123.50**	**0.12**	**0.52**	**0.55**	**3994.45**
USUN4A	L/T		13.80	126.05	0.13	0.64		
USUN4B	L/T		6.00	162.17	0.16	0.69		
USUN4C	L/T		8.40	160.18	0.16	0.66		
AVG.	L/T	EBB	**9.40**	**149.47**	**0.15**	**0.66**	**0.93**	**6696.73**

Summer: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
USUS1A	TO L/T		10.80	39.78	0.04	0.51		
USUS1B	TO L/T		4.80	36.28	0.04	0.25		
USUS1C	TO L/T		14.40	38.24	0.04	0.88		
USUS1D	TO L/T		11.50	43.52	0.04	1.02		
AVG.	TO L/T	EBB	**10.38**	**39.46**	**0.04**	**0.67**	**0.27**	**1959.95**
USUS2A	TO H/T		9.30	49.69	0.05	0.57		
USUS2B	TO H/T		2.40	89.94	0.09	0.29		
USUS2C	TO H/T		8.10	103.12	0.10	0.39		
USUS2D	TO H/T		15.60	118.83	0.12	0.83		
AVG.	TO H/T	EBB	**8.85**	**90.40**	**0.09**	**0.52**	**0.42**	**2992.30**
USUS3A	TO H/T		12.45	93.12	0.09	0.12		
USUS3B	TO H/T		6.30	107.60	0.11	0.11		
USUS3C	TO H/T		17.40	115.91	0.12	0.22		
AVG.	TO H/T	FLOOD	**12.05**	**105.54**	**0.11**	**0.15**	**0.19**	**1333.86**
USUS4A	TO H/T		6.30	13.29	0.01	0.13		
USUS4B	TO H/T		8.10	15.15	0.02	0.12		
USUS4C	TO H/T		22.50	16.39	0.02	0.21		
AVG.	TO H/T	FLOOD	**12.30**	**14.94**	**0.01**	**0.15**	**0.03**	**201.60**

Autumn: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
UAN1A	H/T		4.50	14.25	0.01	0.51		
UAN1B	H/T		10.50	13.66	0.01	0.56		
UAN1C	H/T		13.20	14.16	0.01	0.53		
UAN1D	H/T		17.25	14.35	0.01	0.53		
AVG.	H/T	FLOOD	**11.36**	**14.11**	**0.01**	**0.53**	**0.09**	**615.04**
UAN2A			6.00	14.26	0.01	0.51		
UAN2B			9.75	15.82	0.02	0.50		
UAN2C			10.50	14.60	0.01	0.52		
UAN2D			15.00	14.65	0.01	0.56		
UAN2E			12.00	19.13	0.02	0.50		
AVG.		FLOOD	**10.65**	**15.69**	**0.02**	**0.52**	**0.09**	**622.81**
UAN3A			3.00	17.55	0.02	0.50		
UAN3B			7.50	17.81	0.02	0.53		
UAN3C			11.40	17.69	0.02	0.61		
UAN3D			13.50	17.93	0.02	0.72		
UAN3E			4.40	17.88	0.02	0.53		
AVG.		EBB	**7.96**	**17.77**	**0.02**	**0.58**	**0.08**	**588.31**
UAN4A	L/T		1.50	16.57	0.02	0.50		
UAN4B	L/T		4.50	16.20	0.02	0.56		
UAN4C	L/T		6.30	16.51	0.02	0.54		
UAN4D	L/T		11.70	16.72	0.02	0.60		
UAN4E	L/T		15.75	17.03	0.02	0.71		
AVG.	L/T	EBB	**7.95**	**16.61**	**0.02**	**0.58**	**0.08**	**552.07**

Autumn: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
UAS1A	L/T		3.75	14.91	0.01	0.50		
UAS1B	L/T		9.75	16.48	0.02	0.57		
UAS1C	L/T		10.50	17.55	0.02	0.58		
UAS1D	L/T		5.22	17.73	0.02	0.58		
AVG.	L/T	EBB	**7.31**	**16.67**	**0.02**	**0.56**	**0.07**	**489.17**
UAS2A			1.50	13.60	0.01	0.53		
UAS2B			7.50	17.83	0.02	0.53		
UAS2C			8.25	18.58	0.02	0.55		
UAS2D			4.50	18.93	0.02	0.76		
UAS2E			1.50	19.08	0.02	0.53		
AVG.		EBB	**4.65**	**17.60**	**0.02**	**0.58**	**0.05**	**342.08**
UAS3A			4.50	11.03	0.01	0.68		
UAS3B			11.25	12.68	0.01	0.51		
UAS3C			12.00	13.80	0.01	0.51		
AVG.		FLOOD	**9.25**	**12.50**	**0.01**	**0.57**	**0.07**	**472.99**
UAS4A	H/T		4.50	10.63	0.01	0.52		
UAS4B	H/T		12.00	12.51	0.01	0.53		
UAS4C	H/T		18.00	13.09	0.01	0.83		
AVG.	H/T	FLOOD	**11.50**	**12.08**	**0.01**	**0.63**	**0.09**	**625.63**

Winter: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
UWN1A	H/T		4.50	17.13	0.02	0.52		
UWN1B	H/T		12.75	17.37	0.02	0.58		
UWN1C	H/T		13.80	17.08	0.02	0.51		
UWN1D	H/T		15.75	17.35	0.02	0.60		
UWN1E	H/T		17.25	17.47	0.02	0.50		
UWN1F	H/T		9.20	17.47	0.02	0.51		
AVG.	H/T	FLOOD	**12.21**	**17.31**	**0.02**	**0.53**	**0.11**	**813.09**
UWN2A			2.70	17.11	0.02	0.55		
UWN2B			10.50	18.36	0.02	0.52		
UWN2C			12.75	18.07	0.02	0.52		
UWN2D			11.70	18.07	0.02	0.55		
UWN2E			13.50	17.26	0.02	0.90		
AVG.		EBB	**10.23**	**17.77**	**0.02**	**0.61**	**0.11**	**794.14**
UWN3A			7.80	12.53	0.01	0.52		
UWN3B			9.30	14.18	0.01	0.61		
UWN3C			7.35	15.40	0.02	0.51		
UWN3D			9.30	14.11	0.01	0.57		
AVG.		EBB	**8.44**	**14.06**	**0.01**	**0.55**	**0.07**	**473.67**
UWN4A	L/T		4.50	14.99	0.01	0.50		
UWN4B	L/T		6.75	16.02	0.02	0.56		
UWN4C	L/T		5.25	16.36	0.02	0.57		
UWN4D	L/T		7.95	16.10	0.02	0.66		
UWN4E	L/T		6.30	15.53	0.02	0.62		
AVG.	L/T	EBB	**6.15**	**15.80**	**0.02**	**0.58**	**0.06**	**406.72**

Winter: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
UWS1A	L/T		3.00	13.65	0.01	0.59		
UWS1B	L/T		8.70	16.81	0.02	0.56		
UWS1C	L/T		12.45	16.65	0.02	0.52		
UWS1D	L/T		9.75	16.84	0.02	0.58		
UWS1E	L/T		14.70	16.32	0.02	0.65		
AVG.	L/T	EBB	**9.72**	**16.05**	**0.02**	**0.58**	**0.09**	**653.22**
UWS2A			5.70	15.30	0.02	0.56		
UWS2B			6.75	15.34	0.02	0.53		
UWS2C			9.75	16.25	0.02	0.68		
UWS2D			6.30	15.56	0.02	0.63		
UWS2E			4.00	15.79	0.02	0.62		
AVG.		EBB	**6.50**	**15.65**	**0.02**	**0.60**	**0.06**	**442.62**
UWS3A			6.00	13.45	0.01	0.51		
UWS3B			10.50	15.61	0.02	0.55		
UWS3C			7.50	15.06	0.02	0.56		
UWS3D			7.80	13.78	0.01	0.54		
UWS3E			9.30	13.18	0.01	0.60		
AVG.		FLOOD	**8.22**	**14.22**	**0.01**	**0.55**	**0.06**	**462.07**
UWS4A	H/T		3.75	12.55	0.01	0.51		
UWS4B	H/T		10.50	13.72	0.01	0.56		
UWS4C	H/T		15.00	13.57	0.01	0.67		
UWS4D	H/T		9.75	13.21	0.01	0.66		
AVG.	H/T	FLOOD	**9.75**	**13.26**	**0.01**	**0.60**	**0.08**	**560.25**

Spring: Neap Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
USN1A	L/T		11.10	34.43	0.03	0.26		
USN1B	L/T		9.00	37.32	0.04	0.23		
USN1C	L/T		3.00	40.25	0.04	0.28		
AVG.	L/T	EBB	**7.70**	**37.33**	**0.04**	**0.26**	**0.07**	**529.17**
USN2A			1.50	23.75	0.02	0.01		
USN2B			1.50	28.67	0.03	0.08		
USN2C			12.90	23.21	0.02	0.33		
USN2D			13.50	22.28	0.02	0.45		
USN2E			7.60	23.27	0.02	0.23		
AVG.		EBB	**7.40**	**24.24**	**0.02**	**0.22**	**0.04**	**282.28**
USN3A			6.90	22.41	0.02	0.11		
USN3B			3.00	20.60	0.02	0.21		
USN3C			6.00	22.08	0.02	0.28		
USN3D			18.00	22.27	0.02	0.30		
AVG.		EBB	**8.48**	**21.84**	**0.02**	**0.23**	**0.04**	**301.18**
USN4A	H/T		10.50	19.71	0.02	0.02		
USN4B	H/T		7.80	18.92	0.02	0.01		
USN4C	H/T		9.30	19.96	0.02	0.07		
USN4D	H/T		22.50	20.60	0.02	0.23		
AVG.	H/T	FLOOD	**12.53**	**19.80**	**0.02**	**0.08**	**0.02**	**144.17**

Spring: Spring Tide

Sample	Tide	Flood/Ebb	Area (m2)	Nitrate Conc. (mg/L)	Nitrate Conc. (kg/m3)	Avg. Velocity (m/s)	Flux (kg/s)	Flux f(t) (kg)
USS1A	TO L/T		3.90	22.45	0.02	0.02		
USS1B	TO L/T		2.40	25.31	0.03	0.25		
USS1C	TO L/T		12.90	26.48	0.03	0.72		
AVG.	TO L/T	EBB	**6.40**	**24.75**	**0.02**	**0.33**	**0.05**	**375.93**
USS2A	L/T		2.10	17.65	0.02	0.02		
USS2B	L/T		9.60	22.00	0.02	0.62		
USS2C	L/T		6.90	23.16	0.02	0.55		
USS2D	L/T		12.90	23.54	0.02	0.54		
AVG.	L/T	EBB	**7.88**	**21.59**	**0.02**	**0.43**	**0.07**	**526.63**
USS3A	TO H/T		9.30	23.63	0.02	0.03		
USS3B	TO H/T		6.30	27.23	0.03	0.06		
USS3C	TO H/T		5.00	29.06	0.03	0.07		
AVG.	TO H/T	EBB	**6.87**	**26.64**	**0.03**	**0.05**	**0.01**	**69.81**
USS4A	TO H/T		5.40	16.51	0.02	0.03		
USS4B	TO H/T		3.60	19.49	0.02	0.08		
USS4C	TO H/T		4.80	20.28	0.02	0.24		
USS4D	TO H/T		17.70	21.00	0.02	0.35		
AVG.	TO H/T	FLOOD	**7.88**	**19.32**	**0.02**	**0.17**	**0.03**	**189.51**

MGENI: NET FLUX CALCULATION

Summer: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
12530.15	**2676.34**	**9853.81**

Summer: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
4952.25	1535.46	3416.79

Autumn: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
1140.38	1237.85	-97.47

Autumn: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
831.24	1098.62	-267.38

Winter: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
1674.53	813.09	861.44

Winter: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
1095.83	1022.32	73.51

Spring: Neap Tide

Total Ebbs	Total Floods	Net Flux (kg)
1112.63	144.17	968.46

Spring: Spring Tide

Total Ebbs	Total Floods	Net Flux (kg)
972.36	189.51	782.85