A REVIEW OF STUDIES ON THE MFOLOZI ESTUARY AND ASSOCIATED FLOOD PLAIN, WITH EMPHASIS ON INFORMATION REQUIRED BY MANAGEMENT FOR FUTURE RECONNECTION OF THE RIVER TO THE ST LUCIA SYSTEM

Report to the
WATER RESEARCH COMMISSION

by

GC Bate[1], AK Whitfield[2] & AT Forbes[3]
(Editors)

[1]Botany Department, Nelson Mandela Metropolitan University, Port Elizabeth
[2] South African Institute for Aquatic Biodiversity, Grahamstown
[3] Marine & Estuarine Research, Durban

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orders@wrc.org.za

This report is the outcome of a Mfolozi/Msunduzi Indaba arranged by the Consortium for Estuarine Research and Management (CERM) held at the Ezemvelo KZN Wildlife (EKZNW) Auditorium, St Lucia, on 3-5 May 2010. The workshop and report were funded by the Water Research Commission (WRC Project No K8/930).

EXECUTIVE SUMMARY

This report is structured around 14 contributions from various scientific disciplines, together with a synthesis section (see pages 256-260), all of which assist in understanding how the Mfolozi/Msunduzi rivers and floodplain link with the functioning of the St Lucia ecosystem. The end result is an endorsement for the relinkage of the Mfolozi and St Lucia estuaries and the implementation of measures that will reduce any excessive input of sediment from the former into the latter system.

Historical evidence from early maps and anecdotal evidence at our disposal indicate that changes in the Mfolozi/Msunduzi floodplain have had profound impacts on the Mfolozi Estuary and indeed on the whole St Lucia system. The separation of the Mfolozi from St Lucia in the early 1950s resulted in a major change in the way that St Lucia functioned. Only now are we beginning to see and experience the full implications of that separation for the well-being of the ecosystem, with the lake virtually drying out completely for the first time in living memory. However, it is not simply the loss of this riverine input to the salinity and water levels of the lake compartments that has caused the ecological ‘pendulum’ to swing off the scale and endanger St Lucia’s World Heritage status. There are many other impacts, some of which are well documented scientifically, while others are based primarily on observation or the behaviour of models, including:

- The St Lucia mouth closes more frequently than in the past and, once closed, remains closed for much longer. Modeling of these impacts has shown that the mouth, instead of staying closed for less than 30% of the time after closure, could now remain closed for as much as 80% of the time before breaching naturally.
- River sediment dynamics are affected. Mouth closure means that, with full connection, more river sediment during the high-flow periods enters St Lucia than if the mouth was functioning naturally. Under natural mouth regimes, when the mouth is more likely to be open during wet periods, much of the river sediment would be flushed into the sea. Under closed mouth conditions these sediments may accumulate within the system.
- Marine sediment dynamics are affected. These sediments tend to accumulate inside the estuary mouth, carried in by inflowing tidal water. In the former configuration, the combined flow from the Mfolozi and St Lucia through a single mouth would have been stronger than is the case for either of the separated mouths. Thus marine sediment dynamics are likely to be very different from what they were under natural conditions.
- Sediment flushing on a large scale would have occurred whenever the combined mouth breached, especially when there was a substantial head of water at the time of breaching (estimated to have been approximately 4.6 m above MSL in one case). Separation of the Mfolozi from the St Lucia system and artificial breaching has effectively resulted in a loss of this massive scouring process in the ‘bay’ area.
- Biotic connectivity between the Mfolozi and St Lucia has shown that freshwater prawns can breed prolifically in the Mfolozi wetlands. Their larvae are carried into St Lucia by small floods and there are likely to be several other similar cases for other species when there is a connection between the two systems.
- Prolonged mouth closure affects recruitment and breeding of many species of fish and crustaceans. This should be seen in the context of the life histories of key taxa (*e.g.* fish and penaeid prawns). For estuary-associated marine fish species in particular, once the populations in St Lucia have been reduced or extirpated locally, it takes several years after larval recruitment for the fish populations to recover and be able to contribute to the South African marine spawner stock.

In the future it will be necessary to maintain an overview perspective where each component is seen as part of a larger whole. At this stage, the need is to consolidate existing knowledge about the Mfolozi Estuary and associated floodplain and its relationship to St Lucia, a primary goal of this report. With the most recent expert opinion condensed within this report, it is now possible to proceed with rehabilitation measures with a greater measure of confidence. In this connection, a Global Environmental Fund (GEF) grant has recently been obtained to implement remedial measures and it is hoped that this report will be of value to that initiative.

Part of the reason it has not been possible to effectively link the Mfolozi to St Lucia is that relatively little has been known about the estuarine portion of the Mfolozi/Msunduzi system and how best to create the link between it and St Lucia. This report has collated much of that information and highlighted directly and indirectly that Mfolozi connectivity is of great importance to the future of the St Lucia system. The socio-economic assessments in this report have made a start at addressing relinkage issues around the Mfolozi and St Lucia systems. They also highlight the value of the St Lucia system on a national basis and the need for more work in this area in order to convince administrators and politicians of the necessity to support bold management actions.

Individual aspects that, according to the researchers involved in the workshop, require urgent research attention are highlighted on page 259 of this report. In broad terms, attention needs to be focused on:

- The linkage of the Mfolozi to St Lucia and how to divert large quantities of fresh water northwards when the St Lucia mouth is closed.
- How to reduce sediment input into St Lucia if the Mfolozi water is diverted.
- How to maintain the biotic connection between St Lucia and the sea in as near a natural state as possible.

A number of conceptual ideas are presented in this report to help stimulate a debate that might ultimately lead to a successful management plan for this unique area. Foremost amongst these is a suggestion that the natural subsidence of the floodplain be used as a ‘sink’ for new sediments flowing down the Mfolozi River. Similarly, a number of useful ideas are discussed in terms of the practical re-linkage of the Mfolozi to the St Lucia system and how this may be ‘managed’ to a certain degree using ‘soft’ engineering based solutions.

The overwhelming sentiment that came through at the ‘indaba’, and in the subsequent printed versions of the presentations, is that the time for talking has passed and the time for action to ameliorate the extreme environmental conditions at St Lucia has arrived. The Mfolozi and St Lucia system cannot wait another decade whilst more research is undertaken – sufficient information is already available for management to implement a plan for the long-term benefit of one of South Africa’s most important World Heritage Sites.

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INTRODUCTION

The Mfolozi River historically supplied much of the water to the St Lucia estuarine system. However, since the 1920s when sugar cane farming was introduced onto the Mfolozi/ Msunduzi floodplain, there have been progressive changes to the landscape for a number of reasons. The main result of these changes has been that the quality of the water, especially with respect to suspended sediment, has deteriorated to such an extent that the St Lucia management team considered it necessary to divide what was once a common St Lucia/Mfolozi mouth into two separate entities. The result of this ongoing action has been a shortage of freshwater inputs to the St Lucia system, especially during times of drought.

Developments within the catchments of the river systems that flow directly into St Lucia has compounded the situation in that much of the water which previously fed directly into the various lake compartments has now been diverted for agricultural and other uses. There has also been a considerable development of forestry in those same catchment areas, all of which have resulted in periods of very low river flow, decreasing water level in the lakes, and a progressive rise in salinity. The Mfolozi system still has sufficient water to supply St Lucia but the problem that confronts management relates to the suspended sediment that is associated with summer river flow, especially during times of flooding.

In May 2010 a group of specialists who have worked on the Mfolozi/Msunduzi floodplain (see page 264 for details) was approached by Ezemvelo KZN Wildlife (EKZNW) and a meeting convened by the Consortium for Estuarine Research and Management (CERM) with the following primary aims:

- To bring together researchers who have information on the Mfolozi-Msunduzi estuarine system.
- To give presentations describing recent findings on this system.
- To develop a description of the system, its processes and its dynamics.
- To identify knowledge gaps and set the course for future research.
- To produce a WRC report summarizing our current understanding of the system, with particular emphasis on information required to reconnect the Mfolozi to the St Lucia system.

The assembling of all available information on the Mfolozi/Msunduzi systems is an important service to management authorities in the area. EKZNW hoped that the outcome of the workshop might create a focus and momentum, not only for management decisions, but also to identify research needs and stimulate the initiation of relevant scientific projects. The proceedings documented in this report represent the findings of a diverse array of studies undertaken by a number of independent researchers, using funds made available from various science funding agencies.

There is now little doubt that St Lucia will be unable to survive as a World Heritage Site unless it obtains Mfolozi River water (especially during droughts). It is therefore hoped that this report will assist in the development of a framework to guide future research and management actions, such that we can achieve the long-term conservation of this valuable heritage for all South Africans.

THE ST LUCIA-MFOLOZI CONNECTION:
A HISTORICAL PERSPECTIVE

Ricky Taylor*

Affiliation: Ezemvelo KZN Wildlife, St Lucia Estuary, and
School of Biological and Conservation Sciences, University of KwaZulu-Natal, Pietermaritzburg
**Email:* taylorr@kznwildlife.com

INTRODUCTION

A shortage of freshwater is a recurring problem for Lake St Lucia, one that manifests itself every time there is a drought. It is a problem that is progressively getting worse with each drought, and is one that has attracted a lot of scientific attention in the past. This section provides a historical account of changes that have occurred in the St Lucia area, the responses of the ecosystem to changing land uses and the management actions taken to counter the effects of these impacts.

Without Mfolozi water there is insufficient freshwater during drought periods to sustain the St Lucia ecosystem in the state that it used to be in under those same conditions; the longer and more severe the drought, the greater the ecosystem changes that occur. And then, usually the period between droughts is not long enough for the system to recover fully from the effects of the previous drought before being subjected to the next drought cycle. This is leading to a progressive loss of system 'vitality' as is shown simplistically in Figure 1.

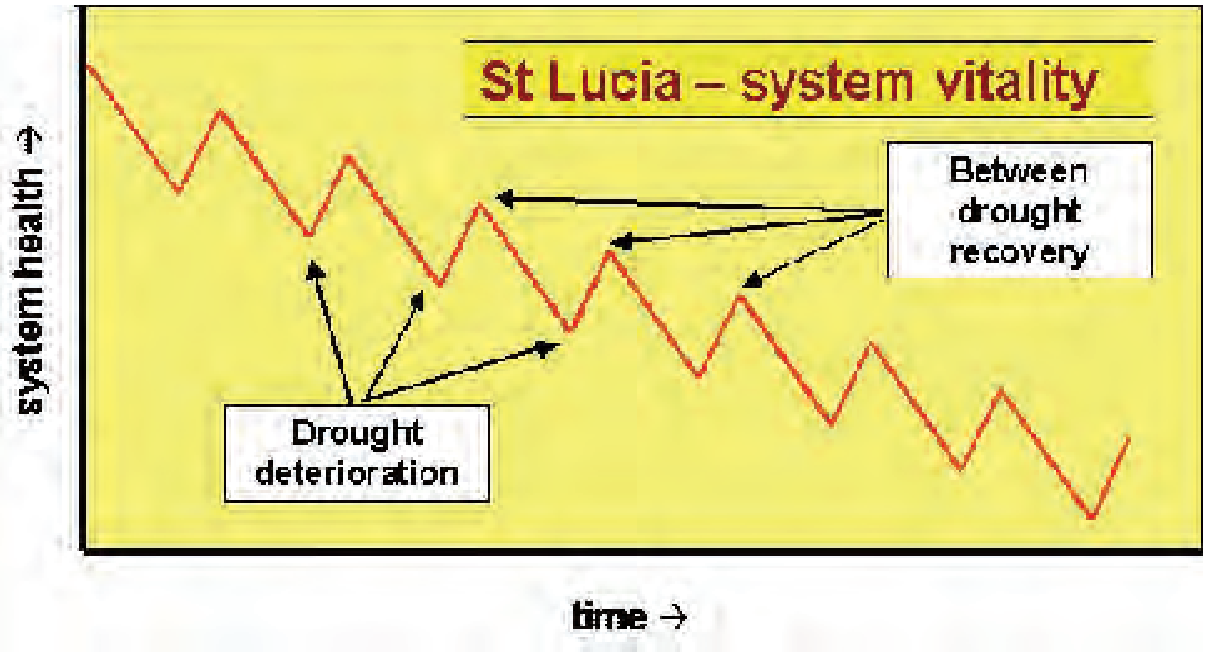

Figure 1. Illustration of the conceptual 'ratcheting down' of the 'vitality' of the St Lucia ecosystem.

This section reviews the historical record of conditions in the St Lucia/Mfolozi mouth area, the anthropogenic impacts that it has been subjected to and the management actions taken to mitigate against these impacts. It then highlights what we have learnt from these

THE HISTORICAL RECORD

Period prior to 1911 (before sugar cane was first planted in the Mfolozi floodplain)

The first historical records available that describe the St Lucia mouth are those of the 16th century Portuguese seafarers. These, and subsequent records from early hunters, travelers and traders into the area (Wearne, 1966), indicate that the mouth was open at times and closed at other times. On occasions sea-going ships would seek shelter in the "St Lucia Bay" and at other times the channel was too narrow. From 1821 to 1826 a hydrographic survey was conducted of the East Coast of Africa by Captain Owen, RN, in the ships Leven and Barracouta. This team mapped the coastline off St Lucia, which is the first accurate map to be produced of the coastline (Boteler 1835). From the mid to late 1800s we have several sketch maps of the mouth area. Typical of these are the map by Cato (1852) (Figure 2) and one drawn in 1883/4 (Figure 3).

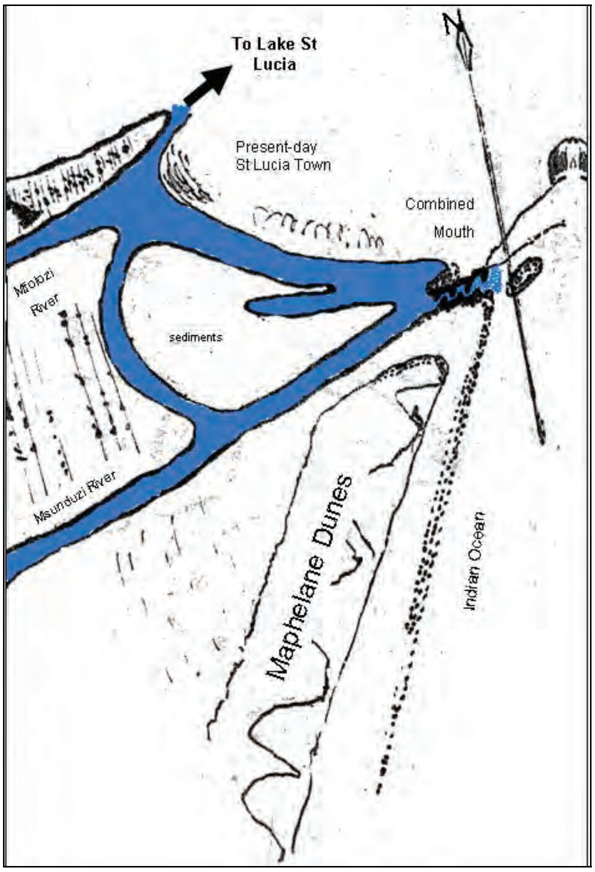

Figure 2. Map by Cato in 1852 showing the Msunduzi and Mfolozi rivers and a single mouth. The "Bay" is not large although the large area shown as sediments may be intertidal. By studying old maps it is possible to learn a lot about the early configuration of the bay. Note: this map has been annotated and modified to remove text that is not relevant to this report.

Figure 3. Map from 1883/84 showing the delta of intertidal sediment deposited at the mouth of the Mfolozi. The above map is interesting as it shows two inlets from the sea. Also clearly shown is an island at Honeymoon Bend. The present day island is composed of dredger spoil deposited on an oyster reef. The Msunduzi River, although shown in Cato's 1852 map (Figure 2) is not shown in the 1883/4 map (Figure 3).

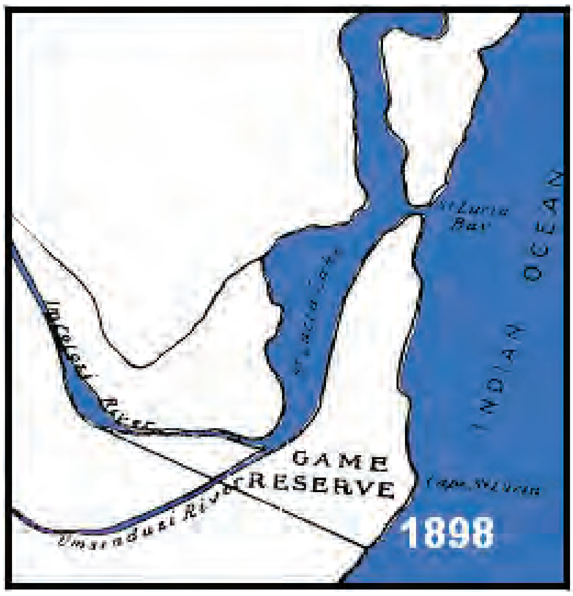

Figure 4. St Lucia was proclaimed a game reserve in 1895. In 1898 the proclamation details were published, containing this map which shows a large "bay" where the Mfolozi River enters the estuary (mislabelled "St Lucia Lake" in this diagram). The Msunduzi River is clearly shown joining the Mfolozi River before entering the "bay". Note: for this report this map has been modified by the removal of some detail north of the area shown.

These maps show that, at times, there was a large water body where the Mfolozi River meets the St Lucia Estuary and that there was a single main outlet to the sea for the two systems. The 1880 map shows two inlets, but this is to a "bay", a feature common to both the Mfolozi and the St Lucia systems. Because these are not accurately surveyed maps, we do need to interpret them with care as is shown in Figure 5.

Figure 5. Maps of the St Lucia system covering approximately the same area. The map on the left is from 1877 and the one on the right from a century later.

The map on the left was drawn when it was impossible to obtain an overview in the way it is now done using aerial and space imagery. It is likely to have been drawn from a compilation of information from a number of sources collected at different times. The coastline appears to be reasonably accurate, probably because of the hydrographical survey done in the 1820s by Captain Owen. Inland there had been no survey and hence the sketch map is a compilation of cognitive maps done by several explorers, traders, seafarers and hunters. The area around the St Lucia mouth was known best and so is likely to be the most accurate. The figure shows "Conical Hill", a dune of distinct shape that was washed away during the 1984 Domoina floods. Also in this map is the "St Lucia Bay and River" which is a distinct body of water. As in the 1883/4 map (Figure 3), the Msunduzi River is not shown. Northwards, the detail is less distinct. The lake is too wide and the orientation of False Bay is distorted. Of interest is that the Mkhuze swamps are shown as part of the St Lucia water body. It is possible that this was an impenetrable marsh and the map-makers assumed open water northwards from a fringe of reeds and papyrus. It is also possible that it was mapped at a time when water was backing up and flooding large parts of the swamp.

In 1905, Charlie Crofts, a Harbour Engineer from Durban, was commissioned to survey the St Lucia Bay to determine its potential as a harbour. The map produced is a fine piece of work that gives an accurate layout of the St Lucia Mouth (Figure 6) joined to the Mfolozi mouth. This first accurate map of the area provides a detailed reference point for any future understanding of the system.

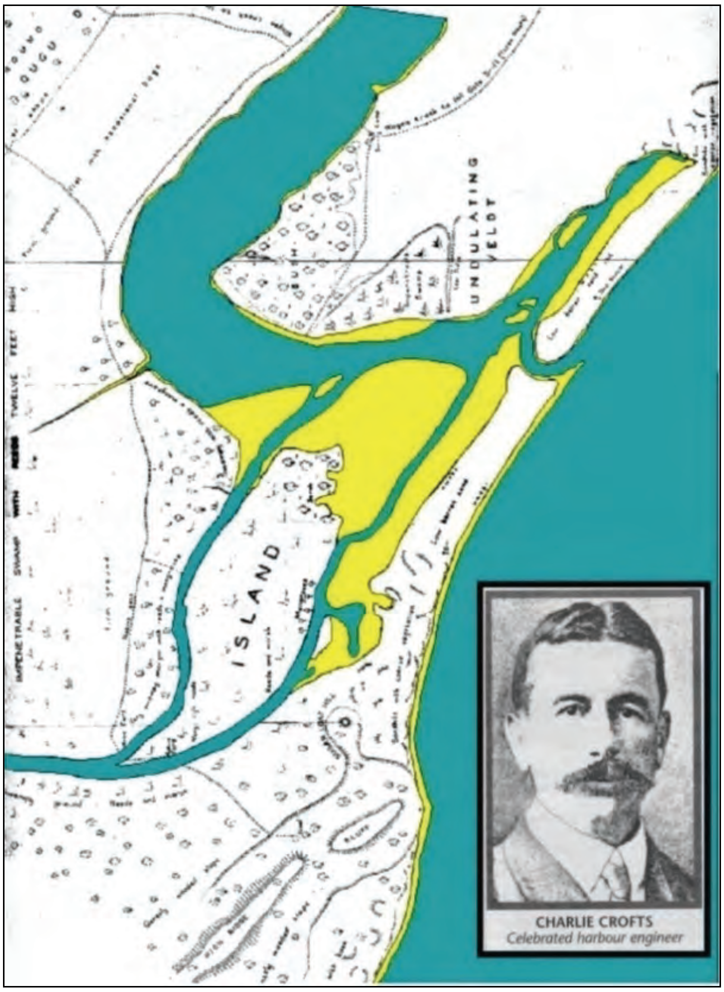

Figure 6. Map of the St Lucia Mouth area drafted by Charlie Crofts (inset photograph) in 1905. Yellow indicates sand banks and blue the water. Note the single mouth, the branched link of the Mfolozi into the bay area. The Msunduzi is not on this map because its confluence with the Mfolozi is upstream of the mapped area.

What has been learned from historical records and maps is:

- The Mfolozi and St Lucia once shared a common mouth.
- That mouth was open at times and closed at others (Wearne, 1966).
- St Lucia Bay was on the inland side of the mouth. It was an area that would have had a large tidal prism. The tidal exchange would have maintained an open mouth for much of the time.
- The Msunduzi was not the main channel draining the Mfolozi Floodplain. It seems that for most of the time the Mfolozi was the main channel.

Period from 1911 to closure of the combined Mfolozi and St Lucia mouths in 1950

In 1911 sugar farming was started in the Mfolozi Flats (Dobeyn, 1987). The impact on St Lucia was small until drainage schemes were implemented. There were large floods in 1918 and again in 1925, both of which flooded the cane fields. Then, in 1932, there was an event that provides an understanding of the dynamics of the St Lucia/Mfolozi system after closure. "The combined St Lucia-Mfolozi mouth closed. It was blocked by a 14 ft [4.6 m] sand bar. The 'Drainage Committee' deputed Mr George Perrier, with a gang of 40 Africans, to make an outlet. This he successfully managed, and dammed up water poured out to sea for the next fortnight. The Kenilworth Castle in passing, falling foul of debris and trees" (Harrison, 1989). This is an important record as it is an indication that much water had dammed up behind the closed beach berm after mouth closure and an indication of how large a volume of water could be released on breaching.

The water, backed-up to a level of 4.6 m amsl, would have inundated large areas of the Mfolozi floodplain and would probably have impeded water outflow from the sugar field drains. This caused water logging of the sugar fields upstream of the Uloa area (near Monzi). To avoid such incidents in the future, and to encourage the more rapid drainage of water after floods, Warner's Drain was excavated. After its completion in 1936 the Mfolozi River was confined to a permanent channel. From then on this canal was the conduit along which the river and its sediments would pass. The river course was subsequently straightened to remove meanders and the levees on its banks were raised. After this time, the point where sediment deposition occurred was transferred from the upper portion of the swamp to the lower part of the swamp where the water was released from the canal. Whenever there was a flood, the water escaped from the canal onto the floodplain. To counter this, the levees along the channel were raised; only to be overtopped during a larger flood. Ultimately, during the Domoina flood the Mfolozi broke out of its channel and diverted into the Msunduzi channel. After this, a floodwater diversion weir was constructed near Riverview. The purpose of this weir was to ensure that the capacity of the canalised Mfolozi River would not be exceeded and that whenever the flow is more than what the levees can contain, the excess water is diverted down the Msunduzi River course.

The first aerial photographs of the St Lucia mouth area were taken in the late 1930s (Figure 7) and in 1937 the first formal vertical photographs were taken by the National Department of Trigonometrical Survey and were used as the base for the 1942 map (Figure 8). These photographs and the map provide a record of conditions at the time.

The topographical features seen in these photographs are very similar to those mapped by Crofts in 1905 (Figure 6). In the intervening period there had been two mega-floods (1918 and 1925) and a mega-breaching event (1932). It is therefore hard to explain that so little change had occurred in these 32 years. Is it possible that this is an artifact of not having information about the state of the mouth area in the intervening period and it is not known if the mouth had passed through a full scouring/sedimentation cycle and was, by coincidence, in more or less the same state each time?

Figure 7. An oblique aerial photograph taken in the late 1930s from west of the present day St Lucia Bridge looking to the south-east. In the distance is the dark mass of the Maphelane dune and stretching from it is the white beach berm that separates the estuary from the sea. To the right and in front of the dune is the branched Mfolozi River entering St Lucia Bay.

Figure 8. The 1942 Trigonometrical Survey 1:50 000 topocadastral map based on the 1937 aerial photography. This was possibly the first accurate map since the Crofts map of 1905.

After the early 1940s the state of the St Lucia Mouth area changed rapidly. Concern was expressed about the accumulation of sediment in the area. To address the “siltation problem” various experts were brought in to provide advice, including Colonel Patterson (the Harbour Engineer in the late 1930s), Dr Von Bonde (the Director of Sea Fisheries, Van Bonde, 1940) and Professor John Day (an estuarine zoologist from the University of Cape Town, Day 1948). The latter two both commented on the way Mfolozi water was diverted into St Lucia Lake at times and all three of these experts were of the opinion that the siltation was a consequence of the canalisation of the Mfolozi Flats. Then in May 1951 the combined mouth closed (Kokot, 1959).

What has been learned from this period is:

- The Mfolozi Flats are affected by 'mega floods' which completely fill the basin.
- The combined St Lucia/Mfolozi mouth used to be closed at times. Breaching would have occurred when the beach berm overtopped. Prior to this, the level would have risen to the extent that the backed up water would have flooded a very large surface, including the lower parts of the Mfolozi and Mkhuze floodplains and swamps, as well as the margins of the lake and up the valleys of the rivers. The breaching after water had backed up would scour the mouth area.
- Due to canalization, the point of greatest sediment deposition by the Mfolozi River was transferred from the upper portion of the swamp to the point in the lower part where the water was no longer confined within the canal.
- Mfolozi water was diverted into St Lucia as the level in St Lucia drops below mean sea level.

Period between the closure of the combined mouth in 1951 and Cyclone Domoina in 1984

In 1952 a new mouth was dredged for the Mfolozi River and in April 1956 a separate mouth was opened for St Lucia Estuary. Following this, and up until 1984 management was guided by two tenets:

1. It was assumed to be necessary to keep the mouths separate to prevent accelerated sediment accumulation in the St Lucia system and;
2. The connection between St Lucia and the sea was to be maintained at all times so that estuarine and marine migrant organisms could move freely between the estuary and the sea.

Since the 1950s the two mouths have been kept separate. This has been the case except for short periods, such as after the Domoina floods, when they merged and were separated once it was possible to do so. Mfolozi water has not been free to enter St Lucia during low-rainfall periods when the lake level is below that of mean sea level. This separation of the two mouths was a pivotal point, after which the ecological functioning of the St Lucia system changed**.** Because there was virtually no scientific investigation prior to this, almost all our knowledge of St Lucia is of this altered system.

The drought of the late 1940s and early 1950s, the accumulation of sediments and the raised salinity in the northern parts of the lake (over 52 was measured in False Bay in July 1948, Day, 1948) led to the Presidential Commission of Inquiry into the state of St Lucia that was conducted from 1964 to 1966 (Kriel, 1966). This was a seminal study of the full system that has been a foundation for much of the current understanding of the functioning of St Lucia.

The Reclamation Unit was formed in the early 1950s (Figure 9). Its first task as to dredge away the accumulated sediment from the St Lucia mouth area; an exercise that was to take 13 years. After that, it deepened the 22 km channel between the mouth and the main lake in an effort to promote better water circulation. At the same time the mouth was stabilised by hard structures (Figure 10). The assumption was that a narrow mouth would be self-scouring but this did not prove to be successful. The “Back Channel” was also dredged in the early 1970s (Figure 11) ostensibly to enhance input of fresh water from the Mfolozi to the St Lucia lakes and the sea.

Figure 9. The first dredger, the Ilanda and a dragline excavator removing sediment from the channel of the blocked mouth area in the late 1950s (Photographer unknown).

Figure 10. Aerial photograph of the St Lucia mouth taken in about 1974, showing the groynes built to stabilise and constrict the mouth. The north groyne was built first followed by the smaller one on the south bank. The estuary mouth is at the lower right corner of the picture (photograph: R. Taylor).

In the period 1968-72 St Lucia was subjected to a severe drought. Without the closure of the mouth, and the diversion of the Mfolozi River away from St Lucia, the system became progressively more hypersaline as seawater entered to replace lake water lost by evaporation. This condition initiated the setting up of a large hydrological study under the leadership of Prof. Des Midgley of the Hydrological Research Unit at the University of the Witwatersrand in Johannesburg. His student, Ian Hutchison, established a monitoring programme and developed a mathematical water and salt balance model to investigate ways to ameliorate conditions at St Lucia (Hutchison & Midgley, 1978). They still were constrained by the management directive that, whenever possible, the mouth of St Lucia should be maintained open. They used the model to investigate various engineering solutions for the management of St Lucia and the decision was taken to excavate the Mfolozi Link Canal. This was a canal designed to carry Mfolozi water into St Lucia. It had an intake works, which allowed for water to be brought in selectively. These works also had a mechanism to automatically close the sluice gates whenever the Mfolozi River was in flood. The assumption was that water could still be extracted from the Mfolozi during below average rainfall periods and only during periods when the sediment load was reasonably low.

Figure 11. Aerial photograph (1975) showing the position of the “Back Channel” south of the St Lucia Estuary and linking through to the Mfolozi Estuary. Also visible is the levee from ENE to WSW that was excavated to prevent the sheet-flow of floodwaters from the Mfolozi towards St Lucia.

Excavation of the Umfolozi Link Canal was started in the late 1970s and was in its final stages of construction at the beginning of 1984 (Figure 12). However, this phase of management by “domination of nature” came to an abrupt end in late January 1984 when the floods caused by Cyclone Domoina swept away the stabilising structures at the St Lucia mouth, washed the dredger into the sea and damaged the Link Canal. It demonstrated how the major geomorphologic processes occur during extreme events (Figures 13 and 14).

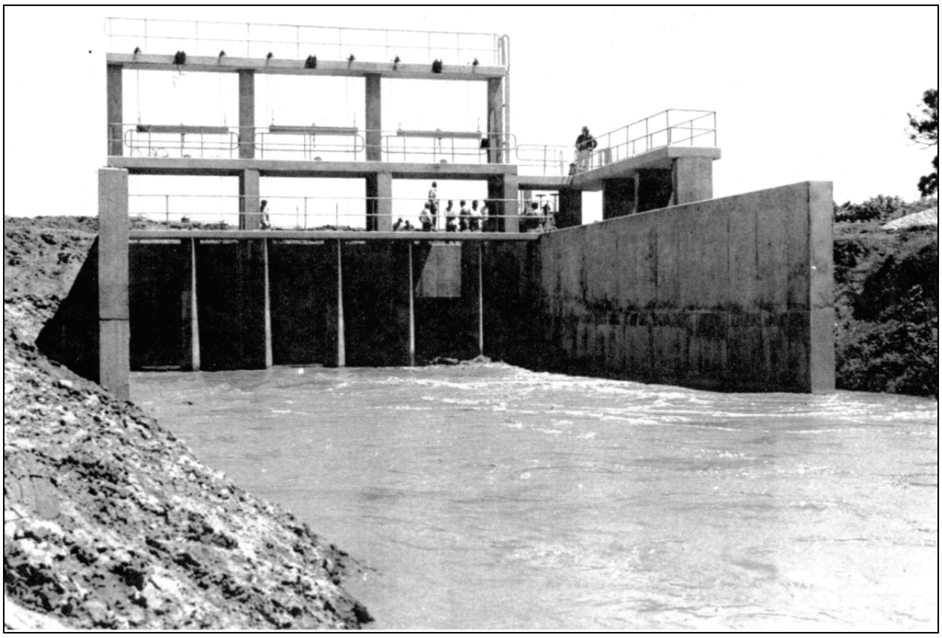

Figure 12. Mfolozi water entering the Link Canal through the Intake Works (photograph: R. Taylor).

The photograph (Figure 12) was taken during the official opening of the canal in late 1983. The canal was not yet completed as there had been delays in the excavation of the silt-settling basin. The gates of the Intake Works were opened to show the visitors how they worked and closed after half an hour. This was possibly the only time the canal was operated. Note the height of the concrete superstructure on which was mounted the gate-operating equipment.

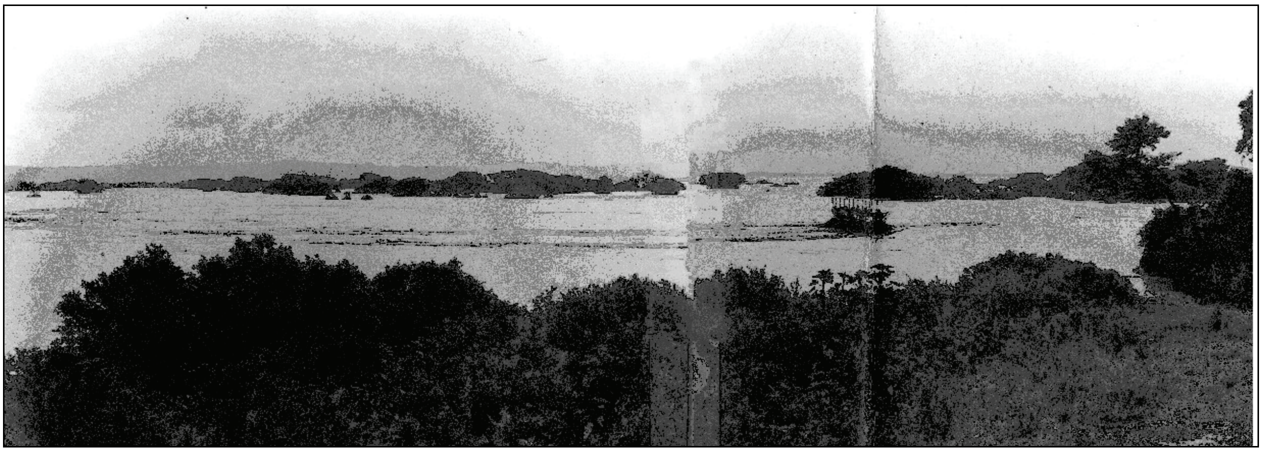

Figure 13. Domoina floodwaters filled the Mfolozi basin. In the centre-right the concrete superstructure of the Intake Works protrudes above the floodwater (photograph: R. Taylor).

Figure 14. The Link Canal was damaged during the Domoina Flood. This photograph shows flood debris caught in the superstructure of the Intake Works (photograph: R. Taylor).

This period, from the time of the mouth separation in 1952 until the 1984 flood, had been one of intensive research into the hydrology of the system as well as the responses of biological species to salinity and other environmental parameters and new knowledge and experience was acquired on several aspects:

- Knowledge of the hydrology of the St Lucia and Mfolozi systems was greatly increased (Kriel, 1966; Hutchison & Midgley, 1978).
- The management approach was one where it was thought possible to control natural processes. On many occasions it was shown that this was not possible.
- It was a period of intense engineering and research activity stimulated by the 1968-1972 droughts.
- From this time onwards the two mouths have been kept separate. Mfolozi water is no longer free to enter St Lucia during periods when lake evaporation exceeds freshwater gain.

Period after Cyclone Domoina in 1984 until the start of the current drought in 2002

The flooding caused by Cyclone Domoina was extreme. Similar floods, although possibly not quite as large, had been experienced in 1918, 1925 and again in 1987. The flood associated with Cyclone Domoina provided insights about how significant such large flooding events are to the system. Personal observations during the flood indicated that there was intense scouring and deposition. During the early stages the Mfolozi floodwater was split, some going seaward and some northward into St Lucia. A boat from St Lucia was later found lodged high in the branches of a mangrove tree along the Western Fork more than 15 km from the St Lucia mouth. The floodwater then changed direction due to a delayed rise in the water level within Lake St Lucia. The fast out-flowing water in the Mfolozi eroded away the "Conical Hill" near Maphelane and the channel on the seaward side of Honeymoon Bend was scoured to a depth of 18 m. The scouring in this area may have been more severe than in previous floods because of the deposition of dredge spoil in the central area of the lower flood plain which created a plug that would have impeded the rapid outflow of the water from the central section. An illustration of the pattern of Mfolozi water movement during closed-mouth and during flood conditions is provided in Figures 15a and 15b.

Beginning in the late 1960s science and engineering at St Lucia was guided by the Scientific Advisory Council (SCADCO), a multidisciplinary committee of experts in various fields of science and engineering. After the Cyclone Domoina flood in 1984 had washed away the hard structures at the St Lucia mouth and damaged the Link Canal, the necessity for a new approach was recognized. A considerable body of knowledge had been accumulated that provided an understanding of how the various components of St Lucia functioned and there was also a good understanding of coastal processes.

SCADCO facilitated post-flood studies to be conducted by Drs Ivor van Heerden and Harry Swart (Van Heerden, 1984; Van Heerden & Swart, 1986). These introduced a process-based management philosophy which guided the managers in their decision of what dredge equipment to purchase to replace that lost during the floods and to install a land-based pipeline in order to pump sediment into the sea to the north of the St Lucia mouth. The dependence of St Lucia on the Mfolozi and its floodplain was highlighted by this research.

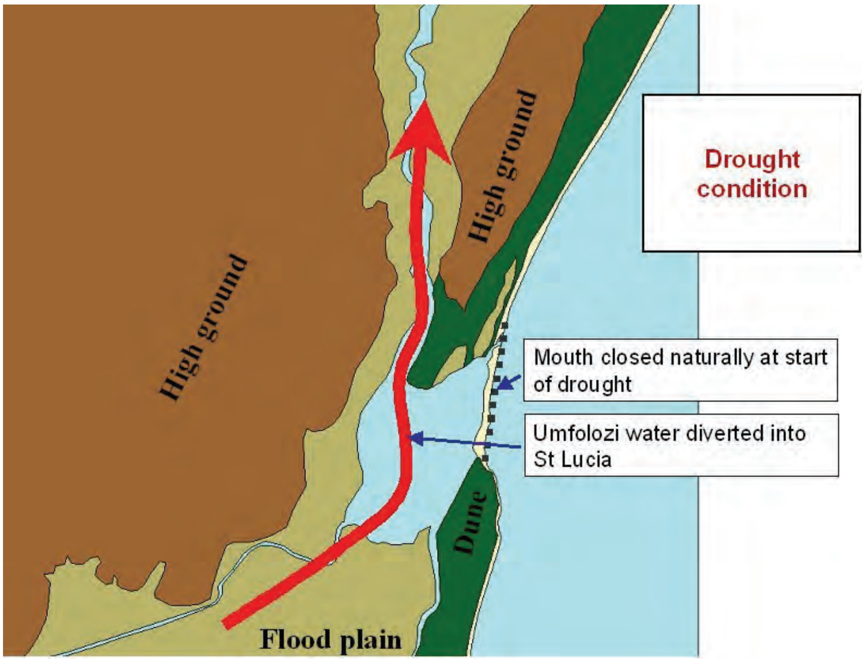

Figure 15a. Schematic representation of the path of Mfolozi water as it is diverted northwards into Lake St Lucia once the combined mouth closed (from Taylor, 2006).

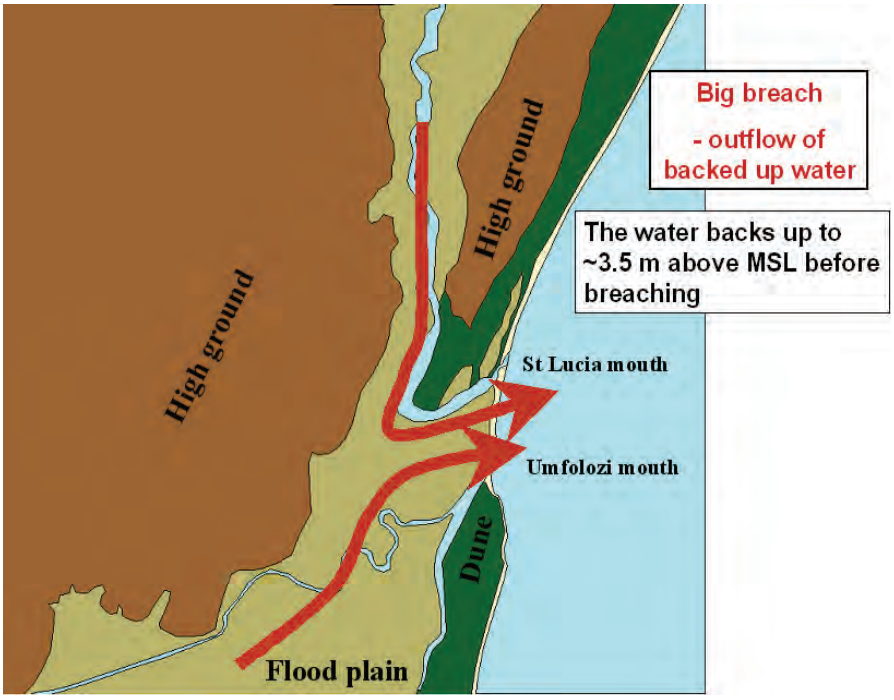

Figure 15b. During flood or breaching conditions the paths are as shown (red arrows), with two streams of water meeting in the mouth area. This area is scoured, removing sediment from the "bay".

Dredging in St Lucia became a maintenance operation where the main objective was to excavate a basin at the upstream margin of the flood-tidal delta to trap incoming marine sediment. This maintained a degree of stability of the St Lucia mouth. The mouth would be allowed to close naturally, but was still breached after a short period of closure, and the Mfolozi would still be kept separate from St Lucia.

In contrast to the research being done on Lake St Lucia, scientific endeavours on the Mfolozi and St Lucia mouth regions tended to focus more on the interactions of system components and less on the biology of individual species. There was an increased understanding of the palaeo-environments and the large-scale processes that have shaped the system in the past and hydrological modeling was being revived.

One of the major questions that remained was: What is the mechanism by which the mouth breaches after a period of closure? In 1932, the water was quoted to have backed up to 14 ft (4.6 m) before the system was artificially breached. But had it been left, it is assumed that the water would eventually have overtopped the beach berm and opened naturally. The outflow of the backed up water would have had a similar scouring effect to that of the Domoina flood. Figure 16 shows a expected dimensions of the scoured “bay” following the mouth breaching described above.

The 1964-1966 Kriel Commission had made recommendations that quotas of freshwater should be set aside for the maintenance of St Lucia, but these have never been formally accepted and were ignored. Now, the National Water Act (Act 36 of 1998) specifies that a Water Reserve shall be determined for each water ecosystem and that this shall be set aside before any water abstractions are allocated (except for the basic amount required per person). An exercise was held in 2002 to determine the Water Reserve for St Lucia. This exercise (Van Niekerk, 2004) was done at a preliminary level for St Lucia and highlighted the importance of reconnecting the Mfolozi to St Lucia.

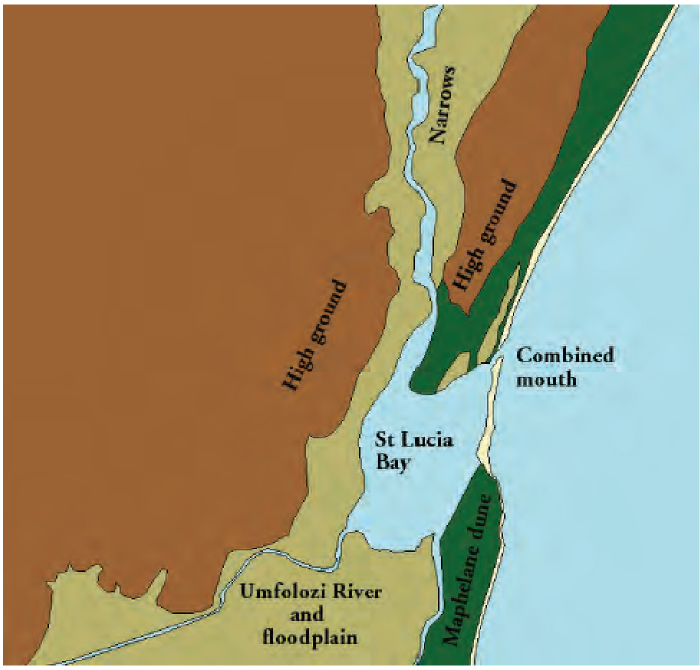

Figure 16. Scouring creates the St Lucia Bay (from Taylor, 2006).

From this post-Demoina period there was a realization that:

- It is necessary to work with natural processes when managing the system.
- That the imperative to keep the St Lucia Estuary mouth permanently open may not always be beneficial.
- A lot has been learned about how the system functions, i.e. the diversion of Mfolozi water northwards when the mouth is constricted or closed; the backing up of water in the Lake and floodplains, and the impacts of large floods and the breaching by overtopping of the beach berm.
- It reaffirmed the necessity to re-establish a degree of linkage between the Mfolozi to St Lucia.

Period 2002 to present – impact of a major drought on an altered ecosystem

In 2002, at the start of the current drought, the St Lucia mouth closed and at that stage a decision was taken to allow the mouth to remain closed for its duration. This was to prevent an excessive amount of salt from entering Lake St Lucia when seawater flowed in to replace water lost by evaporation. However, this drought has been particularly prolonged and severe. The insights into the functioning of the combined St Lucia/Mfolozi system gained during this extreme drought period are as great as those gained from the extreme wet conditions experienced during the Domoina floods. New approaches are now being applied and the previously established tenets that presently guide our management are being challenged. These challenges are based on the scientific understanding that has been gained in the period since Domoina.

The decision to leave the mouth closed was taken to avoid the build-up of a large mass of salt in the system and Management was of the opinion that the system would recover faster if accumulated salt did not have to first be flushed out by inflowing freshwater. However, the cost of this is that the lake water level dropped drastically; to a point in 2006 when over 80% of the system was dry (Whitfield & Taylor, 2009). There was no biological connection between the lake and the sea and species such as mullet *Mugil cephalus*, crabs *Scylla serrata* and many other species are now effectively absent from much of the system. Except for a six-month period from March to October 2007, the mouth of St Lucia has remained closed.

In 2008 and again in early 2010 the Mfolozi mouth also closed. In both cases it was not opened immediately and the water backed up in the lower Mfolozi/Msunduzi floodplain. Once it had reached the level of about that of a high tide, the water started flowing through the old Back Channel (Figure 11) into St Lucia (see Kelbe & Taylor, this report). Since most of the riverine sediment load had already settled on the Mfolozi/Msunduzi floodplain, the water passing through into St Lucia was virtually sediment-free. An estimated 17 million m^3 of freshwater entered St Lucia the first time this occurred and 5 million m^3 the second time. These linkages provide a pointer of how to manage the linkage of Mfolozi water in a manner that will allow sediments to settle before the water is diverted into St Lucia. However, it must be noted that the linkages were conducted primarily during late autumn and winter when sediment loads in the river are much lower than in summer,

Figure 17. Photograph taken from about 3000 feet above the Msunduzi Estuary looking northwards. On the mid-left is the Mfolozi Estuary, which joins the Msunduzi Estuary near the beach. At the time this photograph was taken the Mfolozi/Msunduzi Estuary was closed. At the top is the closed St Lucia Estuary. On the upper left the Narrows extend upwards to join to Lake St Lucia that can be seen in the distance (photo: R. Taylor).

What has been learned during this current drought?

- The Mfolozi link to Lake St Lucia in the past is likely to have been an intermittent link, with the water being diverted into the lake when the mouth was closed or when the lake level was below mean sea level.
- After mouth closure, the water would have backed up behind the beach berm and filled both the lake and other parts of the system, e.g. the floodplain swamps and all other low-lying areas. The lake would have been fed from all the rivers and direct rainfall.
- The mechanism for breaching of the system in its natural condition was probably by overtopping of the berm at the mouth (much less likely to be erosion from the sea side).
- During closed mouth conditions there is a loss of biological connections with the marine environment. This affects specific species groups e.g. the fish and crustaceans that breed at sea but use estuaries as nursery areas.
- Under present day conditions, if the mouth is maintained in the open state during a drought, the system will accumulate a large quantity of salt from the sea. If the mouth is closed, the estuarine water level will fluctuate considerably and the biological link with the sea will be lost.
- Our research must focus on understanding St Lucia mouth processes and management should be directed towards restoring a single mouth situation.

SYNTHESIS AND CONCEPTUAL UNDERSTANDING

Our understanding of the dynamics of the system has been improving all the time as we record how the system responds to different conditions, and as we interpret these responses within the context of our ever-increasing scientific knowledge. We know it is necessary to bring freshwater from the Mfolozi River into the St Lucia system. We have known this since the connection was first severed in the 1950s. The Mfolozi carries more water than the combined total of the other rivers associated with St Lucia and, to alleviate some of the freshwater starvation, there is a need to ensure that at least some of this water enters St Lucia during drought periods. The need for this freshwater manifested itself strongly in the 1968-1972 drought, as well as in the droughts of the early 1980s and early 1990s. Now, with the extended present drought the need to supply freshwater to St Lucia is again very evident.

The mouth closure in 1932 indicated that there was a 14 ft (4.6 m) rise in backed-up water, probably to a level where it would have spread over the whole St Lucia system. The lateral flooding would have been considerable, possibly more than doubling the average surface area of the lake compartments as the water backed up into the lower parts of the Mkhuze Swamp. It would have backed up the river valleys in False Bay, flooded the low-lying shoreline areas around the lake, flooded the lower portions of the Eastern Shores as it expanded laterally adjacent to the Narrows to form a channel of over a kilometre wide and flooded the lower half of the Mfolozi Floodplain. The volume of water at 4.6 m amsl would have been huge compared to the volume that is contained in St Lucia when it is at mean sea level.

Deep-water wave action associated with the large volume would have been severe because the wind fetch was larger and much of the water was deeper than when the lake is at sea level. This water would have been almost fresh, containing only the salt that was trapped in the system when the mouth closed. Hence, if the water level stayed constant for long enough, the shoreline would have been colonised by reeds and other emergent vegetation. Although there could have been remnant populations of marine-breeding fish such as mullet, it is speculated that their numbers would have declined after a few years. The system would then have been dominated by fish such as *Oreochromis mossambicus*, but this was only a temporary system-state. On breaching, there would have been considerable scouring of the mouth area, removing sediment from the ‘St Lucia Bay”. The mud and sand flats exposed after breaching would have formed an attractive habitat for many birds and the pioneer grass and sedge growth after this would have been fed by the sustained seepage of water coming from the Eastern Shores. This would have been considerable as the groundwater table adjusted to a new base set by the lowered lake level. It is possibly this system, rich in hippos and crocodiles, that was described by some of the early European hunters who came into the area.

Much of the foregoing is speculation because there are few records to help understand the past dynamics of the system. It is possible to model the hydrology to give indications of how frequently the water backed up behind the beach berm. There is only a single indication of how high this berm could rise (4.6 m), thus holding a massive volume of water behind it. There is little information on how long the closed condition could have lasted each time the mouth closed. We must therefore use current day understanding of processes to gain information about the dynamics and possible rates of change, including rainfall patterns and river flows that affect mouth closure and rates at which a closed system fills up. Perhaps most important of all is to understand the effects of a full-lake breaching event on the system.

It is necessary to know more about the mega-floods that impact on the area. There were at least four of these during the 20th Century (1918, 1925, 1984, and 1987). It is also necessary to recognise the opposite extreme, i.e. the severe droughts that affect this region when there are several successive years with well-below average rainfall. The floods and droughts are natural extreme events, but their impacts have increased in severity due to human modifications to the landscape – and may increase further as more extreme droughts and floods ate predicted to occur as global change manifested itself. A challenge for the managers is to apply management systems to reduce the extreme (unnatural) severity of these events.

An understanding of past conditions provides insights about how the system used to function, but we cannot put back the clock. There is a need to accommodate the changes that have occurred as a result of anthropogenic developments. There are some impacts that are reversible and some that can be mitigated for at a relatively small cost. These actions will have a large beneficial effect in getting the system closer to its original condition and thus restore and enhance some of the features of the system that are so valued. These are the features that were recognised in the late 1800s when the first areas of the park were set aside for conservation. It is also necessary to consider aspects not recognised earlier but which are now so valuable to us. Pre-eminent of these is the value of St Lucia as a functional nursery for fish and crustaceans that enhance the national sea fishery.

ACKNOWLEDGEMENT

Prof Dougal McCracken of the University of KwaZulu-Natal assisted in the acquisition of historical maps of the St Lucia mouth.

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THE MFOLOZI FLOODPLAIN: WATER AND SEDIMENT PROCESSES

Ricky Taylor

Affiliation: Ezemvelo KZN Wildlife, St Lucia Estuary, and
School of Biological and Conservation Sciences, University of KwaZulu-Natal, Pietermaritzburg
Email: taylorr@kznwildlife.com

INTRODUCTION

To understand the functioning of the Mfolozi/Msunduzi Estuary it is necessary to see it in the context of the end of the Mfolozi catchment and the lowest end of the Mfolozi floodplain. This section provides a conceptual view of the floodplain processes that affect the Mfolozi/Msunduzi Estuary and of the impacts that human activities have on the natural functioning of this basin.

CATCHMENT HYDROLOGY AND SEDIMENTOLOGY

The catchment area of the Mfolozi River that extends from near Vryheid to the sea is 11 070 km^2 (Garden, 2008). It is steep and, in its natural state, sheds a considerable amount of sediment as it erodes (Figure 1). Aggravating this, however, is that there has been considerable degradation as a result of the rapid population increase over the past century (McCracken, 2008). Begg (1988), for instance, estimates that 60% of original wetland in the Mfolozi catchment has been lost and poor agricultural practices have resulted in degradation. Nänni (1982) commented that "….some of the most abused land in Natal is in St Lucia's catchment". As a result of the severe soil loss, the sediment loads in the Mfolozi are considerable (Porter, 1981).

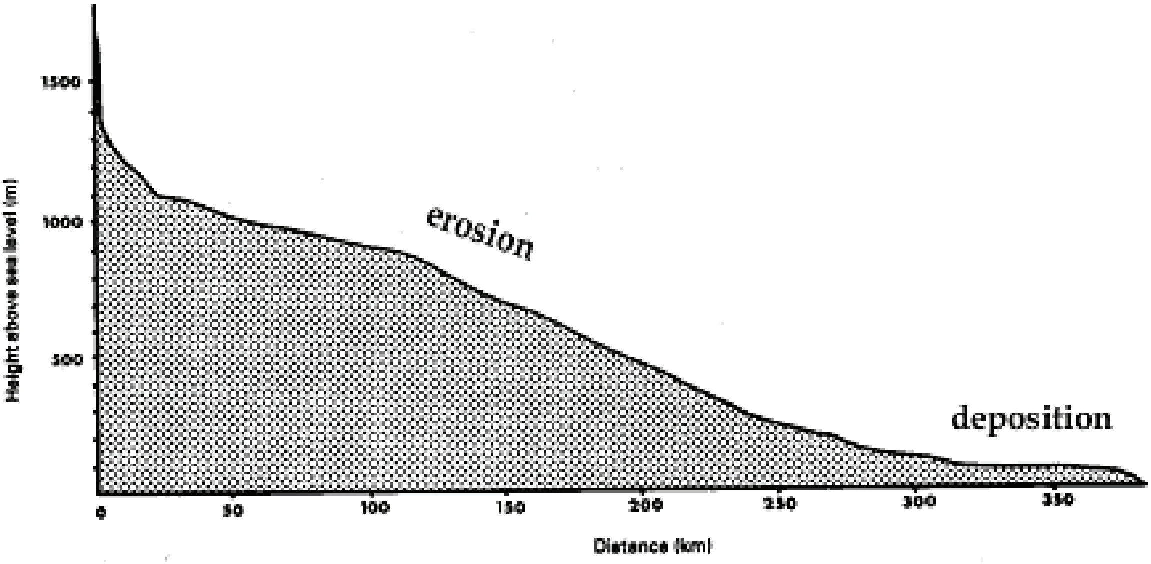

Figure 1a. A profile of the Mfolozi River showing the change in gradient from source to sea. The Mfolozi floodplain is in the right hand portion with little gradient and in which most of the sediment deposition takes place (Looser *et al.*, 1985).

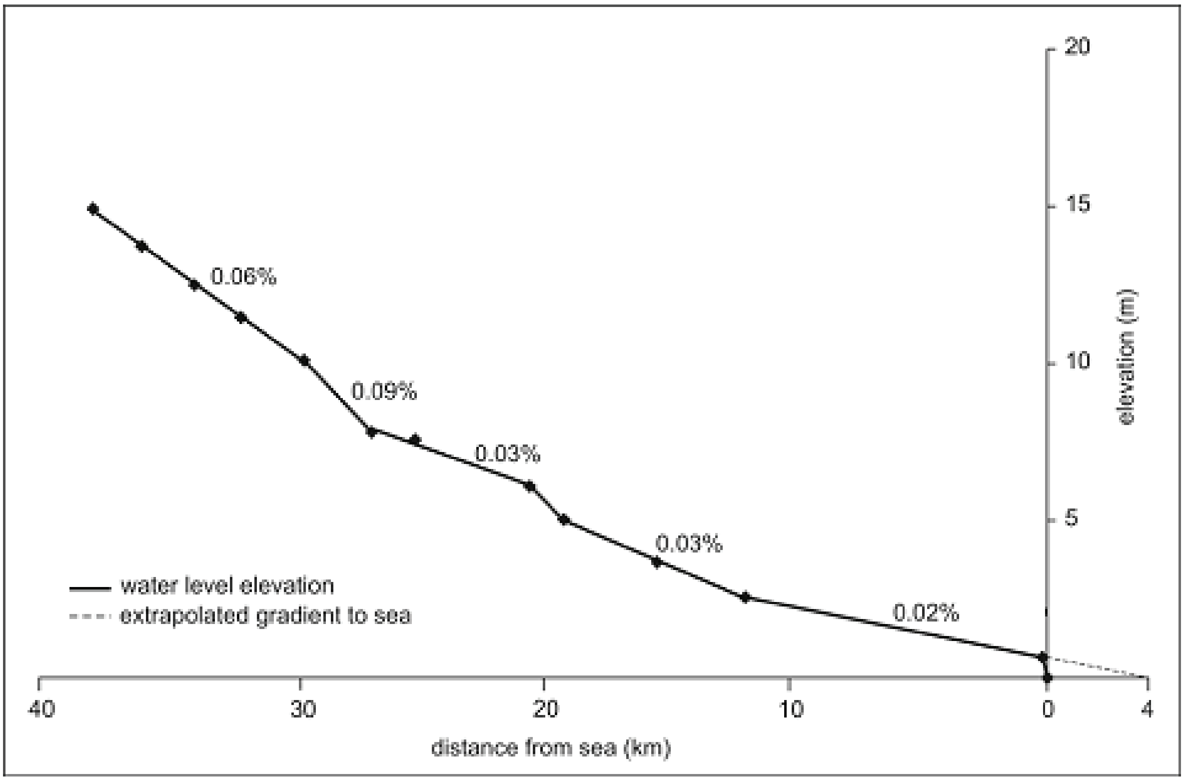

Figure 1b. A longitudinal profile of the Mfolozi River (April 2005) in the lower stretch, from Riverview to the sea (Garden, 2008).

The Mfolozi River has a highly variable flow regime (Garden, 2008), characterised by a low base-flow and a few large, but brief, floods each year. Floods are a feature of the river and they have a profound influence on the geomorphology of the floodplain (Grenfell & Ellery, 2009). Although infrequent and of short duration, these floods carry much of the annual river flow and it is during these that most of the geomorphologic changes occur. The return period of floods of various magnitudes is shown in Figure 2.

Not very much is known about the sediment dynamics of the Mfolozi River. Grenfell *et al.* (2009) showed that the sediment load varies considerably from month to month and from year to year. They considered that past sediment quantities had been overestimated because of this variation. One of these authors Garden (nee Grenfell), 2008 stated “Lindsay *et al.* (1996) estimated a suspended sediment transport of 1.24 x 10^9 kg a^{-1}, which was based on measurements of suspended sediment on one day in January. Rooseboom (1975) estimated suspended sediment transport at 2.36 x 10^9 kg a^{-1}. The current estimation, based on the relationship of turbidity and sediment concentration over a 6-year period is 6.8 x 10^8 kg a^{-1}. Thus, Lindsay *et al.* (1996) and Rooseboom (1975) exceeded the current estimate by 560 million and 1680 million kg a^{-1} respectively”.

Garden (2008) pointed out that the differences referred to by Grenfell *et al.* (2009) are most important as they affect our understanding of how much sediment might be brought into St Lucia if, or when, the Mfolozi is linked to St Lucia. The average suspended sediment yield of the Mfolozi River is estimated at 61 t km^{-2} a^{-1}.

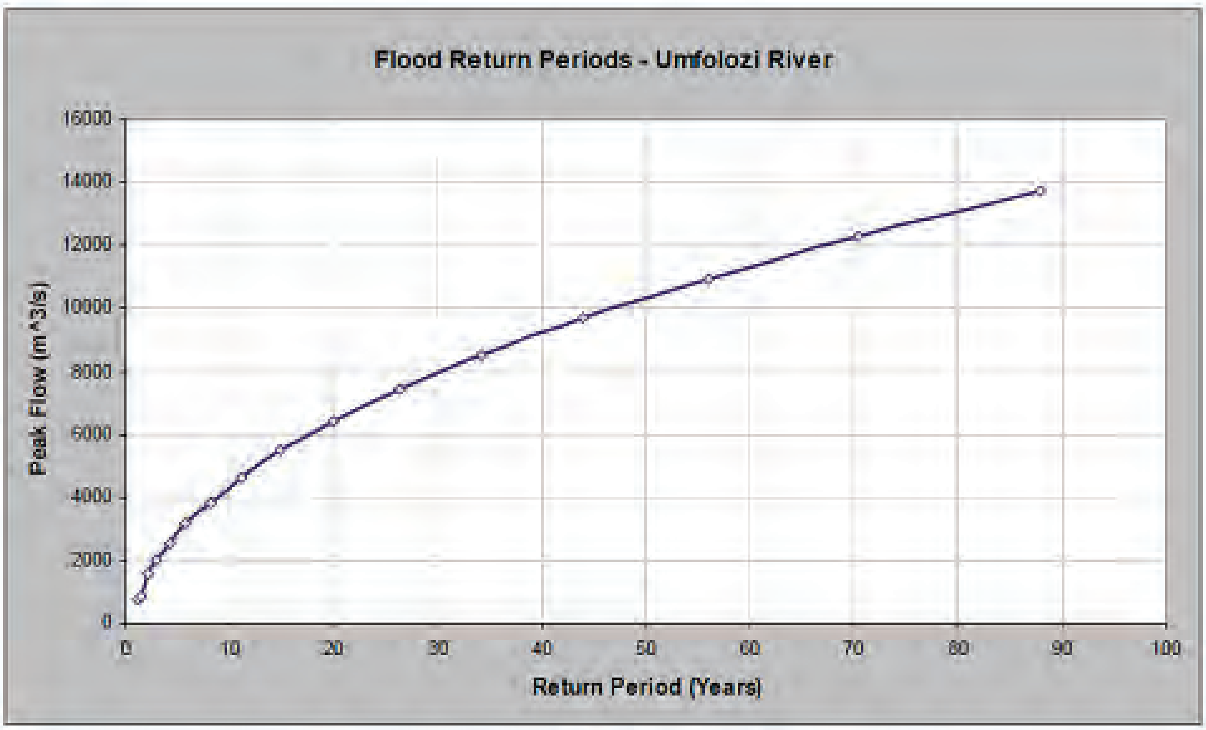

Figure 2. Frequency of floods of various magnitudes in the Mfolozi River (data from Gerrit de Jager pers. comm. 2006).

The differences between these estimates are important as this affects our understanding of how much sediment could be brought into St Lucia if, or when, the Mfolozi is linked to St Lucia. The concern is that little of the sediments that enter St Lucia will be washed out by floods or tidal movements. The main management concern has been that sediment accumulation is effectively irreversible (at the time scales of management), and hence, as St Lucia is in geological terms a transient feature, an increase in the rate of sediment accumulation will reduce the lifespan of the system.

EVOLUTION AND FUNCTIONING OF THE MFOLOZI FLOODPLAIN

This section provides an outline of some of the natural processes taking place on the Mfolozi floodplain, including an understanding of the geological formation of the floodplain that has been driven by these processes. It then identifies those processes that have been disrupted by human activities.

According to Begg (1988), the basin containing the Mfolozi floodplain and swamps covers an area of 21 322 ha. It is a basin that Orme (1974) described as part of the ancestral Lake St Lucia (Figure 3).

Figure 3. Map of ancestral St Lucia (Orme, 1973). To the north of the ancestral lake is the area now filled with sediment to form the Mkhuze floodplain. To the south is the basin that was to become the Mfolozi floodplain.

Van Heerden (this report) described the present floodplain as "…an artificial system, so constructed, (that it) now consists of a river confined by high artificial levees surrounded by much lower, depressed cane fields". Because water flow in the Mfolozi River is so variable there are different phases of geomorphological activity in the floodplain. When river flow is low, the system is stable and only a little sediment is eroded, transported or deposited. Most erosion and deposition changes to the river course and floodplain occur during relatively short periods when the area is subjected to flooding. With an increase in water flow, the river channel can fill to capacity. The water flows rapidly while it is contained within the channel and both suspended and bed load sediments are moved downstream. The flowing water keeps the sediment moving until there is a loss of energy due to a wider channel section or an overtopping of the artificial channel levee. If there is sufficient blockage in the river channel to cause damming, which can occur when there is a large amount of accumulated vegetation or if there is a low point in the levee, then water escapes from the channel to fill the adjacent low-lying area When this happens the water loses its energy and deposits part of its sediment load. If there is a flow path that the water can take that encourages fast water movement, then the river may change course and become erosive as it scours a new channel. It is under these flood conditions that the greatest geomorphological changes in the system take place. For instance, the changes that occurred during the few days of the Domoina flood in 1984 were greater in magnitude than the slow geomorphological changes that had occurred over the previous several decades.

At the end of each flood, there is a drawdown phase. As the river drains seaward the water level subsides and the river is once again contained within a channel. Ponds of standing water often remain for extended periods but the deposited sediments consolidate as they dry out. The larger the flood, the greater the area of the floodplain inundated with water. During the 1984 and the 1987 floods virtually the whole floodplain filled up (Figure 4). The area inundated by these large floods defines the extent of the present day floodplain.

Figure 4. LANDSAT image (NASA) from the 1987 flood showing the full extent of the inundated floodplain. This floodwater delineates the margins of the floodplain and is used in subsequent illustrations.

The geological evolution of the floodplain as described by Orme (1973) indicates that much of the Mfolozi Basin was incised during the most recent glacial period. This occurred 18 000 years BP (Ramsay, 1995). At that time much of the global water was held in ice caps and sea level was 130 m below that of today (Ramsay, 1995) and the land-sea margin was a few kilometres offshore from where it is at present. Under this condition a deep and wide valley was incised by the Mfolozi River, creating the basin that is now the Mfolozi Floodplain. This valley was incised to more than 50 m below present day sea level.

After the glacial maximum there was a rise in the sea level, stabilising close to that of present day sea level some 6000 to 7000 years BP (Ramsay, 1995). While the level was rising the sediments from the catchment area were deposited in the relatively still water of the bay created by the flooding of the Mfolozi valley. From the south a barrier dune accumulated sediments and was progressively extended northwards by long-shore sediment drift. It is likely that in places some of this was a consolidation of the remnants of a barrier system that had formed during a previous glacial period (Sudan *et al.*, 2004). It is this barrier that has developed into the magnificent vegetated dunes of Maphelane that separate the present day Mfolozi Basin from the sea (Figure 5). It was also during this period that the lateral valleys formed by streams flowing into the Mfolozi basin were blocked by Mfolozi sediments brought down in floods forming the blocked-channel lakes of Teza and Futululu.

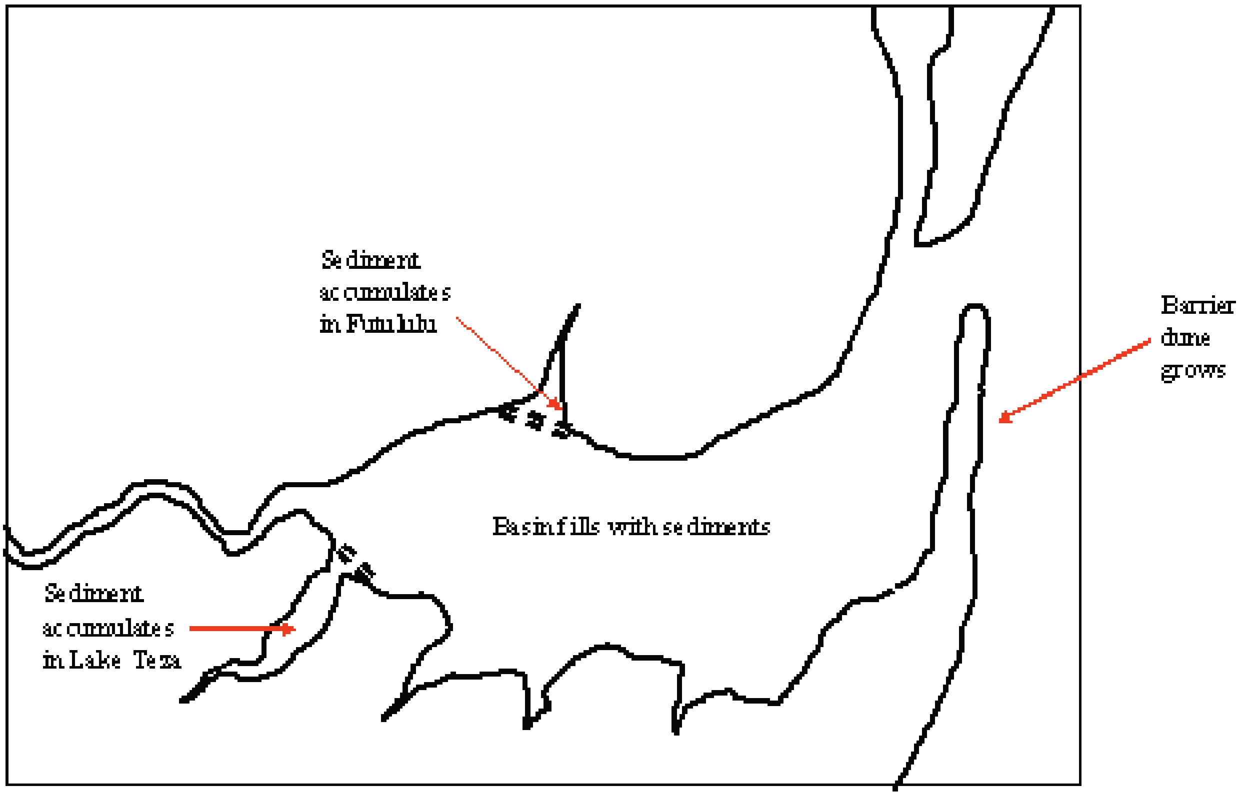

Figure 5. Rising sea level inundated the basin and it became filled with sediment. The barrier dune extended northwards and sediments blocked the lateral valleys to form Futululu and Teza.

The Mfolozi River within its floodplain meanders with a high suspended-sediment load. Sediment deposition built up the alluvial ridge of the river causing it to be elevated above the surrounding floodplain by about 2.5 m (Garden, 2008). The sediments that accumulate in the floodplain are mainly clastic and are predominantly within the grain size classified as silt (Garden, 2008). The sediment in the upper reaches is mainly coarse-grained sand but the grain size decreases progressively towards the coast. These sediments were deposited in a wet environment, trapping a significant amount of water. Because these sediments are more than 40 m deep (Orme, 1974) they are continually slumping due to the overall weight of the sediment above, losing water in the process. This process is accelerated where agricultural canals drain away the surface water. Features of the floodplain (before land transformations) are shown in Figure 6.

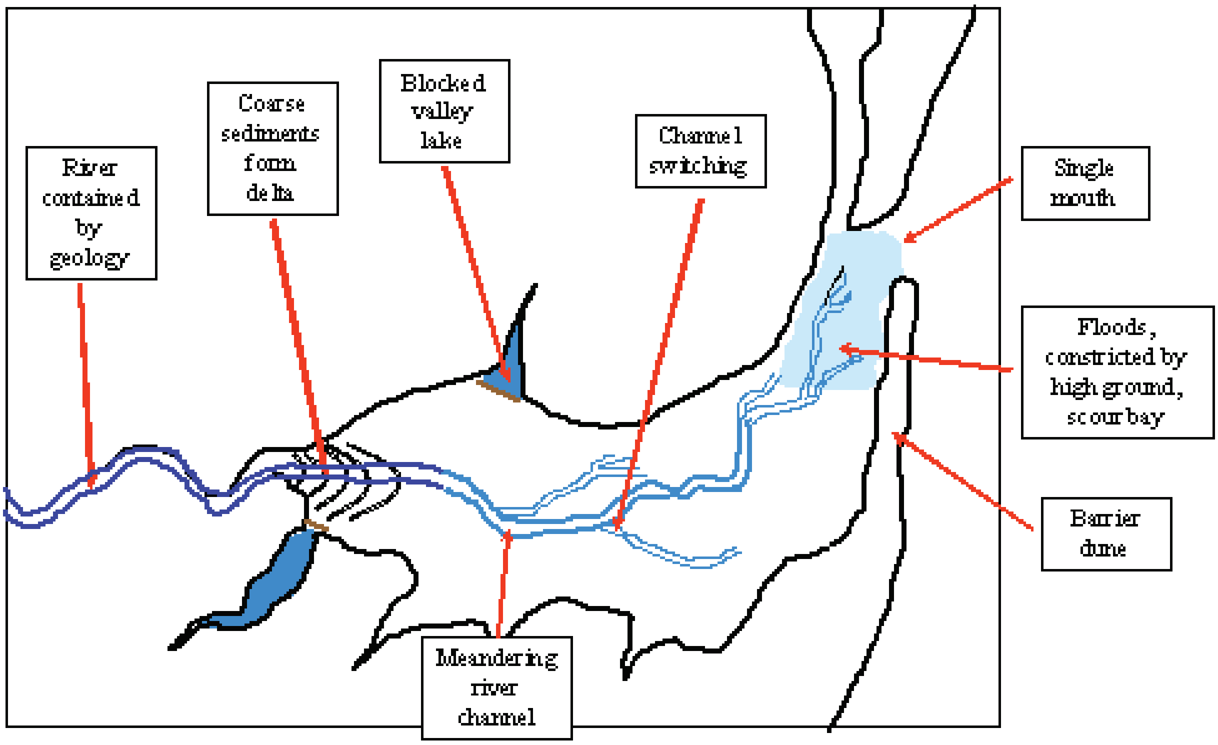

Figure 6. Schematic map showing the main features of the modern Mfolozi Floodplain prior to being transformed for the planting of sugar cane.

The floodplain is a very dynamic area in which there is a continuation of those processes that formed the system, *i.e.* floods, sediment deposition and slumping. In addition to the various processes associated with the different phases of a flood, there are also processes associated with different regions of the floodplain. The combination of physical environment and the dynamic processes within each area determine the type of vegetation found there. Each region of the floodplain, including the regions immediately upstream and downstream of the floodplain, has different characteristics.

The Mfolozi River upstream of the floodplain

The Mfolozi Floodplain starts immediately downstream of the railway bridge near Riverview. Upstream of this bridge the Mfolozi River is contained within a narrow valley that can be up to 600 m wide in places. During floods the water can rise to fill the 60 m deep valley (Garden, 2008). In the 1984 flood both the road bridge on the N2 highway and sections of the railway bridge were washed away, an indication of the height water in this valley can attain during large floods. In this region the riverbed is composed of loose coarse-grained sand. Most of the time, flow is low and the river forms a braided channel. It is a highly perturbed environment, with the riverbed being stirred up by any spate of water and subjected to constant change caused by drying and wetting.

The delta region

At the point where the river spreads out onto the floodplain, its width suddenly increases to 6.5 km (Garden, 2008). Here, when in flood, the river suddenly loses its energy and the coarsest components of the sediment load are deposited in a deltaic fan. This deposition feature was particularly evident after the floods caused by Cyclone Domoina in 1984 when the state had to expropriate 27 farms that had been damaged by sand accumulation and were no longer viable for cultivation. This was due to the sand deposit covering 1935 ha of the land (Mfolozi Sand Plain Planning Committee 1986). A map showing these patterns of deposition is given by Van Heerden and Swart (1986) (Figure 7). This area is inundated during large floods but drains rapidly once the flood subsides. Its coarse sandy soils drain rapidly and dry out.

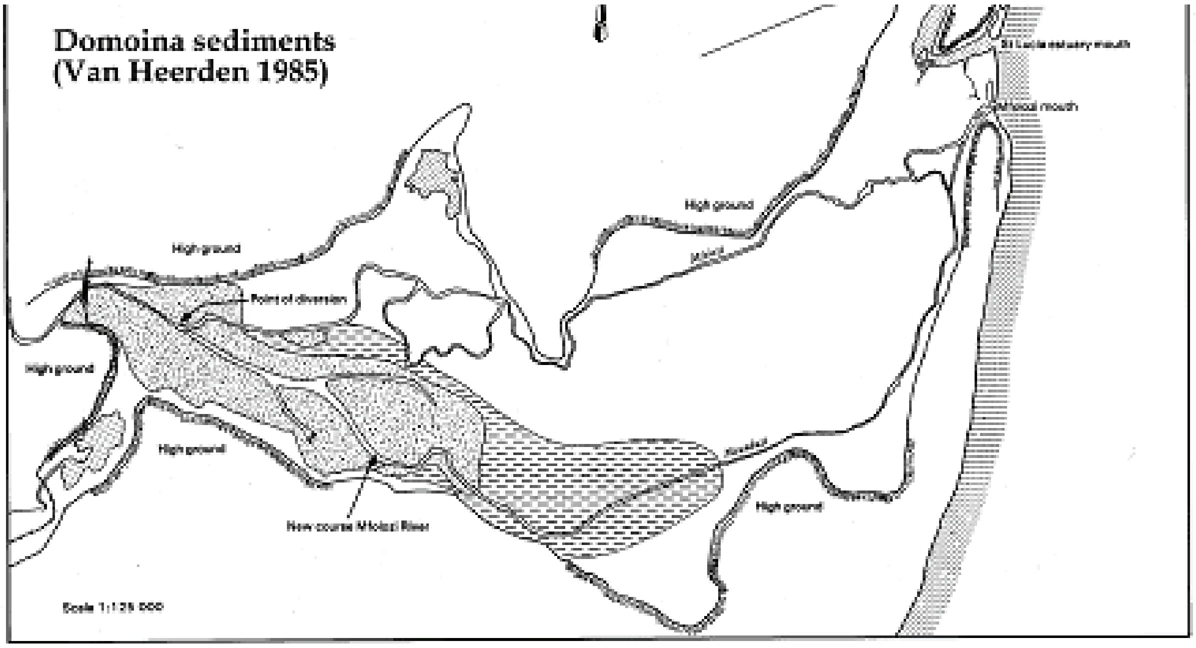

Figure 7. Map of the sediment deposition after the 1984 flood. The depositional fan of coarse sand is clearly shown (Van Heerden & Swart, 1986)

The Mfolozi floodplain

The main body of the floodplain is downstream of the sediment delta. This reaches a maximum width of 11.7 km to the east of Monzi. In the floodplain the river used to meander on its way seawards. It was contained by natural levees, which formed an alluvial ridge rising some 2 to 3 m above the adjacent floodplain (Garden, 2008). Most of the time it would have been a typical meandering river. The river would have eroded the outer edge of each meander and sediment would have been deposited on the inner edge. Thus the meanders would have writhed in a random pattern over the floodplain.

Over the years, as the river meandered and developed a raised channel, the swampland lateral to the river became starved of sediment. Although the area is now modified to a large extent, we can assume that processes similar to those described by Alexander (1976) in the more natural Mkhuze Swamp would have occurred. As a result of processes that were controlled by sediment slumping in places and by sediment accretion in other places adjacent to the river course, relatively low back-swamp areas were formed. These low areas would be flooded whenever the river spilt over its banks. When the overtopping was accompanied by a cutting of a channel through the bank, there would be a hydraulic advantage for the river to change its course, *i.e.* a process of avulsion. Van Heerden (1984) mapped the former courses that can be detected from old aerial photos (see Figure 5, van Heerden – this report). In places, in the central parts of the floodplain and during low-flow periods, it is likely that the channels anastamosed to form a network without any single dominant river course.

The lower portion of the floodplain, the area that is within the proclaimed nature conservation area, tends to have a flatter gradient (van Heerden, this report) and to be wetter. Nondoda *et al*. (this report) have mapped and described the vegetation here. Currently the swamp forest is likely to be more extensive than would have been the case prior to manipulation of the floodplain. In the past, whenever the estuary mouth closed, this area would have flooded for much longer periods than nowadays and the water would have been deeper than is the case nowadays when the Mfolozi mouth is artificially breached after closure. The more natural water regime would have limited the growth of swamp forest trees in this locality.

The estuarine area

Due to the flatness of the area, the Msunduzi is tidal for a distance of more than 15 km from the mouth (this is indicated on the Cotcane water level gauge). The lower reaches of the Mfolozi have a steeper gradient and it is therefore only tidal for a few kilometres. Because the area adjacent to the tidal channels is flat and low-lying, lateral flooding occurs during high spring tides or whenever there is back-flooding caused by water backing up behind a closed Mfolozi Mouth. The Mfolozi/Msunduzi estuarine system can be in either one of two main ecological states:

Mouth open state

When the Mfolozi mouth is open there is tidal exchange and the water level is contained between the high and low water marks (although this is modified by wind-effects). The water is contained within the channel except when there is a particularly high tide. Sediment continually transfers as the water moves back and forth with the tide. This keeps the fine sediments suspended and the bed of the channel very soft. The substratum is unstable and has little in the way of benthic fauna (Cyrus *et al*., 2008). During the extreme high marine water levels experienced in March 2007, seawater entered the estuary and then flooded the adjacent areas of swampland. The water must have been saline as it killed many *Ficus trichopoda* and *Bridelia micrantha* trees.

Mouth closed state

When the Mfolozi mouth is closed, water backs up and the level rises. This is a condition that can last for many months at a time, depending on the amount of water flowing in the Mfolozi River. The rising water then spills into the swamp adjacent to the channel. This is mainly river water with low salinity (<6 PSU), which does not kill swamp vegetation. Because there is little water movement under closed mouth conditions, much of the suspended silt settles out. Where it has flooded into lateral swampland, the water is clear.

The blocked-valley pans

Lakes Teza and Futululu are blocked valley pans. The former has been described by Scott & Steenkamp (1996) and by Aardal & Ødegård (2000), and the latter by Grenfell *et al*. (2010). Scott & Steenkamp (1996) drilled a core in the bed of Lake Teza which has an elevation of 14 m amsl (Garden, 2008). Scott and Steenkamp, (1996) found that sediment at 22 m (i.e. 8 m below current msl) had started accumulating before ca. 8 330 years BP. This indicates that sea level had risen to be at, or above, that level at that time. This provides us with an indication of when this portion of the Mfolozi basin started accumulating sediments.

In a similar manner, Grenfell *et al*. (2010) cored into the barrier that holds back the water at Lake Futululu and interpreted the strata they recorded. Lake Futululu floods to an elevation of 17 m amsl (Grenfell *et al*., 2010). At a depth of 6.75 m the sediments have been dated at 3980 +/- 140 yrs BP (Grenfell *et al*., 2010). They also described the sedimentology and vegetation of the alluvial ridge that dams the lake and of the lake itself (Figure 8).

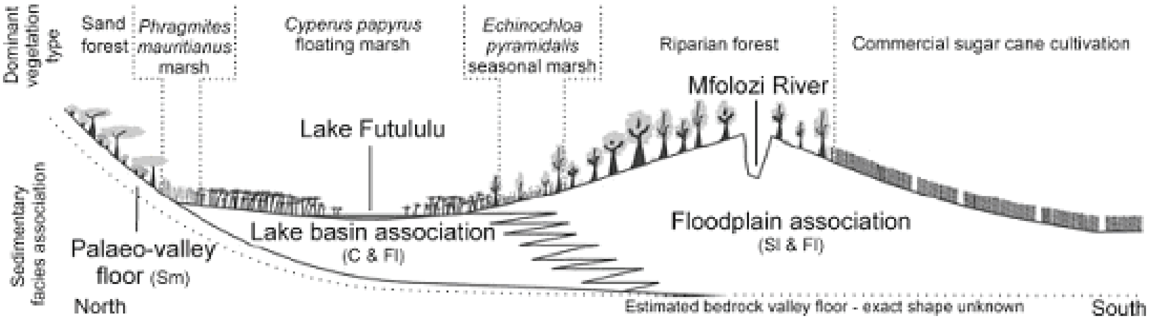

Figure 8. Sedimentological facies associations and longitudinal variations in vegetation type in Lake Futululu. Key: 'C' indicates organic material that has been deposited in situ. 'Fl' indicates facies containing fine to medium silt deposits where there is settling of sediments from overbank water and of a waning floods. 'Sl' indicates fine to medium sand as would be expected in abandoned channel courses. 'Sm" sand with indications that it was wind deposited (Grenfell *et al*., 2010).

For Lake Teza, Scott and Steenkamp (1996) noted that "Environmental changes, which resulted from recent human impact, left a record in lake deposits" and they warned that "Sedimentation rates in the lake basin have increased greatly during recent decades, suggesting that human activities have had a marked effect on the lake" and will "continue to deteriorate at an increased rate" as the lake gets progressively shallower".

The lower swamp constriction

The high ground of the Maphelane dunes, the raised Dukuduku ridge and the area that is now the town of St Lucia form a constriction about 3 km wide at the lowest end of the swamp. During large floods flowing water that has slowed down in the body of the swamp speeds up as it passes through this constriction. The water becomes erosive and it scours what was formerly known as St Lucia Bay (see Taylor, this report).

The low-lying areas of the lower Mfolozi Swamp are subjected to back-flooding whenever the estuary mouth closes and Mfolozi water accumulates. In the state where there was a single mouth, closure of the mouth resulted in the diversion of Mfolozi water into St Lucia as well as the Mfolozi Floodplain, rather than the rapid backing up of water in the Mfolozi/Msunduzi floodplain only as happens at present. So, in the pre-1952 state, after closure the water level would have risen slowly as it filled the whole St Lucia system, a process taking many months. Once a high enough level was attained to overtop the beach berm, breaching occurred. This was a major event; with a huge quantity of water flushing out if the berm had been up to 3.5 m amsl. When such a large volume of water drained, it flowed for days and, in the process, eroded much accumulated sediment from the combined mouth area.

St Lucia Bay

This was the open stretch of water into which both the St Lucia Estuary and the Mfolozi River connected. It was an area that usually had a single mouth to the sea and was tidal. Habitats along the margins were intertidal mud flats and, as is evident from the 1937 aerial photographs, the bay was lined with mangroves. Associated with the mouth were typical ebb and flood tidal deltas composed of marine sand. This single mouth would sometimes close during severe droughts, deflecting the Mfolozi water northwards into St Lucia.

Figure 9. View of St Lucia 'Bay'. The photo was taken in the early 1930s from where the ski-boat club is now (photographer unknown).

Separating St Lucia Bay from the sea was a sand berm of marine sand deposited by wave action and shifted by wind. After the mouth closed, wind and wave action would have built this dune. If closed for long enough this would have built up to a height of 3 to 3.5 m (P. Huizinga, pers. comm.).

The Narrows and adjacent floodplains

North of St Lucia Bay, linking into Lake St Lucia coastal lagoon, is a narrow tidal channel called 'The Narrows'. Shells dredged from the Narrows north of the Mpate River mouth and no longer found in St Lucia, such as *Murex* sp., are typical of sheltered marine sea-grass beds (R. Kilburn, pers comm.) and are evidence of a greater marine influence at times in the past.

The plains on either side of the Narrows are composed of fine sediments. It is likely that these sediments were deposited by the northward diversion of the Mfolozi River during large flood periods or periods of extended mouth closure. This is now an area where there is surface-flow of water after rain events. On the east of the Narrows the water flows mainly towards Oxbow Creek. To the west of the Narrows the floodplain drains into the lower reaches of the Mpate River. During periods without rain the area dries and the hydromorphic soils crack as they contract.

LAND TRANSFORMATIONS IN THE MFOLOZI FLOODPLAIN

Land transformations have occurred in the Mfolozi floodplain over the past 100 years. Sugar was first planted in 1911 in the area near Riverview (Dobeyn, 1987). To cope better with floods and standing water in the fields, drains and canals were constructed to lead the water off. In 1918, and again in 1925, there were extreme floods. These covered the whole floodplain basin. The 1925 flood lasted 11 days demolishing the newly-built sugar mill that was on the floodplain between Riverview and Lake Teza.

In 1932 the St Lucia mouth closed and water in the St Lucia/Mfolozi system reached a height of approximately 14 ft (4.5 m) above mean sea level before the mouth was artificially breached. After breaching there was a huge outflow of water for the next fortnight. (Harrison, 1989). Prior to the mouth opening it is likely that this water backed up in the Mfolozi floodplain as far back as Monzi (or possibly even further) and would have raised the water level in the whole of Lake St Lucia, flooding the lower part of the Mkhuze Swamp, up the river valleys in False Bay and the low-lying portions of the Eastern Shores.

In the Mfolozi floodplain, the backing up water would have severely affected sugar farming operations and, to enable floodwaters to drain away unimpeded by swamp vegetation, a canal (Warner’s Drain) was excavated in 1936. This channeled the Mfolozi River and was followed by various smaller modifications to straighten the river upstream, by removing meanders, and the construction of levees to contain the water in the river channel. Prior to this, Wilson’s Drain had been excavated along the Msunduzi course. There are many smaller drains that feed into these main canals. Most of the irrigation is accomplished by pumping water from the Mfolozi River and allowing excess water to drain towards the Msunduzi River via Wilson’s Drain.

During the 1940s, sediments accumulated in the combined St Lucia/Mfolozi mouth area. In 1950 this common mouth closed (see Taylor, this report); to protect the sugar fields from the effects of flooding while the mouth was closed a separate mouth was dredged for the Mfolozi in 1952 and the lowest meander in the Msunduzi River was straightened. After this it took another 5 years of dredging before the link between St Lucia and the sea was opened; and another 8 years of dredging to remove all the accumulated sediment. At this stage we do not know what proportion of these sediments was derived from the Mfolozi River or from the marine environment.

Nowadays very large floods still fill the Mfolozi floodplain basin, damaging sugar farms and road and rail infrastructure on the flats. However, it is the smaller floods flowing down the Mfolozi canal that often breached the Mfolozi levees at unpredicted sites. Initially the solution was to continue raising the levees. However, during the 1984 Domoina flood the flood water took a preferential channel by switching course at Riverview into the relatively lower-elevation Msunduzi route. The insights gained from this flood enabled the sugar farmers to design and construct a weir at Riverview to divert excess water during large floods down the Msunduzi, once the capacity level had been attained in the Mfolozi canal. The flood-bypass system currently in operation was constructed as shown in Figure 10. A hydrograph during a flood, measured at the Monzi low-water bridge, is given in Figure 11. This clearly shows the capping of the amount of water moving in the canalised Mfolozi River at the level where excess water is diverted over the flood-bypass weir.

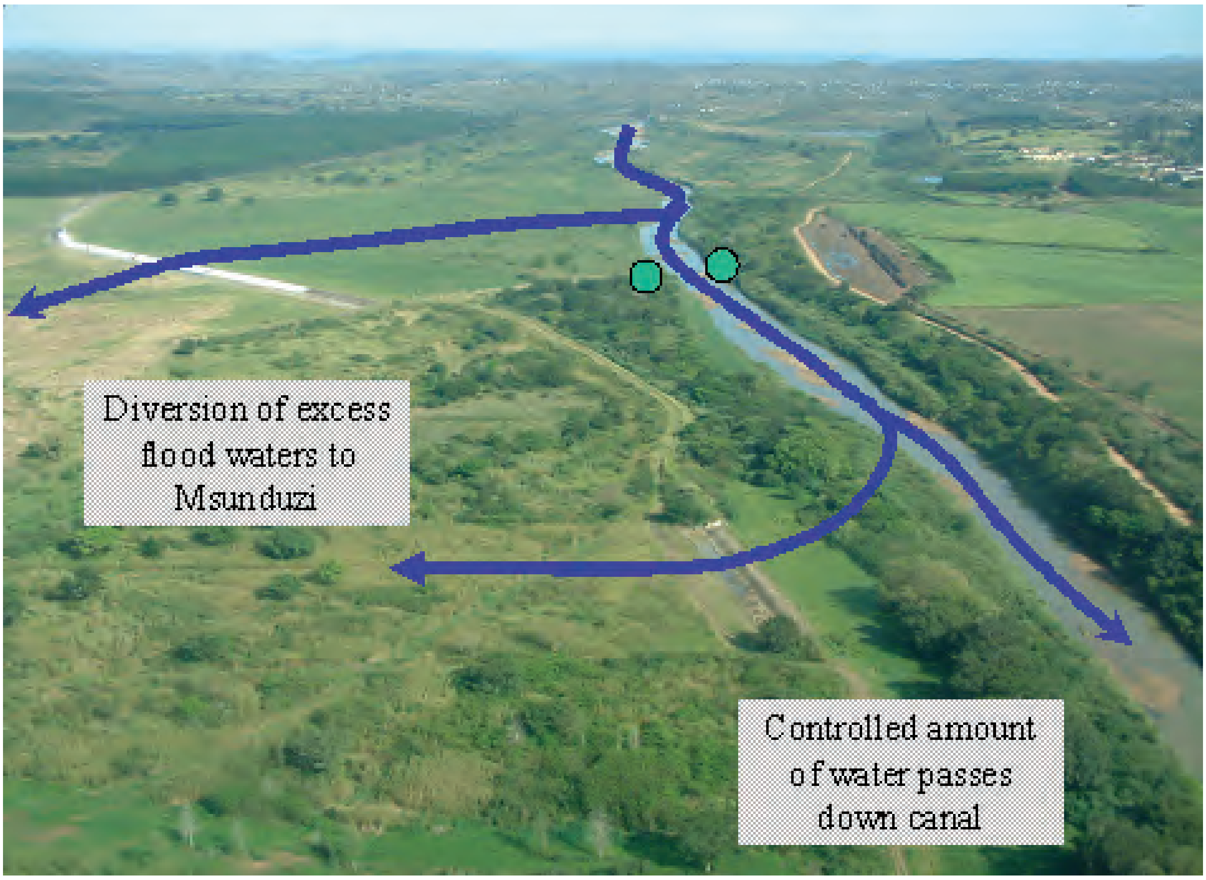

Figure 10. The flood-bypass system. Constriction points (circles) on the Mfolozi course limit the maximum amount of water that can pass down the Mfolozi canal. This is a quantity that is not large enough to overtop and breach the levees. Excess floodwater is then shunted down the Msunduzi route. This water is spread over a 1 km long weir to prevent it eroding a channel that will erode back into the Mfolozi course (photo: R. Taylor).

Lake St Lucia was badly affected by the drought of the early 1970s and became hypersaline. Hutchison & Midgley (1978) developed a hydrological model of St Lucia and used it to test the ameliorative impacts of various management options to prevent a repeat of the hypersalinity. They recommended that the Mfolozi Link Canal, with its associated intake works on the Mfolozi River be constructed. This is a 13 km canal excavated to carry Mfolozi water into St Lucia at times of low flow.

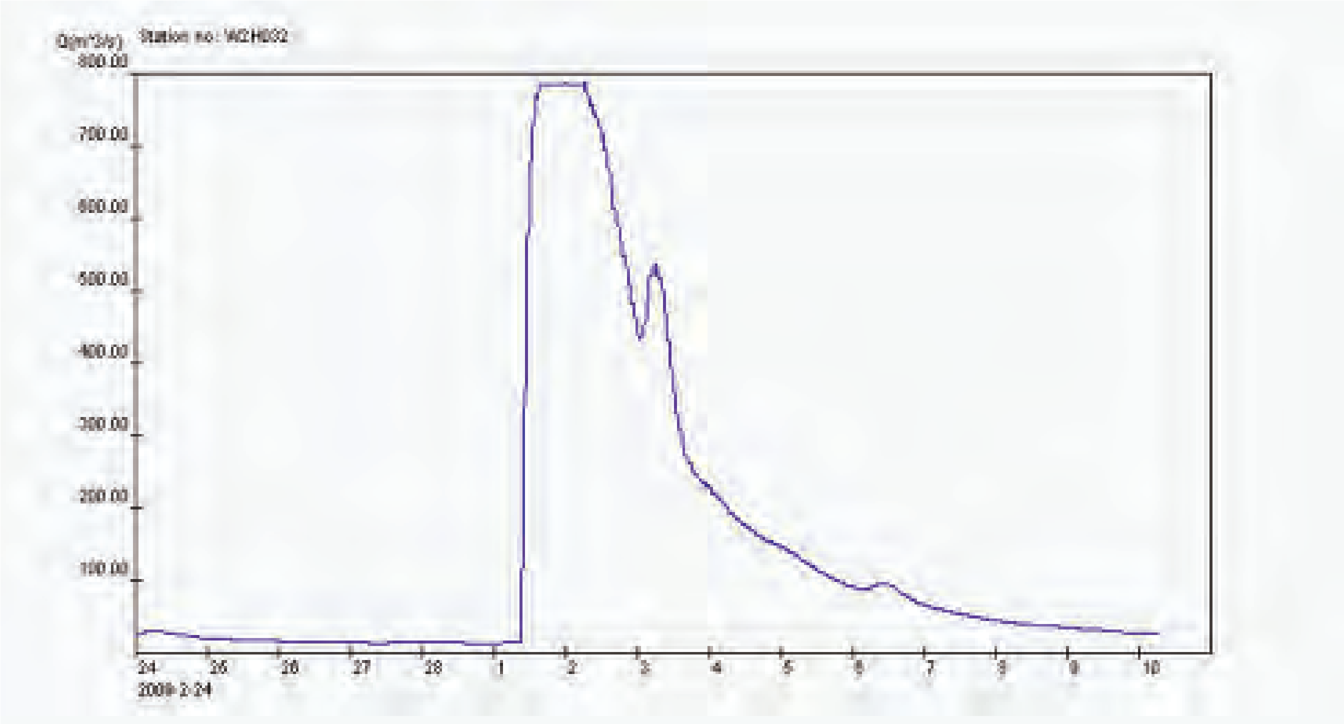

Figure 11. Flood hydrograph from the Monzi recorder showing the capping effect caused when the excess water is diverted down the Msunduzi by the Riverview weir (data from Department of Water Affairs).

Following the separation of the mouths in the 1950s the management philosophy has been to keep them separate and, until 2002, the strategy was to breach both the mouths after natural closures. With better understanding of the hydrology of St Lucia the mouth was allowed to stay blocked after it closed naturally in 2002. Also, with a better understanding of inlet dynamics, the necessity to keep the two mouths separate is being questioned and ways of introducing Mfolozi water into St Lucia without its full sediment load are being pursued (Taylor, 2006; Lawrie *et al*. this report, Kelbe and Taylor, this report).

One insight gained from the Domoina Flood was the understanding of how Mfolozi floodwater could be simultaneously routed into the lake and seawards. The water heading northwards into St Lucia flooded a 1 km wide channel along the Narrows. The water also eroded away the 50 m high ‘Sugarloaf’ dune at Maphelane and scoured to a depth of 18 m opposite the St Lucia boat lockers. The erosion of the Sugarloaf dune and the deeply scoured channel may have been aggravated by the plug of dredge spoil deposited by the 1952 to 1984 dredging operations. Much of this spoil would have been deposited in a spoil pile between the St Lucia and Mfolozi mouths. This would have reduced the capacity for water free-flow out to sea via this route.

RESPONSES TO TRANSFORMATIONS IN THE MFOLOZI FLOODPLAIN: A CONCEPTUAL UNDERSTANDING

Very large floods, the so-called mega-floods, still fill the whole floodplain basin.. During these big floods the gross flooding pattern still operates as it did before the land transformations for sugar production were implemented. It is during the moderate sized floods (greater than about 1000 $m^3 s^{-1}$) that excess Mfolozi water is diverted at the Riverview flood diversion weir (Figure 12) into the Msunduzi system. This allows some of the flood waters to take the Msunduzi channel route. The water in these moderate floods that pass down the Mfolozi channel, and that of the smaller floods are totally confined within the canals until it reaches the lower part of swamp. It is this water and associated sediments that is changing the patterns of the geomorphology of the floodplain to the greatest degree.

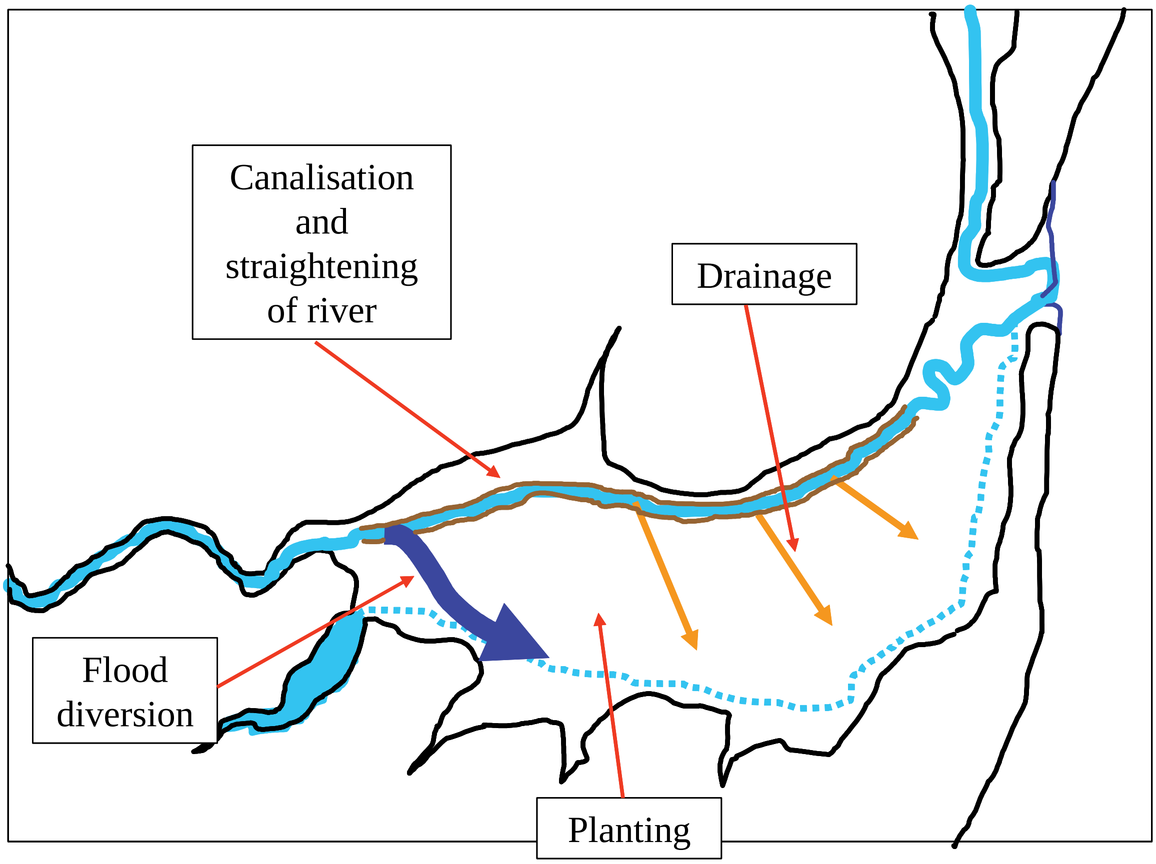

Figure 12. Schematic map showing the diversion of floodwater from the Mfolozi into the Msunduzi. Also shown is the straightened and canalised Mfolozi River course and the direction of flow of irrigation water that is pumped for irrigation from the Mfolozi and drains towards the Msunduzi.

These canals through the floodplain (mainly Warner's Drain) transfer the point where water is released from the confines of the Mfolozi channel (and hence where sediment deposition takes place) from the upper reach of the Mfolozi floodplain to downstream of the Link Canal Intake Works in the lower part of the floodplain. Thus the site of most active sediment deposition has been shifted (Figure 13) and this is the region where avulsion is likely to occur (Figure 14). The conceptual impacts of the transformations of the floodplain are shown schematically in the Figures 13 to 20.

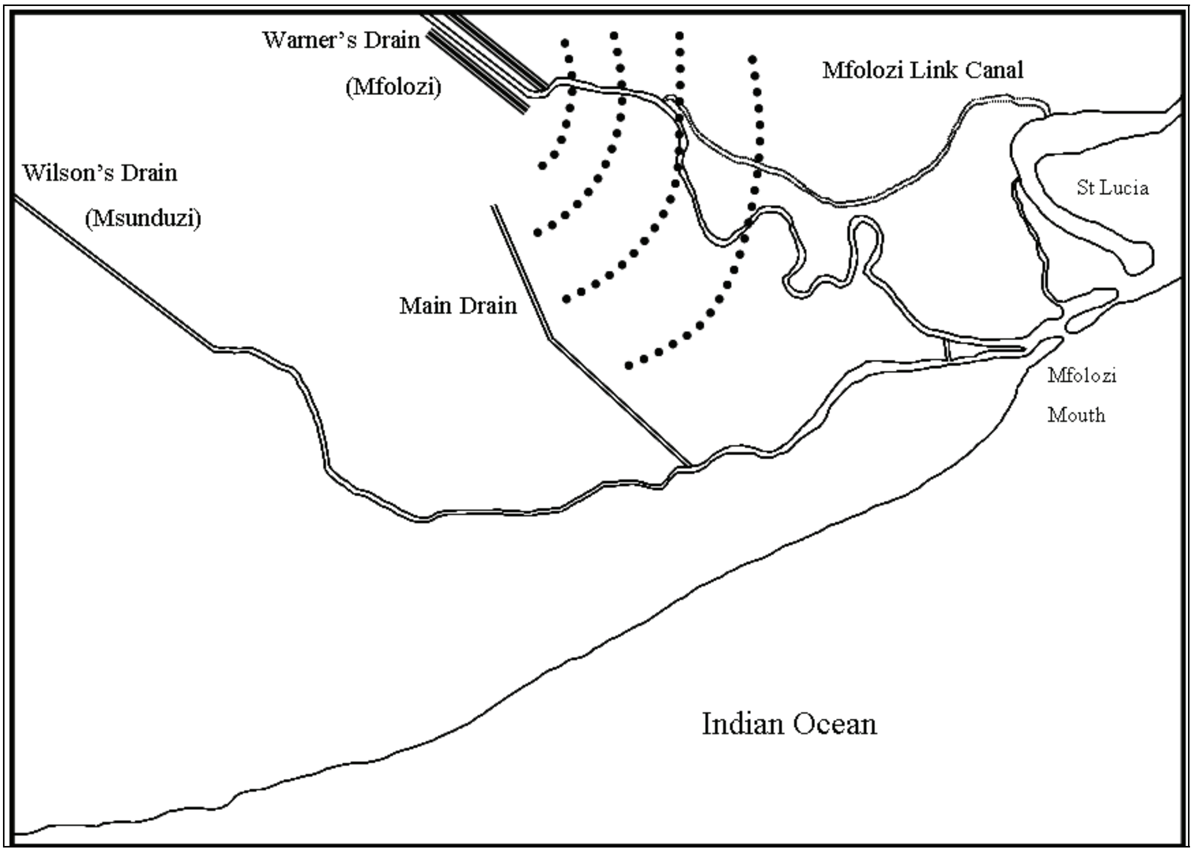

Figure 13. Map showing the area where a new sediment fan is likely to be forming (dotted lines). This is where sediments are deposited during floods where the river bursts its banks. In effect, the sediment that used to be deposited in a deltaic fan near Riverview during flood periods is now transferred by the canals to this point.

During the Domoina flood, the avulsion of floodwaters from the Mfolozi channel occurred near Riverview. As a result, a large quantity of sand was deposited in the upper reaches of the floodplain. Under the present conditions the sediment brought in by smaller floods is contained within the Mfolozi Canal and is eventually flushed out at the lower end where there are no levees and the canal ends. This sediment deposition so close to the mouth (Figure 16) could be affecting the functioning of the Mfolozi mouth. Adding sediment to the mouth area will increase the size of the ebb-tidal delta in this region. Should high seas bring this sediment into the Mfolozi mouth during a neap-tidal period, then there is an increased possibility of the mouth closing.

The perception is that the Mfolozi mouth has closed more frequently in recent years when compared to the period between the 1950s and the Domoina flood in 1984. A further consequence of agriculture in the floodplain is its effect on water quality. Agricultural chemicals such as nematocides, insecticides, herbicides, ripening hormones and fertilizers are used in the cane industry. There are some indications of nutrient enrichment (Nondoda *et al.* this report).

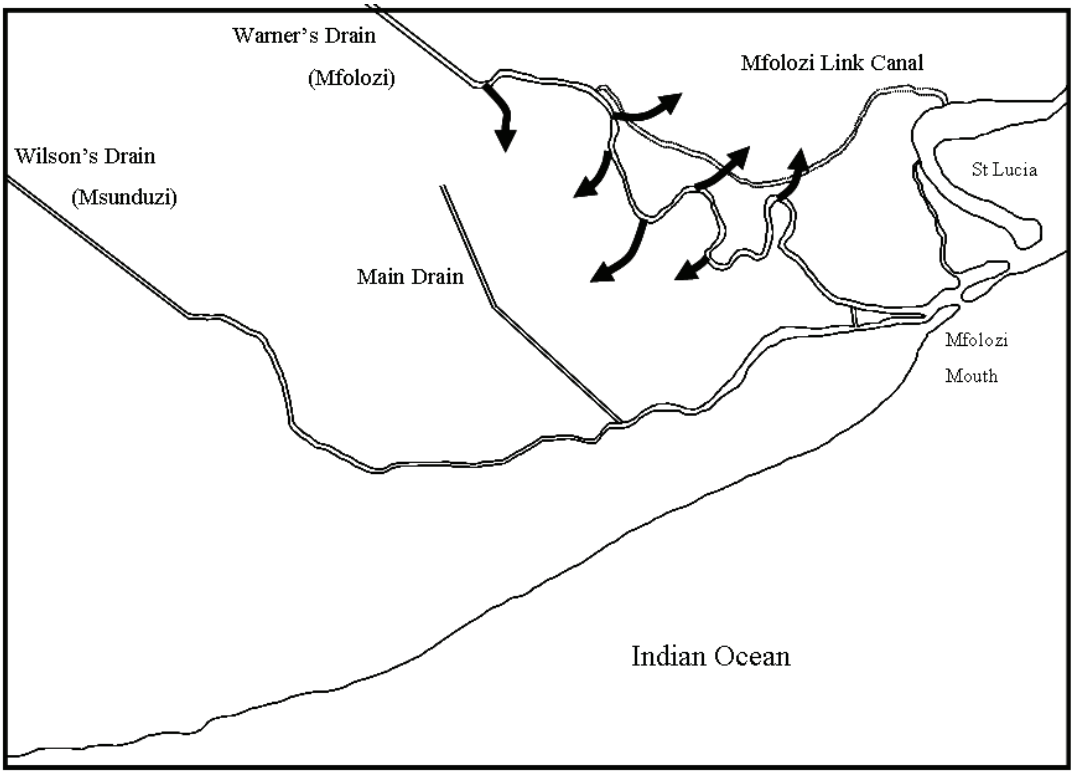

Figure 14. The river is now contained by artificial levees. The arrows indicate where the river first has the opportunity to overtop its natural levees. This is where avulsion occurs and it is likely that, if left unchecked, the river will change course.

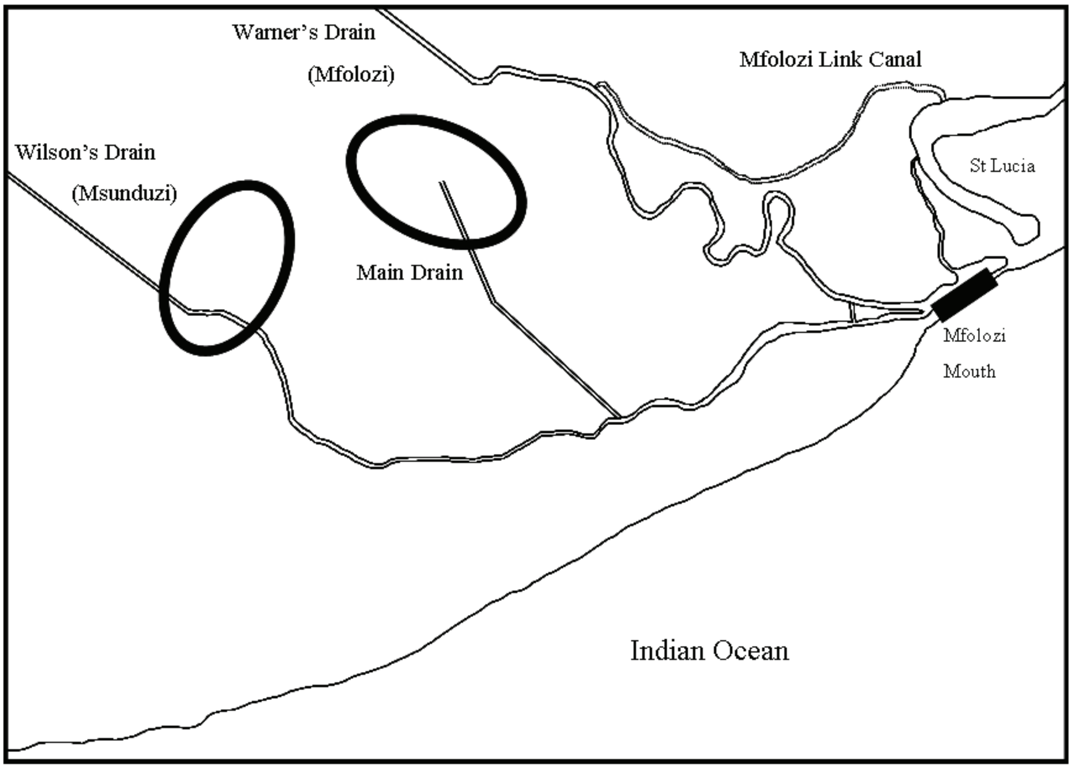

Figure 15. The circles indicate the sugar areas that are lowest and therefore most susceptible to flooding when the Mfolozi mouth closes (indicated by a dark bar).

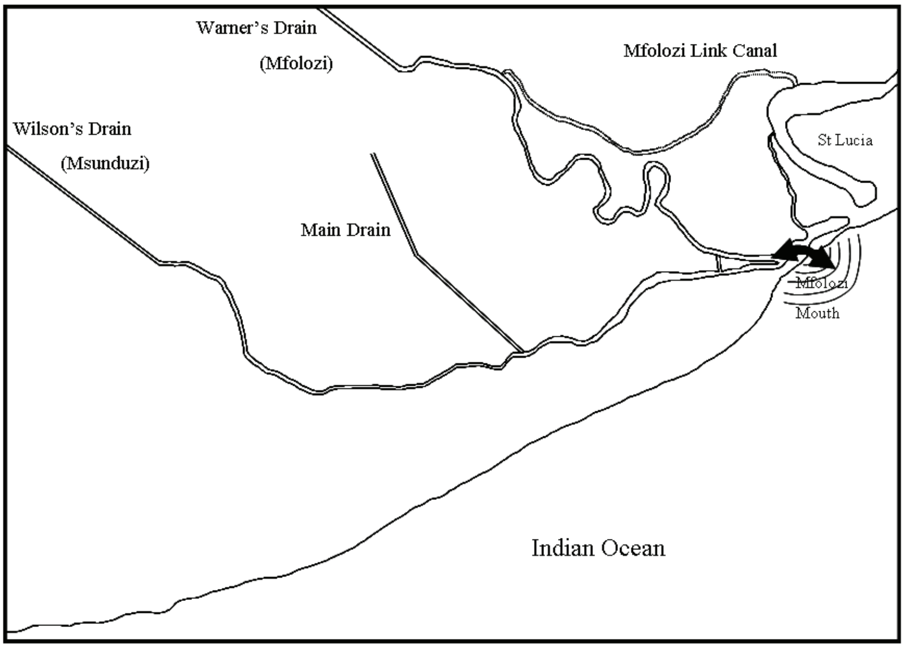

Figure 16. As sediment accumulates in this lower swamp area, some is also flushed seawards. It is likely that the ebb-tidal deposition in a delta in the surf zone of the sea accumulates at an accelerated rate. Conceptually, this promotes more frequent closure of the mouth than in the past.

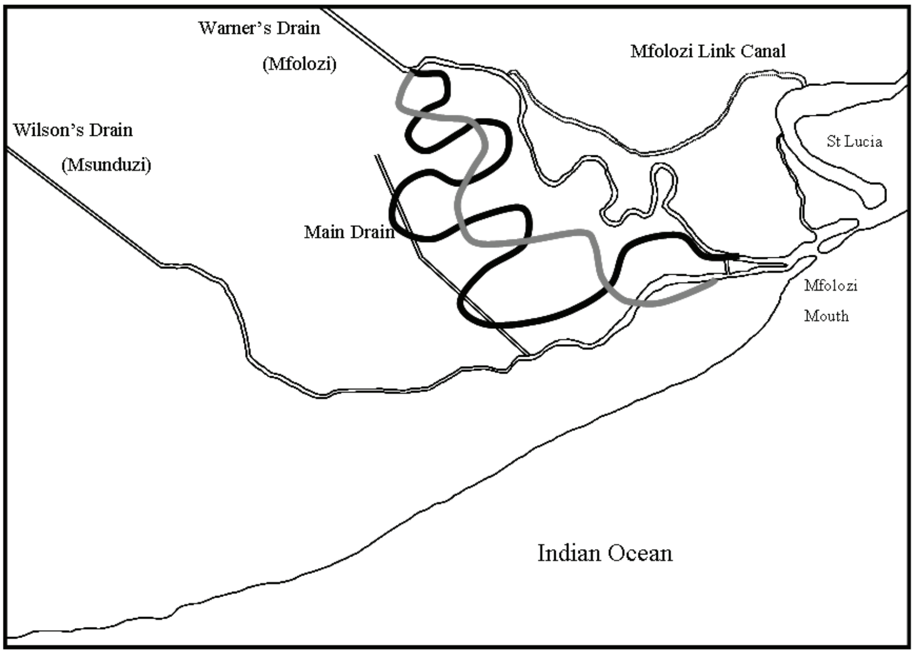

Figure 17. More meandering of the river channel in the low-lying portion of the swamp can be expected as indicated in this sketch. The area where meandering will occur is downstream of the modified section of the river. This is where the course has not been straightened, there are no artificial levees and the bends are not artificially protected with poles.

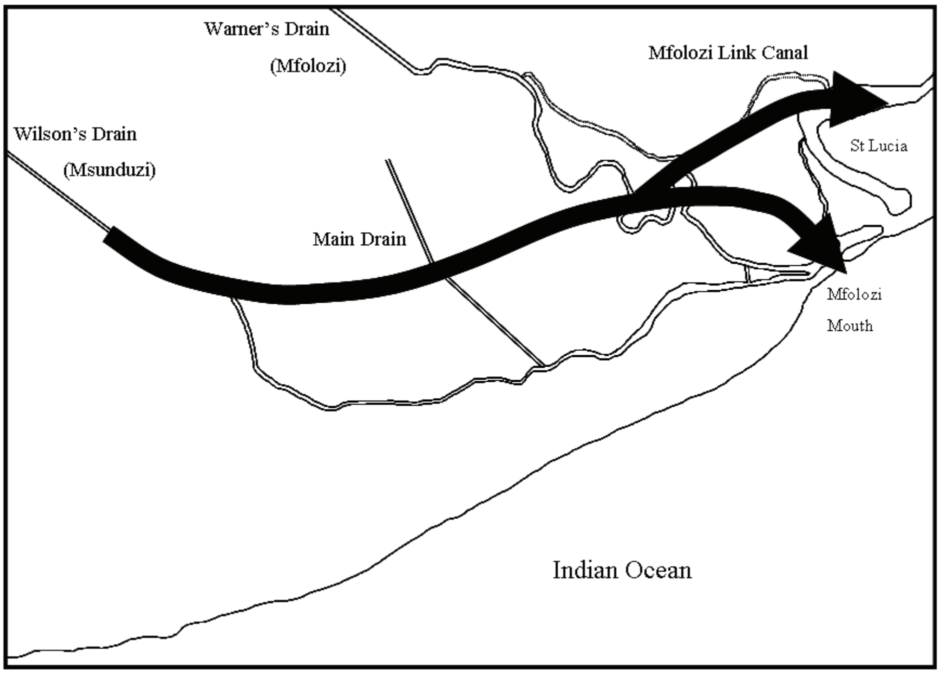

Figure 18. Large floods will still fill the whole basin and much of the water will be channeled through the Msunduzi course. As the swamp basin fills, so the flood processes will behave in a close-to-natural manner. The flood path will be out to sea and also northwards into St Lucia as depicted by the heavy arrows.

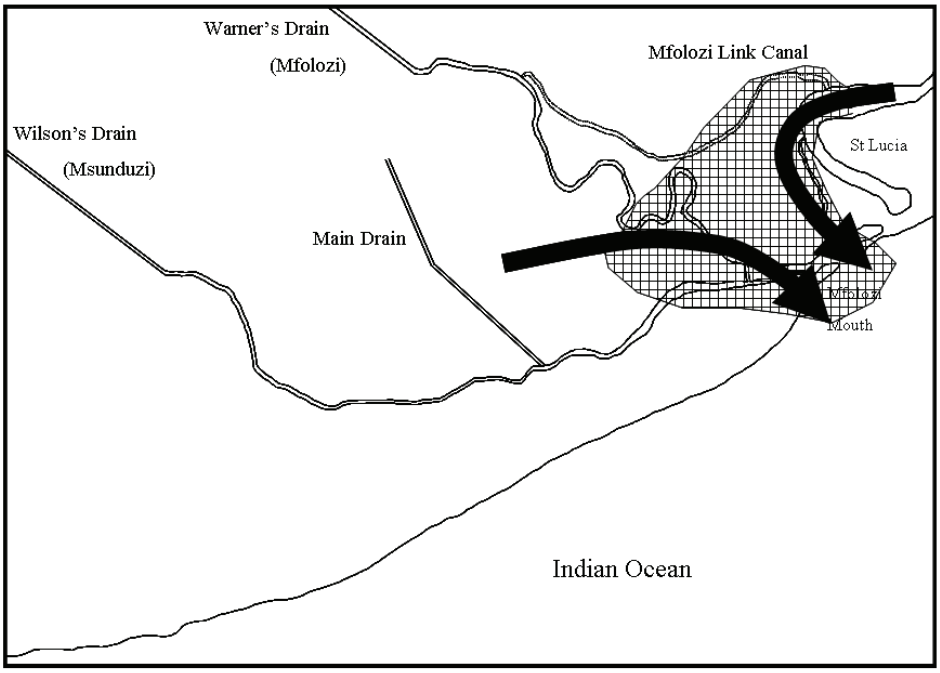

Figure 19. Floods, and fast flows from both the Mfolozi floodplain and St Lucia occur after breaching if there has been a large backing-up of water, will scour the hatched area on the map (as indicated by the arrows). Conceptually, this is how "St Lucia Bay" would be maintained.

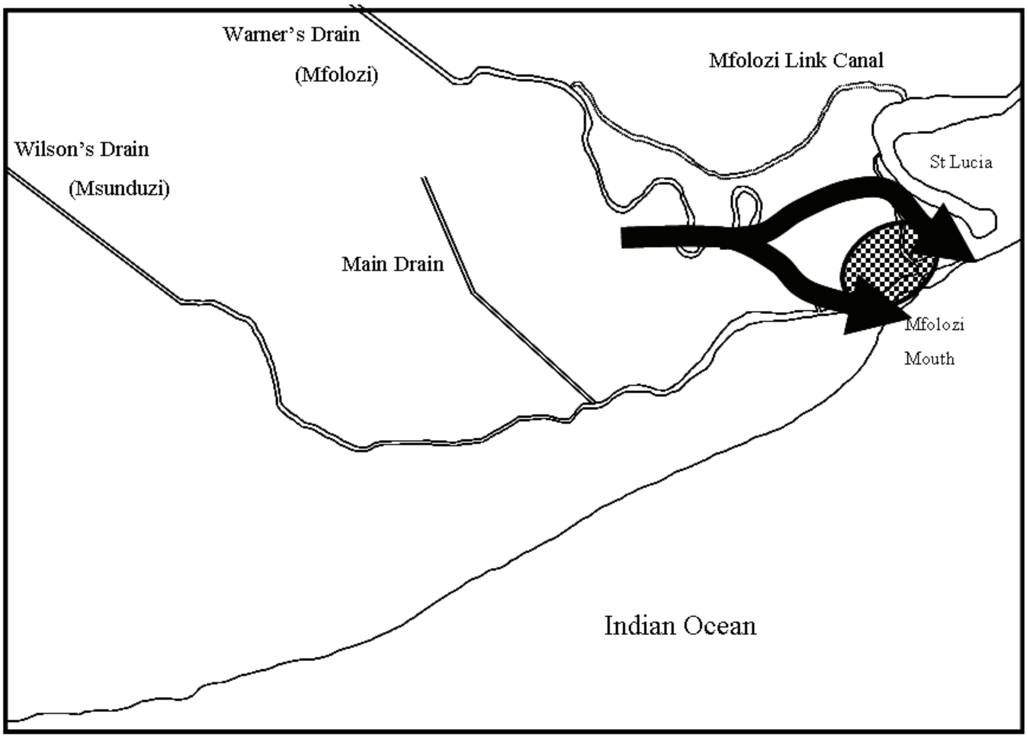

Figure 20. The pile of dredge spoil between the St Lucia and the Mfolozi (shown schematically as the hatched area) acts as a plug which impedes the natural flow of large floods out to sea. The concentration of river flow at both the St Lucia and the Mfolozi mouths (as shown by the arrows) probably leads to 'abnormal' additional scouring of these specific areas. The plug is likely to cause an increase of water backing-up onto the floodplain during a large flood, and may also divert additional water northwards into St Lucia.

FINAL COMMENTS

Much of this contribution is conceptual, based on knowledge of general floodplain features and processes. A lot of refinement to the thinking around the water and sedimentary processes is needed and preferably should be based on careful scientific investigation. However, management actions cannot be delayed and corrective measures need to be implemented as soon as possible.

Conceptually, the geomorphologic activity associated with the sudden release of water contained within the artificial levees at the lower end of the canalised Mfolozi River is similar to that of the water being released from the constraints of the narrow valley upstream of Riverview. The sediment deposition fan, the tendency for river avulsion and the processes associated with these have now been transferred from the upper reaches of the swamp to the lower reaches. This plus the changes in relative elevation (due to sea-level rise and the slumping of deep sediments) is altering the processes driving floodplain geomorphology and ecology. This conceptual understanding provides insights as to where areas might be found to develop into sediment filters. These areas are likely to be along the course of the Msunduzi River as it has a generally lower bed elevation than the Mfolozi River.

Because much of the suspended sediment in Mfolozi water is in the silt size range, rather than in the clay size range, it could be settled in the field in a large enough settling basin. The size of settling basin will depend mainly on (i) the quantity of sediment in the water, (ii) the amount of water flowing and (iii) the amount of sediment retained in the water column that is deemed to be at an acceptable level for transfer into St Lucia. Knowing the settling rate of silt in still water, it should be possible to calculate the dimensions of the required settling basin. As well as settling sediment, this shallow basin, with a large surface area, will allow the oxygenation of water once the detritus, which has a high biological oxygen demand (BOD), has settled.

Possibly the most important lesson to learn from what has been done to the Mfolozi floodplain is that we need to prevent similar damage from occurring in floodplain systems elsewhere. In this connection it is vital that we should not allow a similar situation to develop in the Mkhuze Swamp which functions in a similar manner to the original Mfolozi Swamp. Degradation in that system would possibly have even greater impacts on St Lucia by virtue of its location at the head of lake. The recent rapid increase in small-scale commercial sugar farming in the Mkhuze Swamp should cause the sounding of alarm bells for the future well-being of St Lucia, a situation that needs to be dealt with as a matter of urgency before it becomes very difficult to manage.

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MANAGEMENT CONCEPTS FOR THE MFOLOZI FLATS AND ESTUARY AS A COMPONENT OF THE MANAGEMENT OF THE ISIMANGALISO WETLAND PARK

Ivor L. van Heerden*

Affiliation: Agulhas Ventures Inc., Livingston, Louisiana, USA
**Email: exnatalia@aol.com*

ABSTRACT

Since 1920, agricultural activities on the Mfolozi Flats have severely restricted the natural channel switching processes responsible for the build-up and maintenance of the surface elevation of this river basin. Also, contributing to deflation has been the draining of part of the wetlands for sugarcane cultivation, which has increased the rate of natural soil compaction and has resulted in the loss of soil bulk due to oxidation of these highly organic soils. The resultant surface subsidence in the lower flats, combined with global warming induced sea level rise, has resulted in a relative rise in sea level of 0.5 m in the last 20 years. The artificial system, so constructed, now consists of a river confined by high artificial levees surrounded by much lower, depressed cane fields. Sediments previously deposited on the Flats during floods and periods of high river flow, either through the filtering action of the wetlands or through channel avulsion, are now advected through the Mfolozi Basin to the estuary mouth region. This excess sediment promotes long periods of mouth closure, especially during droughts, and is thus ecologically stressing for the whole St Lucia Wetland system.

Managers of this World Heritage Site need to recognize and incorporate the fact that large floods are as much part of the management plan as are droughts. The Mfolozi Flats can act as a sediment trap during the former, and be a filter for much needed fresh water during the latter.

INTRODUCTION

The iSimangaliso Wetland Park incorporates a number of coastal river basins with associated wetlands draining into the 37,000 ha St Lucia lake system linked to the Indian Ocean via the 20 km long St Lucia Narrows. Due to the natural diversity of the ecosystem, World Heritage Site status was awarded in late 1999. The St Lucia Estuary shares a common mouth with the Mfolozi Estuary, which meanders through a 10,000 ha coastal river basin/swamp, the Mfolozi Flats (Figure 1), before reaching its mouth (van Heerden, 1985). The Msunduzi River drains the southern half of the flats and shares a common mouth to the sea. This is the largest fluvial coastal plain in South Africa and the vegetation biomass is high. At present the natural productivity of the area is somewhat lower as the natural vegetation over much of the plain has been replaced by extensive sugar cane plantations. However, sugar production is important to the local economy.

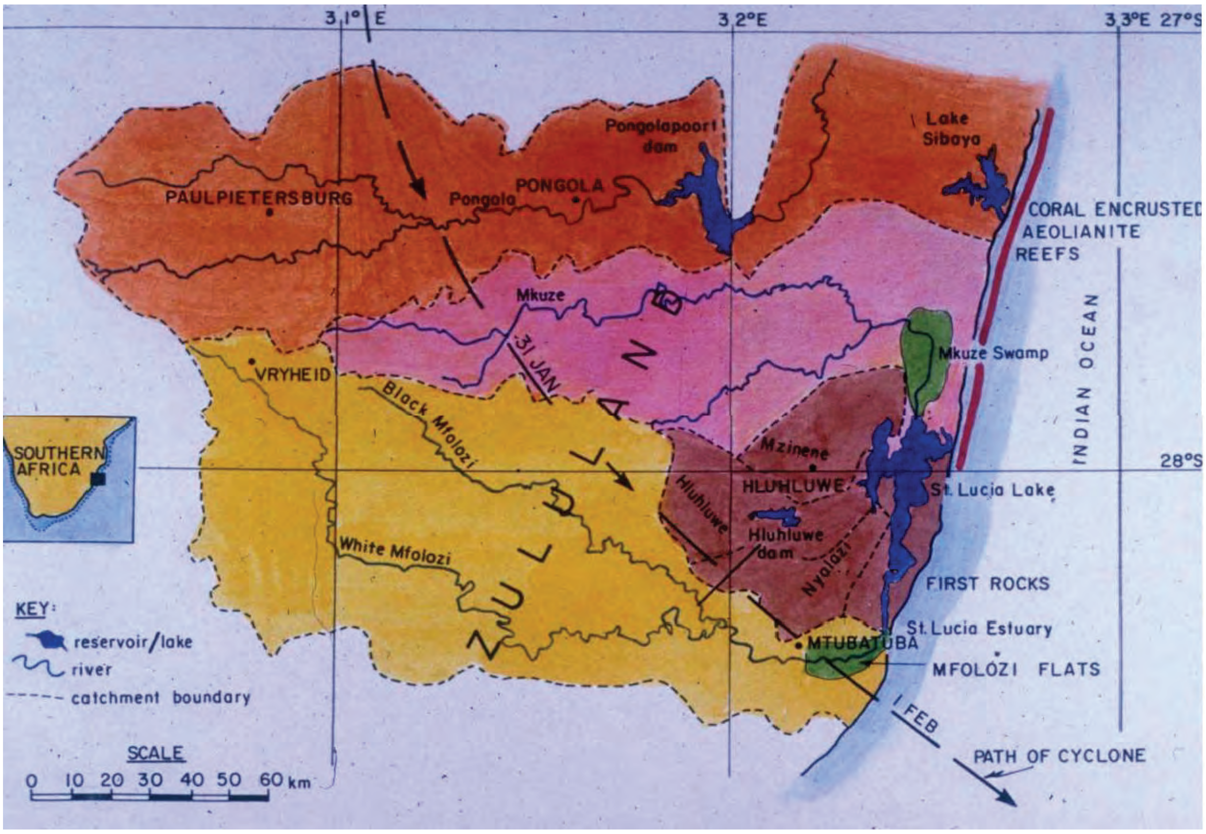

Figure 1. Location of the Mfolozi Flats study area.

At the seaward extremity of the Mfolozi Flats is the St Lucia Estuary/Lake system (Figure 1). The Mfolozi and St Lucia Estuaries are closely interrelated, having shared a common mouth until Man's intervention in the 1950s. St Lucia is the largest estuarine system in Africa (Cameron-Dow, 1974; Wallace, 1975) and the most productive along the eastern seaboard of South Africa. In addition to the abundant wildlife, the St Lucia Estuary and Lake are the breeding grounds for large numbers of hippopotami and crocodiles. The St Lucia/Mfolozi systems are often quoted as being one of the richest avifaunal areas in Africa (www.environment.gov.za/Branches/BioConservation/17Ramsar/st_lucia/st_lucia_ris.htm) and St Lucia village at the mouth of the estuary is an important sport fishing holiday resort.

ENVIRONMENTAL INFLUENCES AFFECTING ESTUARINE SEDIMENTATION

The system is very dynamic with a strong fluvial influence, albeit erratic, which interacts with marine processes to reshape the lower estuary. Given the dominance of the fluvial processes both short-term and long-term variability in atmospheric circulation patterns can play a role in re-shaping the landscape.

Climate and Rainfall

Situated between latitudes 27°S and 31°S, KwaZulu-Natal has a subtropical coastal and temperate inland climate. Thunderstorms and mid-latitude cyclonic activity contribute to the weather pattern, the former predominantly in summer (October-March), the latter in winter (April-September). Precipitation is the most important climatic variable in this context because of its influence on stream flow and sediment load capacity. The average annual rainfall in KwaZulu-Natal is approximately 850 mm. However, this amount is distributed unevenly over the province. Precipitation above the mean value occurs along the entire coastline and in the Drakensberg escarpment zone. Along the southern Zululand coast annual precipitation exceeds 1250 mm and is associated with almost daily thunderstorms during the summer months. The often intense nature of the rainfall leads to rapid overland flow and to frequent peaks in the stream hydrographs. Winter rainfall, associated with depressions and troughs moving northeast along the coast, are more widespread and not as intense. Nevertheless, when these disturbances are blocked by anticyclonic activity off the KwaZulu-Natal coast, continued widespread rainfall may cause extensive flooding further inland. Precipitation totals also vary significantly from year to year, causing great variability in stream flow, especially in the drier portions of Zululand where a succession of low-flow years may have a profound effect on the physical and ecological characteristics of Lake St Lucia.

Tropical cyclones

Data from South Africa, Madagascar, Mauritius and Reunion reveal that since 1927 approximately 10 tropical cyclones are generated every year in the tropical regions of the Indian Ocean (see for instance Dunn, 1984). Forty percent of these are formed in the Mozambique Channel.

Since 1950, twelve cyclones have caused significant rainfall (in excess of 100 mm) over KwaZulu-Natal (Kovacs, 1985), albeit only Domoina traversed South Africa. However, historic records on file in the library of the Mfolozi Cooperative Sugar Planters (UCOSP) indicate that major rainfall events occurred in 1911, 1913, 1917, 1918, 1925, 1932, 1940, 1949, 1957, 1963, 1984, 1987, 2000 and 2004.

Although it is not possible to speculate on the repetition of a Domoina-size event, the tracks of the 12 cyclones observed over the last 60 years suggest that a real possibility exists of a similar event (in terms of penetration and residence) taking place within a few decades. In March 1925 up to 1200 mm of rain fell in nine days in the Mfolozi catchment (Kovacs, 1985). The ensuing floods were apparently larger than those associated with Domoina (van Heerden & Swart, 1986a), although the origin of the storm is not documented but it was most likely a tropical cyclone. In 2000, heavy rains in Zululand were associated with a cyclone that devastated Mozambique. The above-mentioned review reveals that Domoina-magnitude rains (more than 600 mm) are not rare in the Mfolozi catchment.

River floods

Extreme rainfall events, which lead to large river floods, are one of the most important physical phenomena influencing the coastal zone. Heavy precipitation and attendant erosion within the river drainage basin increase both the carrying capacity of the river and the amount of transportable sediment. Steep gradients, erodible soils and unwise land-use practices combine to produce high sediment yields that eventually find their way to the coast where deposition occurs, sometimes forcing considerable environmental change.

The Mfolozi River has a catchment of approximately 10,000 km^2. The average annual run-off appears to be between 393 x 10^6 m^3 (Kovacs, 1985) and 887 x 10^6 m^3 (van Heerden & Swart, 1986a). Van Heerden & Swart (1986b) determined the simulated monthly run-off of the Mfolozi River for the period October 1921 to September 1975, based upon HRU 9/81 data (Pitman *et al*., 1981). Review and characterization of these data reveal that during the above-mentioned 55-year period there were 20 single months when the run-off was approximately equal to the average annual run-off (400-900 x 10^6 m^3) and four single months when the run-off was much larger. These data, although only simulated run-offs, reveal three important features of the Mfolozi, firstly that it is very erratic in nature, secondly that large floods are fairly common (24 in 55 years, 1921-1975), and thirdly that floods can occur at any time of the year. Quantitative examples of peak flood discharges are 15,000 to 22,000 m^3 s^{-1} in March 1925, 8500 m^3 s^{-1} in July 1963 and 16,000 m^3 s^{-1} during Domoina in January 1984.

Meteorological forcing

Coastal winds and especially the longshore components of such winds play an important part in the sea level and current variations in the shallower shelf region adjacent to a coastline (Niiller, 1975). Of particular importance are the "coastal lows" that form on the west coast with the approach of a suitable leader front and then propagate around the Southern African coastline.

Dramatic changes in the wind regime can occur along the KwaZulu-Natal coast during the passage of such a low. Thus it is common for the wind to change from north-easterly to south-westerly in a matter of minutes with the total wind velocity change being up to 20 m s^{-1} and more. The prevailing winds are spread fairly evenly over the 12 months of the year and are almost equally divided in frequency (Weather Bureau, 1960; Orme, 1973).

Ocean swells

The most important marine physical force along this section of the coast is the wave climate. Although the south-easterly swells produced in the "roaring forties" become deflected and progressively weakened before reaching the KwaZulu-Natal coast, wave processes force most sediment movement. The two most important characteristics of waves in terms of beach and spit responses are the angle of swell approach and wave height. For 87% of a two-year period from March 1971 to February 1973 (CSIR, 1973) the ocean swell along the KwaZulu-Natal coast varied from 1-3 m, with 2-3 m swells occurring 35% of the time.

Direction of swell approach along the KwaZulu-Natal coast has two dominant modes. Swells have a south-easterly orientation about 40% of the time (CSIR,, 1973; Begg, 1978). On-shore swells (north-easterly to easterly) in the St Lucia area have a similar frequency. The onshore swells do not produce a unidirectional longshore current. However, during southerly swells a northerly longshore current is set up, which is responsible for moving large quantities of sediment in a northward direction annually. Although a northward-directed longshore current does dominate under southerly swells, local reversals in the longshore drift do occur around such features as ebb-tidal deltas seaward of inlet mouths. Van Heerden (1976a) found that there was a strong correlation between angle of wave approach and wind direction. Southerly winds tend to enforce south-easterly swells, while northerly winds generally create conditions of onshore swells.

Coastal subsidence.

The term subsidence is applied to the relative rise in sea level and/or the relative lowering of base level in coastal environments. A number of mechanisms are responsible for these apparent changes, including eustatic sea-level fluctuations, continental down warping, dewatering and compaction of sediments and human activities (van Heerden, 1985). A drowned river valley such as the Mfolozi Flats is filled with highly organic sediments composed predominantly of leaf litter and rootlets with a very high water content. As more and more sediment is added, any particular layer can get compacted by the new load overhead and therefore be compressed and shrink (i.e. it sinks). Thus, marshland is just about the least stable of all soils. Left absolutely alone, marshland will slowly compress under its own weight at the rate of up to a metre per century. However, the subsidence rate can be greatly enhanced by the activities of man.

In a setting such as coastal Louisiana, developments in former marshes and swamps rapidly enhance the local subsidence rate due to draining (dewatering) of the soils and resultant rapid decomposition of the organic matter (loss of bulk). The ground surface in new subdivisions can sink within months after the occupants move-in, necessitating expensive additional soil replenishment. The only way to compensate for the compression of the sediments is with ongoing, never-ending, inexorable sedimentation; otherwise, the wetlands will sink and seawater will encroach and eventually kill the freshwater plants (van Heerden & Bryan, 2006). On the other hand subsidence does have a role in areas with sufficient, or an abundance of sediment. The constant lowering of the landscape creates space for new sediments to accumulate; thus accretion can occur without a significant change in elevation.

Long-term fluvial processes

Rivers are the main agents that transport sediments from land to the coastal regions of seas and lakes where they are deposited in thick sequences, or transported further to continental shelves and deep-sea basins to produce deep-water sediments.

The river discharge regime depends on the climate factors active within the drainage basin. In general, rivers characterized by temporal discharge tendencies and variation in discharge throughout a hydraulic year exert a strong influence on alluvial valley and coastal sedimentary body geometries (Coleman, 1976). The geology, morphology and dominant physical processes of the receiving basin or coastal plain dictate how the fluvial sediment is deposited and the form of the deposits. Narrow steep-sided coastal plains ensure that most of the river-borne sediment is advected to the coast, with resultant changes in coastal configuration. Wide, flat coastal plains generally act as sinks for river-borne sediment and the coastline configuration is very stable. Extreme floods, however, can create both short-term and long-term changes in the coastline.

In wide, flat coastal flood plains river gradients are generally low and suspended sediment loads are high by comparison with bed loads and the stream produces a network of meandering channels. In addition, wide coastal flood plains have an in-built ability to accept most of the sediment supplied to them by rivers. Build-up occurs as a consequence of differential sedimentation associated with the periodic switching of loci of deposition, as channels switch from one part of the plain to another.

Meander channels on coastal flood plains occupy only a small part of the plain at any one time and show an organised distribution of channel processes and a clear separation of channel and overbank environments (Figure 2). The meander channel lies within a meander belt, which is a complex of active channels, abandoned channels and near-channel sub-environments. Shifts in the meander belt reflect natural subsidence and concentration of sedimentation.

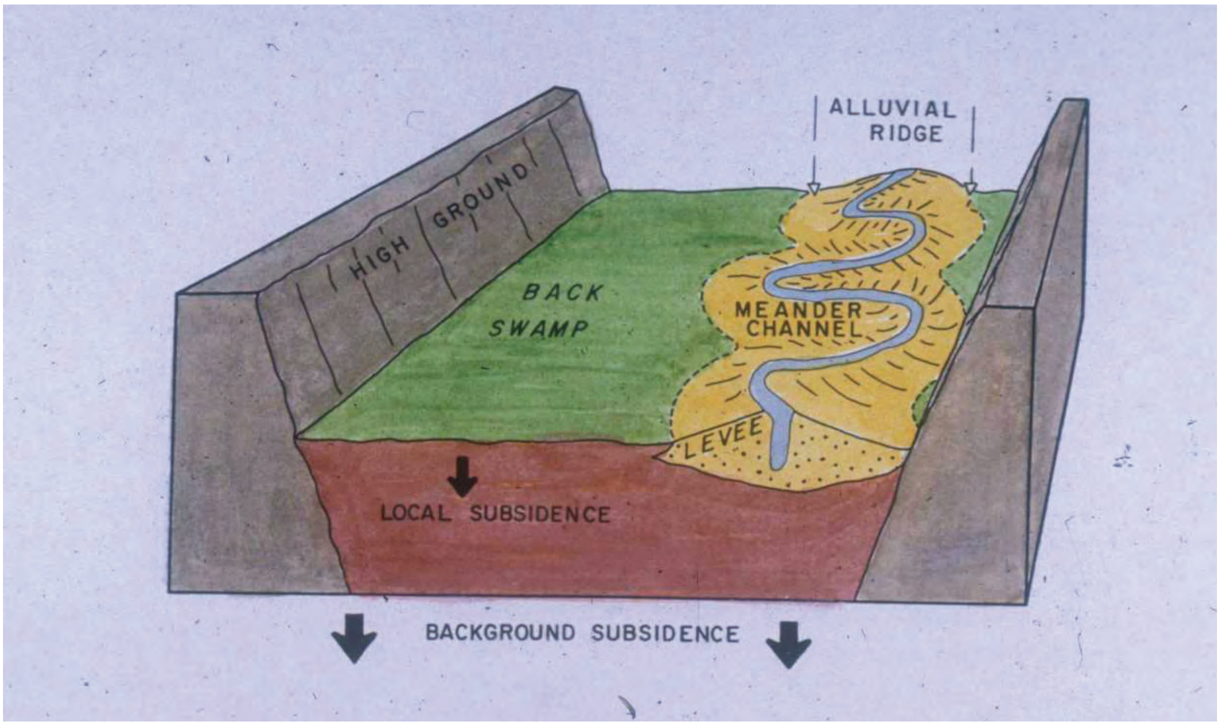

Figure 2. Generalised morphology of a river basin.

Sedimentation is concentrated close to the meander belt and an "alluvial ridge" is built above the level of the flood plain (Fisk, 1952) (Figure 2). This increasingly unstable situation is periodically relieved by the breaching of a channel bank during floods and the sudden shifting of the meander belt to a new position on the alluvial plain, a process known as "avulsion". The new course captures an increasing proportion of the flow and the old meander belt is abandoned.

Subsidence is the second important mechanism that forces channel switching in coastal fluvial plains. Swamps and marshes more distant from the channel cannot maintain base level due to a sedimentation rate that does not balance subsidence. Thus topographic lows are created in inactive parts of fluvial plains. During a flood the river may break into such areas and occupy a new course to the sea. Associated with the new channel would be a new episode of levee building and meandering. As natural levee height decreases in a downstream direction on coastal plains, the frequency of switching increases in the same direction.

The channel switching process results in the floodplain being built up of inter-fingering sediment lobes (Figure 3). Recently Garden (2008) presented auger data collected from the Mfolozi Flats which are indicative of a typical stacked river basin deposit, created through time by the avulsion of river channels (Figure 4).

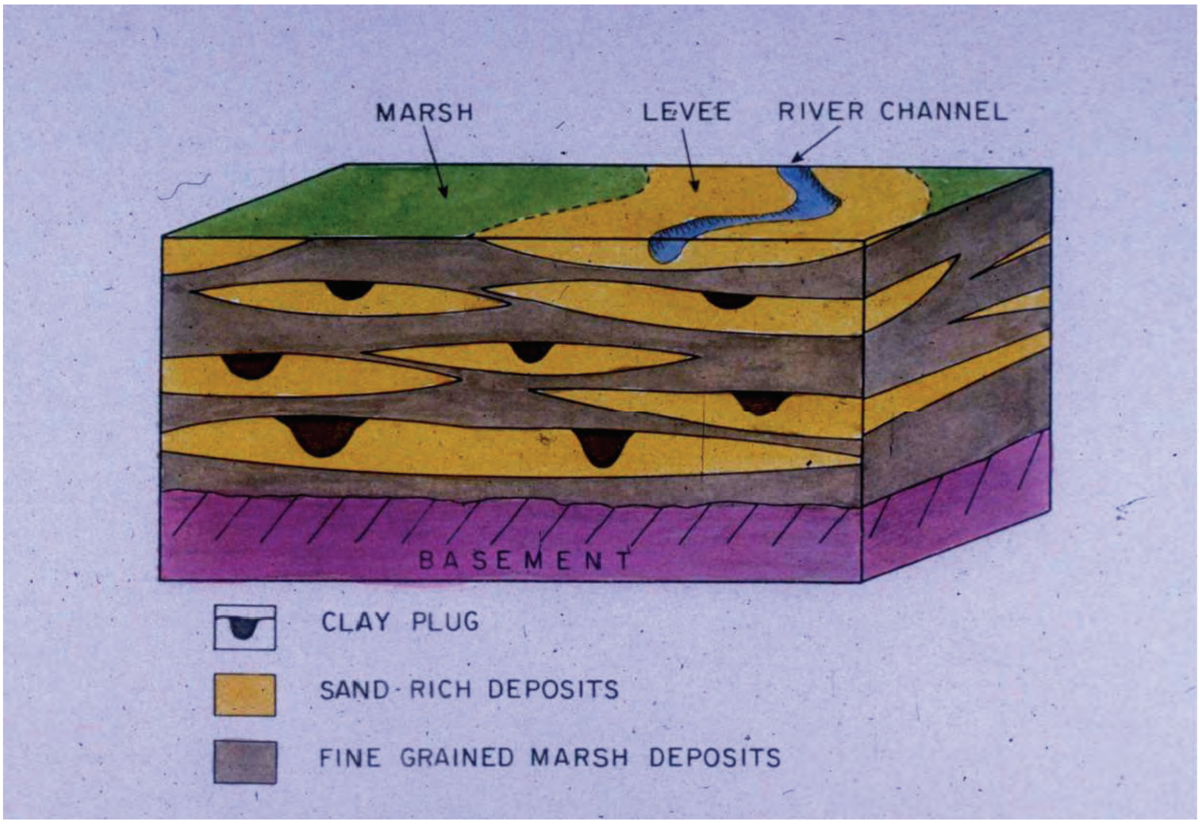

Figure 3. Generalised stratigraphy of a river basin such as the Mfolozi Flats.

Human influences in coastal plains

Human activities can greatly enhance the subsidence rate. Firstly, draining (dewatering) wetlands increases compaction and hence subsidence. Secondly, the channelisation of rivers and the creation of artificial levees impede the spread of sediment to areas adjacent to the channel. Thus sedimentation does not balance local subsidence and consequently the lowering of the base level continues.

Lastly, channelisation and artificial levee construction, especially if levee material is dredged from the river floor, create a situation where the local water table is lowered. Such dewatering increases the local subsidence rate. Therefore, although channel switching is a natural process in subsiding coastal fluvial plains, it can be restricted by Man's activities. Consequently, situations can be created for major, flood-induced channel switching.

MFOLOZI FLOODPLAIN AND ESTUARINE PROCESSES PRIOR TO 1930

Figure 5, compiled from aerial photo mosaics and oblique air photos, shows the location of numerous old channel traces, indicating that channel switching commonly occurred on the Mfolozi Flats (van Heerden, 1984). The Mfolozi Flats are apparently underlain by more than

50 m of relatively fine-grained sediments (Orme, 1973) typically deposited from suspension consisting of silts and clays and originally having a high water content. Given this thick sequence of fine-grained sediments, subsidence due to dewatering and compaction must be an active process on the Mfolozi Flats aided after each flood by the sediment "loaded" during the flood.

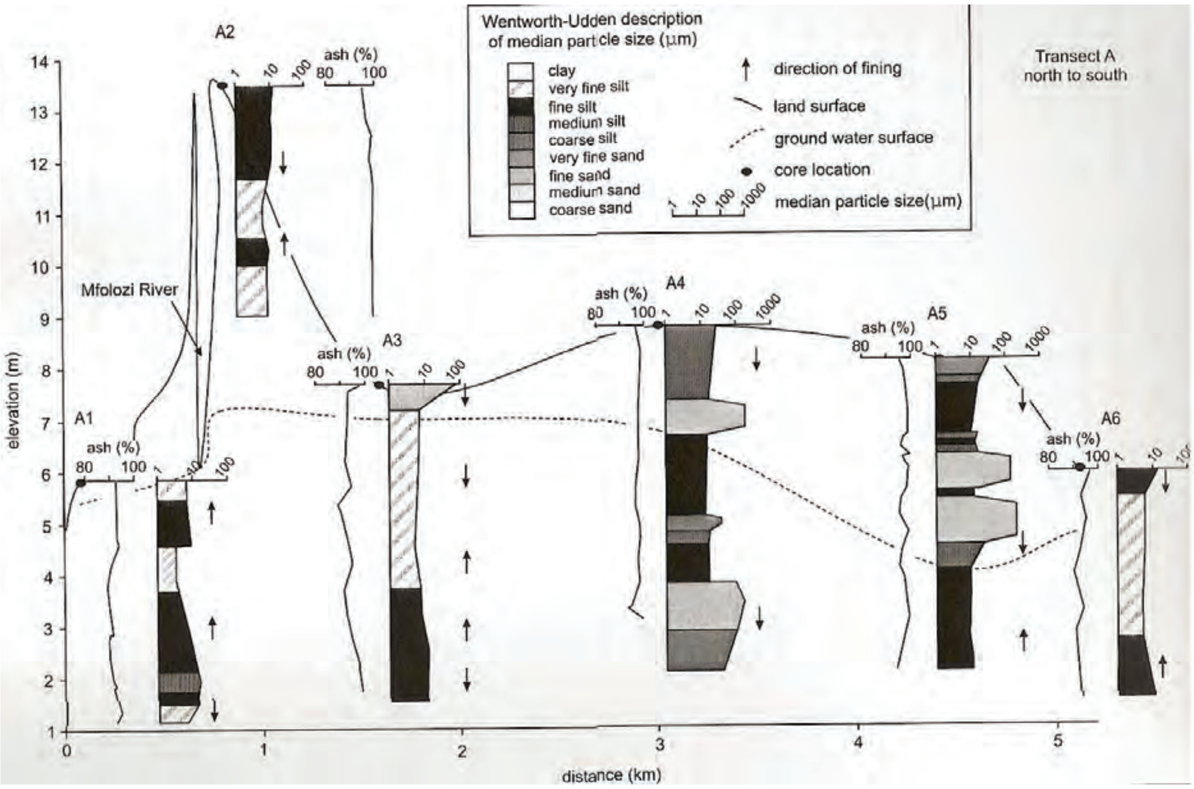

Figure 4. Sedimentology and topography, central Mfolozi Flats (modified from Garden, 2008).

The background subsidence rate of the surface of the Mfolozi Flats is not known at present but subsidence rates of 1.3 cm per year have been recorded (van Heerden, 1983) in a similar type of environment in the Atchafalaya River Basin, Louisiana, USA.

Review of the historic aerial photographs reveals that the Mfolozi River had occupied its course between points A and B in the upper section of the Flats (Figure 5) for quite a long period. The pre-Domoina river course was relatively deep and wide with well-established confining natural levees. Traces of old crevasse splays or channels displayed in earlier photography (1960) indicate that sedimentation in the upper section during this period occurred through the overtopping of the natural levee system (Figure 5) rather than through channel switching. River channel elevation would have progressively increased with each successive flood.

Channel switching in the midsection of the flats appears to have occurred chiefly at two locations (van Heerden, 1984). Major, fairly long-term upstream diversions occurred in the upper reach of the mid-section (Area C, Figure 5), while switching was more common further downstream (Area D, Figure 5). The well-developed meander pattern of the channel between Areas C and D indicates that this channel was in use for a long period. Using historical maps and photographs and features such as the abundance or lack of tree cover on old levees enables one to infer the chronological order of channel switching. Trees exist along relatively new water courses that have levees high enough to support them. As river courses are abandoned and the levees subside, the trees start to disappear due to water logging. This absence/presence of trees is a valuable geomorphic interpretation tool. Interestingly, the order of switching reveals that the southern half of the mid-section had not been occupied by a major course of the Mfolozi for some time (Figure 5).

The earliest known maps of the St Lucia area (1884, Figure 6a) reveal that at that time the Mfolozi flowed in a predominantly easterly direction before moving northwards to reach the St Lucia Estuary at Honeymoon Bend. Shortly thereafter, however, it switched to course 3 and then to course 4 (Figure 5). As a result the Mfolozi entered the St Lucia Estuary at a point downstream (seaward) of Honeymoon Bend (Figure 6b) in 1905.

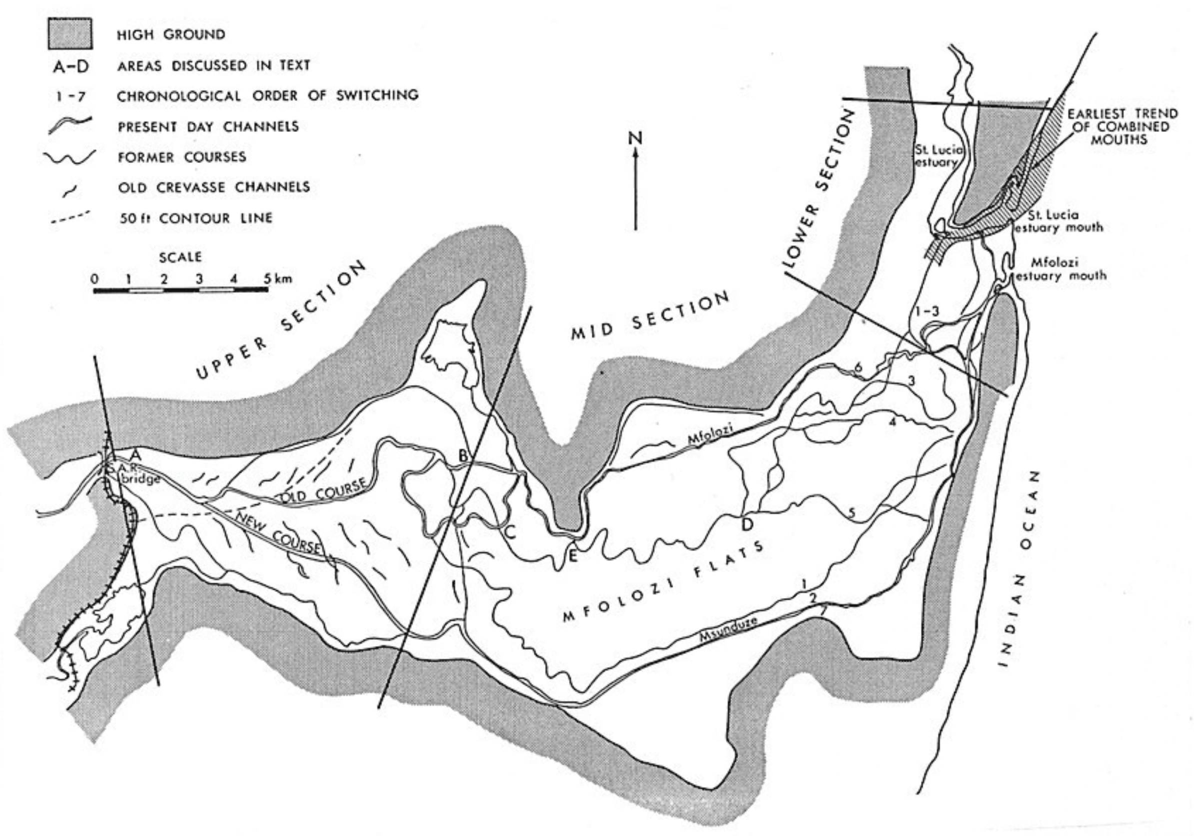

Figure 5. Channel courses and scars indicative of channel avulsion over time.

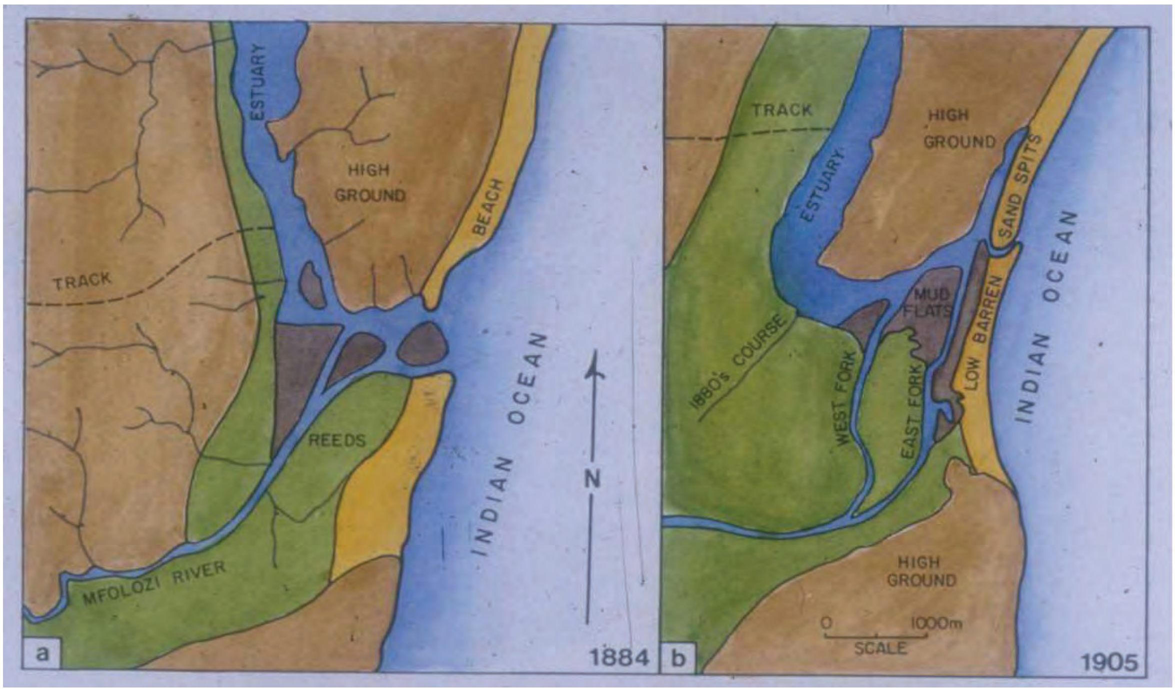

Figure 6 (a) and (b). Maps from 1884 and 1905 showing the mouth of the St Lucia Estuary.

St Lucia and Mfolozi Estuary conditions prior to 1930

The St Lucia Estuary and lower Mfolozi River each occupy drowned river valleys that are deeper than 50 m at the coast (inferred from Orme, 1973; van Heerden, 1976b). Apparently both palaeoriver systems had a common mouth at St Lucia, reflecting the lack of Pleistocene "beach rock" between Mapelane and a point a few kilometres north of the St Lucia mouth. Historical reports and modern surveys (Begg, 1978) indicate that both systems had a common mouth until human intervention in the early 1950s.

During the last 100 years the point of junction of the two estuaries appears to have slowly migrated seawards. Although one can question the accuracy of early maps, charts published in 1879 and 1884 (Kriel *et al*., 1966) reveal that the confluence of the Mfolozi River and St Lucia Estuary was near Honeymoon Bend and that the mouth was further north than it is at present (Figure 6). Interpretation of aerial photographs and ground truth surveys (van Heerden, 1984) confirm this feature shown in early charts. Judging by the size of the dune field that built up from windblown estuarine sediments north of the mouth, this condition must have been stable for some time (van Heerden & Swart, 1986b).

All early surveys and maps reveal that the combined system had an opening in the general area of the present mouth, with a shallow-arm extending northwards from the estuary behind the beach (Figure 6b). Although very little historical coastal process data are available, this central location was most likely representative of periods of low river flow. During and immediately after floods, when large amounts of sediment were deposited in the nearshore, the mouth could well have migrated further north along the arm north of the mouth. At such times the oblique southerly swell approach combined with a large littoral sediment pool would have forced the southern bank or spit of the estuary to extend rapidly northwards, while the estuary waters eroded the northern bank. Similar processes have been documented elsewhere on the Natal coast following major floods (van Heerden, 1976a).

In general, during low-flow periods the mouth would have closed sometimes for months until the next big Mfolozi flood. At such times, low flows would have dominated in the Mfolozi and fresh water would have been forced up the St Lucia Estuary towards the lake. Fine-grained sediments were most likely deposited in the mouth area as well as in the lower reaches of the St Lucia Estuary.

The high Mfolozi flows during the wet season would have intersected the low barrier somewhere north of the mid-point and the mouth may even have migrated further north. However, the important feature of the floods would have been that the mouth and lower reaches of the Mfolozi River would have been scoured open. At the same time rising water in the lake system would have increased flows down the lower reaches of the St Lucia Estuary, thus scouring the system. A few months following the flood the mouth may have switched to a more central location in the fronting barrier due to overwash and tidal scour processes. Van Heerden & Swart (1986b) suggest that on a more or less annual basis the estuary was scoured open, then sealed (followed by some deposition) and then opened again. Superimposed on this cycle would have been periods of either longer closure or opening.

An important aspect, prior to 1930, of the two estuaries having a common mouth was that direct discharge of the Mfolozi into the St Lucia Estuary maintained the ebb-dominated character of the estuary for months following a major flood. However, with low Mfolozi discharges the overriding influence of the high swell regime would eventually force mouth closure.

MODERN (POST 1930) MFOLOZI FLAT PROCESSES AND THE ST LUCIA ‘PROBLEM’

Land-use practices of the farmers on the Mfolozi flood plain severely restricted channel switching because the farmers lowered the base level of the river as they excavated and used channel bottom sediments to raise the artificial confining levees. In addition, the draining of wetlands for cane increased the rate of compaction and hence subsidence. The artificial system thus created consisted of a river with high banks surrounded by much lower, depressed cane fields.

An assessment of subsidence in the Mfolozi Flats

Van Heerden & Swart (1986b) stated that they felt subsidence to be a feature of the Mfolozi Flats landscape and that subsidence actually creates some 'accommodation' space for fluvial derived sediments. They made comparisons to subsidence rates in a similar type of setting in the Mississippi River flood plain that the first author had previously researched. Roberts *et al.* (1994) determined very accurately that subsidence rates in a 50 m thick drowned river valley beneath the Mississippi flood plain, a setting not too dissimilar from that of the Mfolozi flats, were 10 times higher than the surrounding basement material.

In 2000 the author was contracted by the Mfolozi farmers to determine why some relatively new sugarcane fields, along the very eastern edge of the farmlands, were constantly being flooded by tidal action. While the sugar farmers had rejected subsidence when first discussed in the 1980s, a review of survey maps, as a time series, made in 1974 and 1990 suggested that vast areas of the farmlands had subsided about 1 m over the 26 year time span between surveys. In order to get a better understanding of the validity of this apparent subsidence a direct 1974 to 1990 map comparison was performed utilising 19 points on a 500 x 500 m grid that covered 300 ha in the eastern half of the flats (Figure 7). This was considered a big enough area to determine if, based on the map data, there had been any real subsidence, be it due to levee construction, drainage and dewatering, or to long term compaction of the underlying substrate.

In 1974 the elevation averaged 1.2 m above Mean Sea Level (MSL) but by 1990 it was 0.5 m MSL. Typically, such a rapid loss of elevation reflects local subsidence due to dewatering and oxidation of the highly organic soils. However, one suggestion advanced was that there may have been survey datum errors in one of the maps and therefore additional investigation was required.

A professional surveyor was contracted to undertake a series of detailed elevation surveys in various locations of the flats. Firstly he determined the elevation at two locations on high ground and then compared these with the 1974 and 1990 data. The sites were chosen because they were felt to be outside of any dewatering induced subsidence zones. The 1974, 1990 and 2000 elevations at these two ground control sites were exactly the same suggesting that there were no datum errors and that the maps did indeed represent an elevation time series data set, albeit that there was some concern that the 1974 surveys had a greater potential error than the 1990 data.

Four grid points were then surveyed within the central section of the 300 ha grid site discussed previously (Figure 7) and the 2000 elevations averaged 0.2 m lower than the 1990 map data, suggesting that subsidence was still occurring. However there was still some speculation by the farmers as to whether subsidence was a reality. The final demonstration was to establish a 1000 m line along the extreme eastern boundary of the 'new' cane fields, where the fields abutted the *Phragmites* wetlands and to collect survey data in the wetlands and also in the cane field at locations opposite to each other, every 20 m along the 1000 m survey line (Figure 7). The idea was to establish the elevation in the wetlands that seemed over time to have maintained their elevation at about 1.1 to 1.4 m, and compare them directly with the drained and leveed cane fields. The wetlands still had the same elevation as first measured in 1974. On average the cane fields were 0.3 m lower than the wetlands, but the difference between the wetland elevations and cane fields increased as one moved down slope towards the Mzinduze River with a maximum deflation of the cane lands being about 0.5 m at the river. This is the same deflation that the 1974 to 1990 comparison revealed.

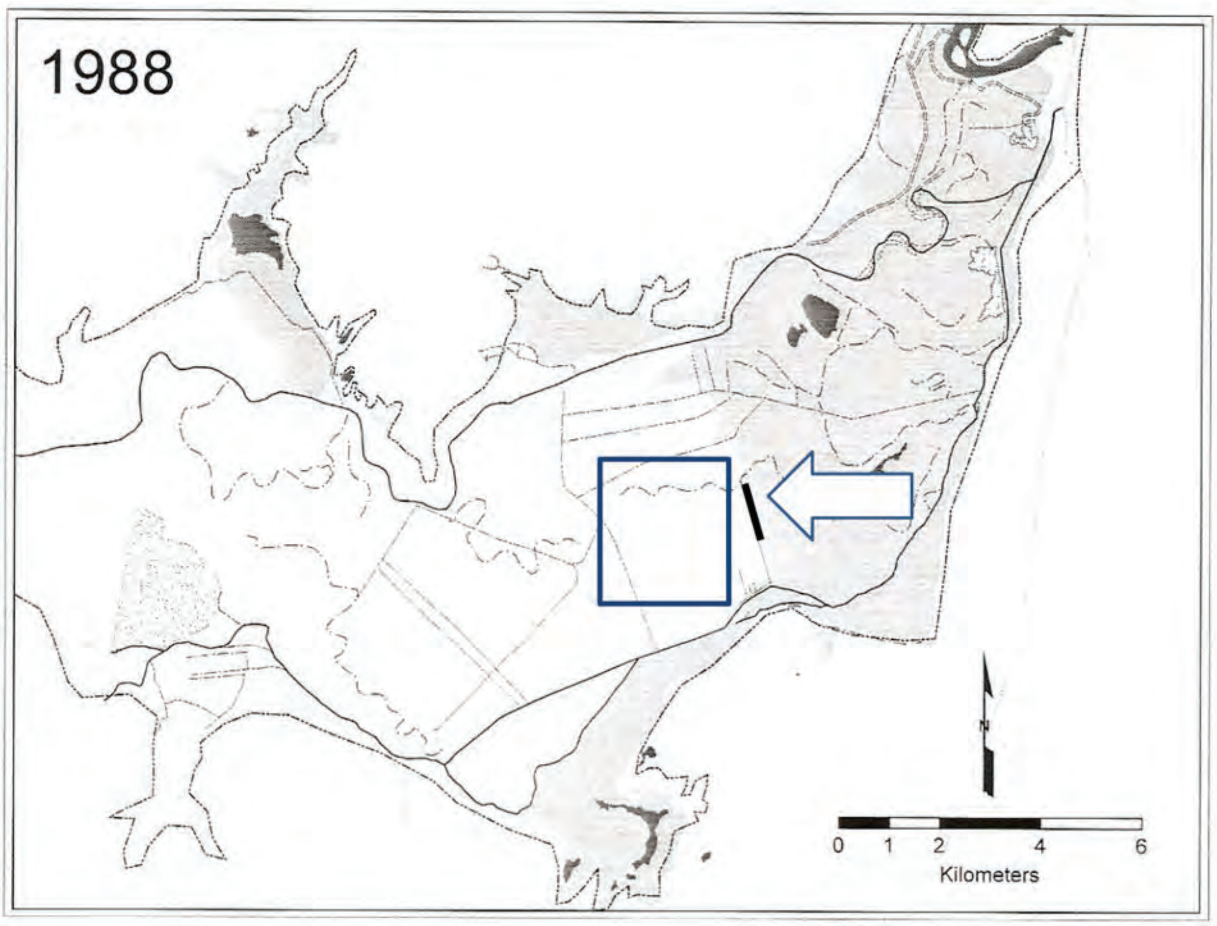

Figure 7. Subsidence study area. Blue box represents the grid area and arrow points to 1000 m survey line discussed in the text (based on map from Garden, 2008).

So subsidence of the cane fields is a reality, once they are stripped of their wetland vegetation, ring leveed and then drained. However, the 'natural' *Phragmites* wetlands, if they have access to inorganic sediments and nutrients, manage to maintain their elevation. The subsidence phenomena exhibited by the Mfolozi Flats is very well documented in other parts of the world in similar settings. What could not be determined was the extent that the long-term background loading induced dewatering and compaction subsidence of the flats contributed to the overall subsidence measured. It is hidden within the farmland drainage induced subsidence.

As previously mentioned all surveying was undertaken by a professional surveyor and all efforts were made to be as accurate as possible, although there are always potential datum and bench mark errors when comparing historic data sets. Nevertheless, within the drained and dewatered cane fields, subsidence is of the order of 0.5 m every 20 years. This creates a vast amount of accommodation space, assuming one would just want to maintain an equilibrium base elevation. Subsidence in essence creates a huge depression that from time to time a river in flood, carrying sediment, could fill.

The fact that the wetlands to the east of the cane fields do not seem to have changed elevation does not mean there is no background subsidence. Wetlands, if given nutrients and some inorganic material, will maintain their elevation as they build their own highly organic substrate. Just what the actual background subsidence rate of the wetlands may be is still unknown, although it at least includes the predicted 0.4 m by 2100 sea level rise for St Lucia coast of South Africa (Været *et al*., 2009).

The question then becomes – how do you manage the landscape for both sugarcane production and wildlife resources, given enhanced subsidence rates within the cane lands and the Mfolozi River with, and at times abundant, sediment loads? Before we can answer that we need to better understand the river dynamics.

Consequences of human manipulation on river dynamics

Changes in the sedimentation patterns as a result of river channel manipulation were the underlying cause for the ecological stress experienced by the St Lucia Estuary following the initiation of farming on the Mfolozi Flats after 1930. Prior to farming, the flats accepted most of the river-borne sediment and the relatively sediment-free waters reaching the coast kept the then combined systems open and free of silt. After farming was initiated, sediments were transported down the Mfolozi River and right through the Flats to the coast due to the confined, artificially stabilised channel. As a result of this increased sediment supply, both estuaries became heavily silted and estuary mouth closures became common and were of long duration.

Response to channelisation appears to have been fairly rapid because in 1932 the mouth was artificially opened for the first time and in 1935 oyster collection for the Durban markets was suspended because of "too much silt" (Kriel, 1966). In 1936 the first public complaints were made about the deterioration of fishing (Kriel, 1966). Mouth closure became more common and the estuary reached a sediment-filled state in 1951. It was only in 1955 that the estuary was finally opened. The Mfolozi River was given an artificially separate mouth in 1952. This move plus the siltation problem prompted the artificial stabilisation of the mouth of the St Lucia Estuary. Because the Mfolozi River flood and tidal basin scour effect was missing, dredging became a perennial activity.

RESPONSES TO CYCLONE DOMOINA

Van Heerden (1984), who conducted site visits immediately after the floodwaters had subsided, stated that the floods associated with the passage of Cyclone Domoina had enhanced many natural processes. In addition, he felt that flood responses on the Mfolozi Flats were similar to those documented on other coastal fluvial plains such as the Atchafalaya River Basin and Mississippi Delta Plain of Louisiana, USA.

Mfolozi Flats

Depositional responses were dramatic on the Mfolozi Flats, mostly due to the Mfolozi River creating a new course to the sea via the older Msunduzi River (Figure 8). Prior to Cyclone Domoina the Mfolozi Flats consisted of an artificially leveed river channel surrounded by much lower cane fields. The extreme flood generated by cyclone Domoina was all that was needed to force channel avulsion.

A major new channel was initiated as a switch occurred in the upper reaches of the flats (Figure 8), an area where switching seldom occurs. Judging by the amounts and localities of sediment deposition, avulsion must have occurred early in the flood. As will be shown shortly, this early switch of river channel location was indeed fortunate for the St Lucia and Mfolozi estuaries. Barring human intervention, the new channel had the potential to be a long-lived feature. The former Mfolozi River, seaward of the new confluence with the Msunduzi, was not carrying much water after the Domoina flood as its upstream end had been sealed by a subaqueous levee, typical of what occurs when older channels are abandoned.

The sedimentary wedge seaward of the railway bridge, deposited during Cyclone Domoina (Figure 9), is a typical shallow water fluvial delta displaying the characteristic branching and rejoining of channels around sand-rich lobes (van Heerden, 1984). The thickness of the "sand" deposited varied between 1 and 2 m (Roberts & Pyke, 1984). Fluvial delta sediments sampled near the railway bridge in the upper reaches of the flats consist of fine to medium-grained, well-sorted sand (van Heerden, 1984). Such sediments are usually deposited from suspension as flood water passes from a confined to an unconfined state. In this case, as the floodwater moved out of the confines of the river valley and specifically out of the confines of the artificially leveed Mfolozi River, they spread out rapidly over the flats with a resultant drop in velocity. At the diversion point the coarsest fraction of the suspended load was deposited, this being the medium to fine-grained sands sampled by van Heerden (1984). Floodwater would have continued its lateral spreading as it moved down the progressively broadening flats.

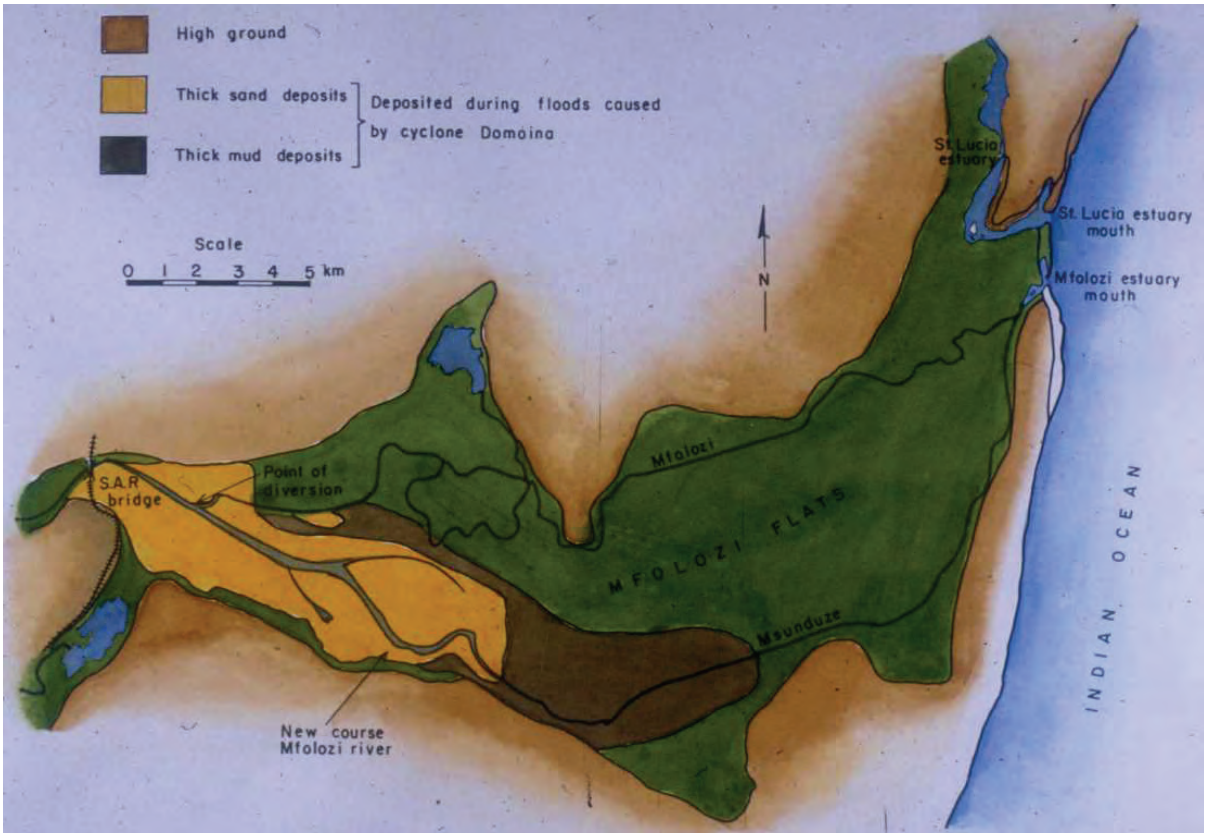

Figure 8. Responses to Cyclone Domoina flooding

As a result, a longitudinal reduction in velocity occurred so that even finer portions of the sediment load were deposited. The spreading of fluvial waters when moving from the

Simple calculations indicate the ability of the coastal flood plain to accept vast volumes of sediment. Firstly, if subsidence were 0.5 cm year^{-1} over the whole plain, 1.2 x 10^{6} m^{3} of sediment could be deposited annually to keep pace with subsidence. Secondly, sea level has risen 23 cm in the last 100 years (Barnett, 1984). Thus 52.2 x l0^{6} m^{3} of sediment could have been deposited during this period to maintain base level. Combining subsidence and rise in sea level gives a potential for the system to accept an annual sedimentation of 1.75 x 10^{6} m^{3} with no change in base level. This is a substantial amount of potential sedimentation (sink) annually and more than equals the estimates of sediment supplied from the catchment (van Heerden & Swart, 1986). Therefore, it would appear that under natural conditions very little sediment would be transported to the coast. However, the system broke down once channelisation was initiated in 1927 and overbank spillage and flooding with associated sedimentation was prevented. Instead, most of the sediment load was carried to the coast via the deep artificially confined channel on the flood plain.

The floods associated with Cyclone Domoina forced a fairly natural channel switch. Resultant processes strikingly demonstrated the capability of the Mfolozi Flats to absorb vast amounts of river-borne sediment and the ability of the sediment-free water to erode and restore the Mfolozi and St Lucia estuaries. It is estimated that, during Cyclone Domoina approximately 80 x 10^{6} m^{3} of sediment were deposited on the Mfolozi Flats – equal to what could normally have been deposited in about 50 years prior to the commencement of sugar cane farming!

SUMMARY OF RESULTS AS RELATED TO A MANAGEMENT STRATEGY

Based on an understanding of natural processes as presented here, the following management plan is proposed for the Mfolozi Flats and estuary:

1. Cane lands that now lie below or close to sea level should be appropriated and allowed to revert to wetlands.
2. Spillways or training works within the Mfolozi Flats should be built as a means of diverting sediment-laden flood waters to low-lying receiving basins to capture most of the sediments so that relatively sediment-free water reaches the estuary systems during floods.
3. The lower portions of the Mfolozi Flats, as well as the appropriated cane fields, should be used as overflow pathways to remove suspended sediments prior to directing the water into the St Lucia Estuary, especially during drought years.

Conceptually the management plan could have the following elements. A ring levee or dyke (Figure 10) should be constructed around the farmlands in such a way as to ensure there would be no catastrophic flooding. The direction of floodwater should initially be into the upper basin (Area 1, Figure 10) until that location becomes sediment-filled. Then the floodwaters should be directed to Area 2 (Figure 10). Thereafter the ring levee could be partially degraded and the sugar fields moved to the 'new' high ground created in areas 1, and 2 (Figure 10) through the deposition of flood water sediment. The deflated, subsided area that used to be within the ring levee could then be utilised as the flood sediment catchment. In this way, if managed carefully and including annual LIDAR surveys with careful monitoring of sea level rise, a large portion of the annual sediment load of the Mfolozi River could be trapped on the flats, in the way it did before human intervention in the 1920s. This would ensure a healthy Mfolozi estuarine system and provide a significant source of fresh water during droughts to the St Lucia lake system. In a nutshell, the call has recently been for sustainable management options, but now we need 'smart' sustainable management.

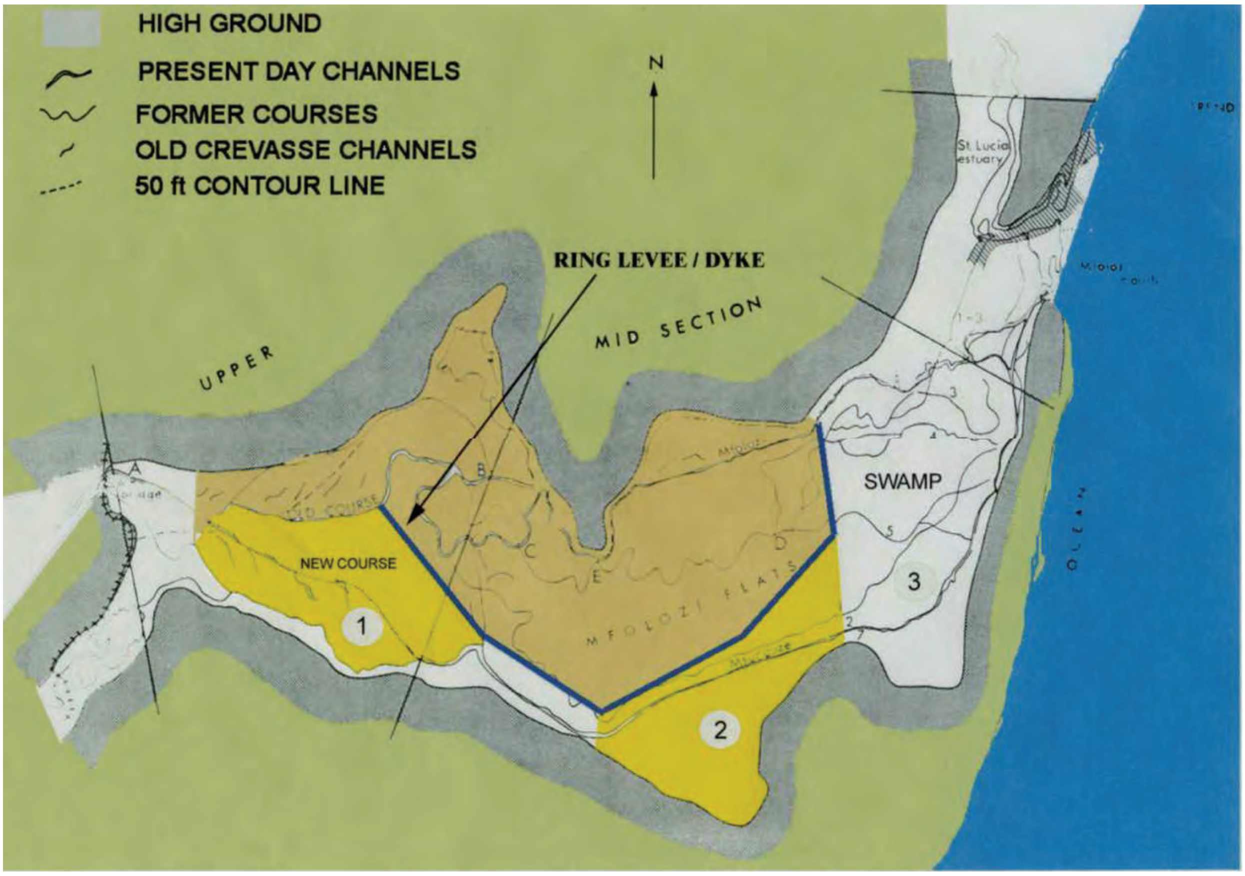

Figure 10. Components of a suggested management plan for the Mfolozi Flats.

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ANALYSES OF THE HYDROLOGICAL LINKAGE BETWEEN MFOLOZI/MSUNDUZI ESTUARY AND LAKE ST LUCIA

Bruce Kelbe[1*] & Ricky Taylor[2]

Affiliations: [1]Department of Hydrology, University of Zululand, KwaDlangezwa
[2] Ezemvelo KZN Wildlife, St Lucia Estuary and School of Biological and Conservation Sciences, University of KwaZulu-Natal, Pietermaritzburg
*Email: bekelbe@gmail.com

INTRODUCTION

Lake St Lucia has been impacted by frequent droughts and extreme floods that have had a big impact on the lake volume (water level) and salinity profiles leading to major changes in the ecological status of the system (Bate & Taylor, 2008). These, together with anthropogenic impacts involving mouth management (Taylor, 2010a) and land use practices (Været *et al.*, 2009) are the major driving factors that determine the health and function of the lake system. During the severe drought from 2002 to 2008 when the mouth closed, the lake system shrank to less than 10% of the surface area under bank-full conditions (Whitfield & Taylor, 2009) causing severe ecological stress on the system.

Prior to 1952, St Lucia and the Mfolozi/Msunduzi rivers shared a common bay where flow from the Mfolozi/Msunduzi would enter before flowing into the St Lucia Estuary and/or out to sea (see Taylor, this report). From 1952 this hydrological coupling between the Mfolozi/Msunduzi rivers and Lake St Lucia Estuary was severed for various reasons (see Taylor, this report). The de-coupling of these catchments and the severe droughts during which the St Lucia catchment was unable to supply the necessary freshwater inflow to the lake has resulted in the lake becoming highly stressed. Researchers have been calling for the restoration of the hydrological linkage to the Mfolozi/Msunduzi system to alleviate much of the stress on the system (Kelbe & Taylor, 2005; van Heerden, 2010).

Lake St Lucia is a large shallow water body that was generally open to the Indian Ocean in its natural state and is fed by several river catchments (Figure 1) that influence the lake level and salinity conditions. During high rainfall seasons there is generally a net flow of freshwater through the lake to the ocean, thus creating an oligohaline system with freshwater in places. During drought conditions, when the evaporation rate from the lake surface exceeds freshwater inflow into the lake, hypersaline conditions (>40 PSU) do occur (Bate & Taylor, 2008). It is probable that prior to 1952, the influx of freshwater from the Mfolozi/Msunduzi system during low rainfall periods would have influenced the lake level fluctuation and dampened the salinity fluctuations. This contribution examines the response of the inflow from the Mfolozi/Msunduzi catchment (Figure 1) to the highly depleted state of St Lucia during the severe drought conditions from 2002 to 2005 and then models the hydrological conditions for the Mfolozi/Msunduzi to provide inflow to the lake system during periods of mouth closure. Once the Mfolozi/Msunduzi system was separated from Lake St Lucia in 1952, the freshwater inflow to the Lakes became extremely variable, leading to large fluctuation in lake conditions.

The run of river flow into Lake St Lucia for the past 60 years is shown in Figure 2. Also included is the corresponding duration curve for the Mfolozi River monitored at W2H032 near Monzi. It is important to note that the Mfolozi flow at W2H032 is an underestimate of the high flow conditions because a proportion of the runoff is diverted to the Msunduzi when the flow exceeds a certain magnitude.

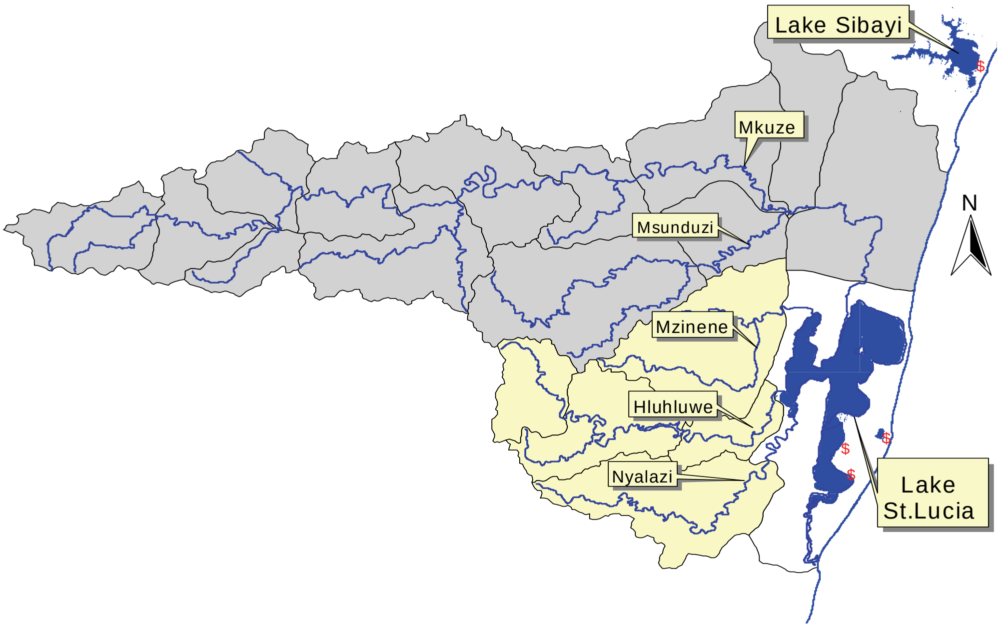

Figure 1. The main catchments supporting freshwater inflow to Lake St Lucia.

Two approaches are presented to examine the hydrological linkage between Mfolozi/Msunduzi and Lake St Lucia. The first approach examines the impact of overtopping of the Mfolozi/Msunduzi system during mouth closure when the St Lucia system was under extreme stress. The second examines the general conditions for routing flood water from the Mfolozi/Msunduzi into the St Lucia Estuary under low flow conditions.

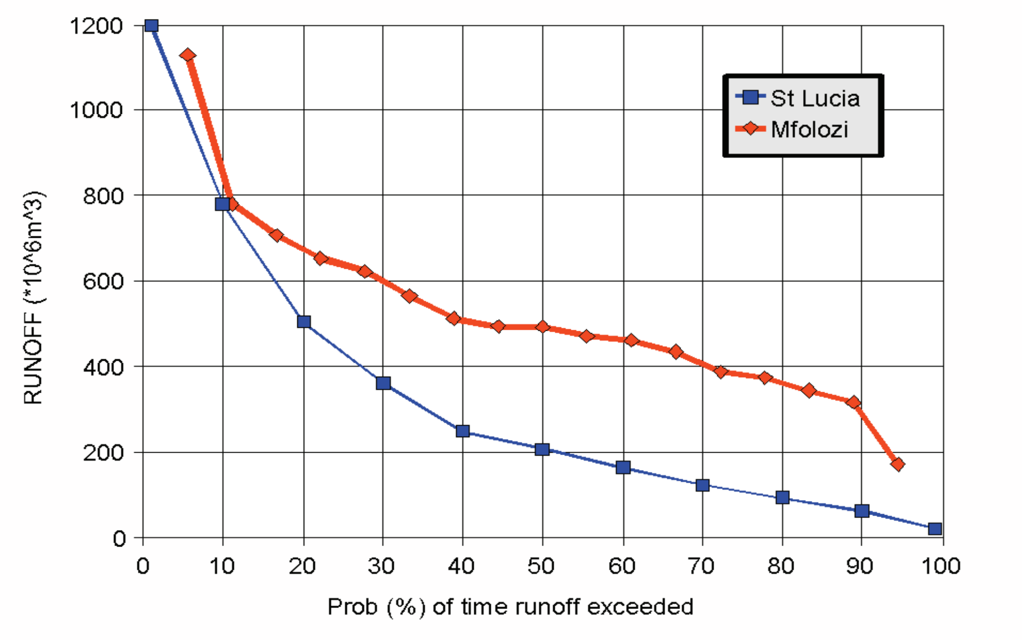

Figure 2. The probability of exceeding runoff in the Mfolozi River (gauge W2H032) and the combined St Lucia Rivers (data from Stassen, 2000).

Impact of pulses of freshwater into Lake St Lucia

Previous studies by Hutchinson & Midgley (1978) and Lawrie & Stretch (2008) have modeled the hydrological status of St Lucia during a period of compartmentalisation but have not included the pulses of Mfolozi/Msunduzi flow on the southern compartments. This study examines the potential impact of releasing freshwater from the Mfolozi into Lake St Lucia under extreme drought conditions when the lake had dried up to form isolated compartments. The computer model created a water balance for each compartment and then established the interchange in flow between the compartments during periods when they were linked. The model provides for the influx of water from the various sources and then diverts it to other sections when the linkages occur. Consequently, it can be used to simulate the effects of introducing freshwater from the Mfolozi into the lake systems under different conditions when the mouth is closed.

Hydrological features of the St Lucia System during the recent prolonged drought

When the mouth is closed and the drought has been ongoing for an extended period, the water level in St Lucia drops to the extent that the lake is divided into several discrete compartments (Figure 3). Under such conditions each compartment functions independently of the adjacent compartments and has its own hydrological characteristics. Figure 3 depicts the lake shoreline when the mouth is open (lake full) and the compartmentalised systems in January 2005 when the mouth was closed and the lake had shrunk to form several discrete compartments. Inflow from the Mfolozi would be expected to recharge the Narrows, which would overflow into Makakatana and ultimately into Catalina Bay and possibly further north. The intricacies of the linkage between compartments were established from the bathymetry and water balance of the system during the period from 2003 to 2005.

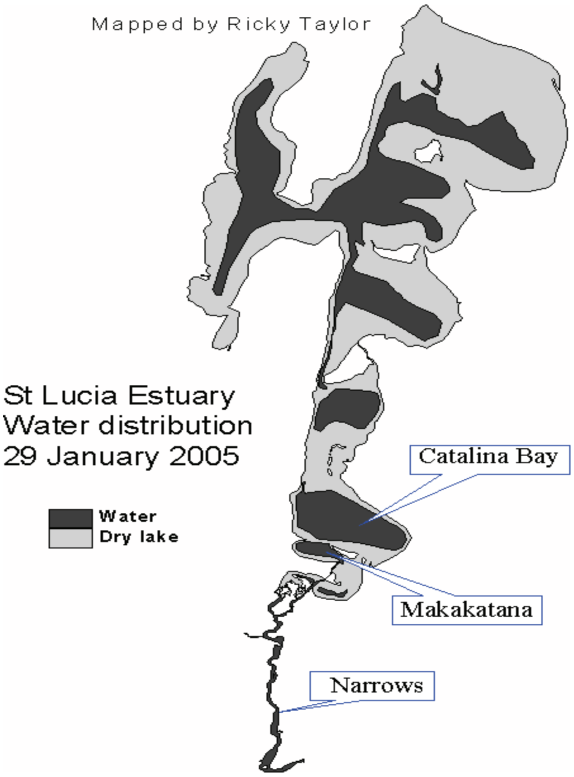

Figure 3. Map of St Lucia in January 2005 showing the basins (compartments) which still retained water.

The water balance concept is also applied to the salt balance in the model to estimate the variability in salinity during the mouth closure period when extreme hypersalinity occurred in certain compartments. If no salts are introduced into the system from the sea during mouth closure, then the salinity levels are controlled entirely by the fluctuations in water volume (level) in each compartment. Figure 4 illustrates, in a schematic way, the main hydrological features of each basin that describe the water balance. The freshwater inflow is derived from direct rainfall, river inflow, groundwater seepage, inflow from the other compartments when they are connected and the inflow from the Mfolozi should this occur. Freshwater losses when the mouth is closed are derived from the lake evaporation and outflows to adjacent compartments (should they be connected).

The water balance concept is also applied to the salt balance in the model to estimate the variability of the salinity during the mouth closure period when the salinity was found to reach unacceptable levels in certain compartments. If no salts are introduced into the system from the sea during mouth closure, then the salinity levels are controlled entirely by the fluctuations in water volume (level) in each compartment. Figure 4 illustrates the main hydrological features of each basin that describe the water balance. The freshwater inflow is derived from direct rainfall, river inflow, groundwater seepage, inflow from the other compartments when they are connected and the inflow from the Mfolozi should this occur. Freshwater losses when the mouth is closed are derived from the lake evaporation and outflow to adjacent compartments; should they be connected.

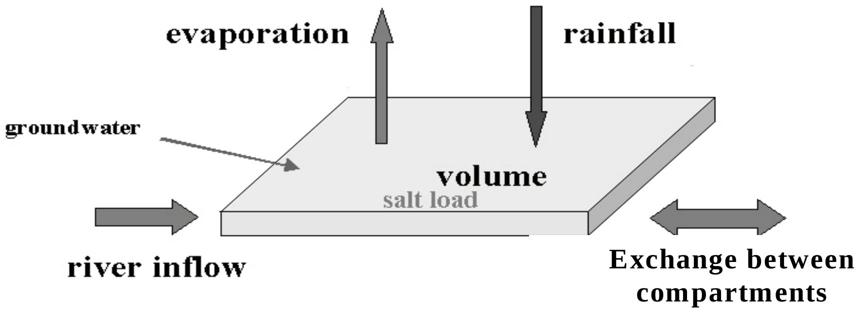

Figure 4. Schematic illustration of the hydrological balance of each compartment.

The compartments each have different dimensions. This means that each compartment has a different surface-area to water-depth (stage) relationship (Figure 5). In some compartments, a small change in depth means little change in surface area, while in others the effect can be considerable. This is important because the evaporation rate is affected by the surface area of each water body.

When the lake level drops the amount of salt trapped in the different compartments does not change after the compartments become isolated from their neighbours. However, as the volume changes, so the concentration of salts changes. The initial mass (concentration) of salt in the lake system when it becomes isolated will remain relatively constant when the mouth closes and only small quantities of salts (not considered to be significant) are introduced from relatively freshwater sources (rivers, groundwater and rainfall). Some quantities of salt are lost to the system when volumes of water flow out of the system but not through evaporation.

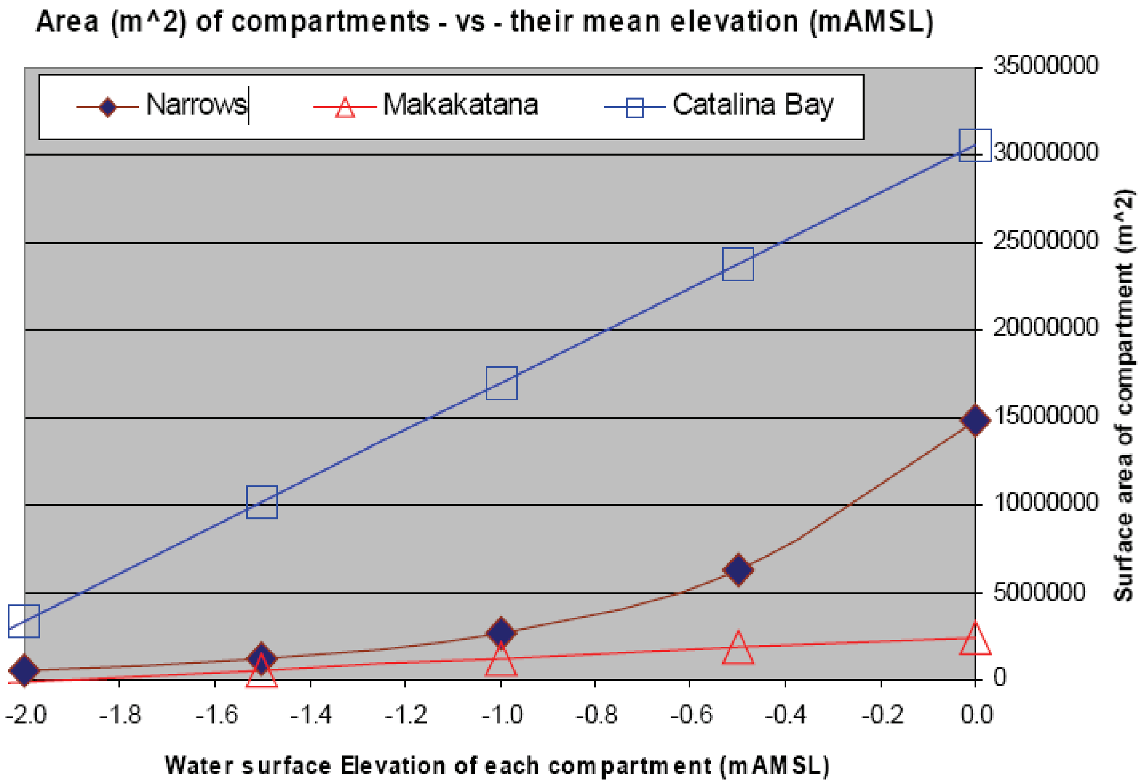

Figure 5. The relationship between the elevation of the lake compartment levels (mAMSL) and their evaporating surface area (m^2).

Knowing the mass of salt trapped in the system at the start of a drought is very important in understanding how the system will cope with subsequent drought periods. At low salinity (associated with relatively large volumes) a large evaporation loss has little influence on changes in salinity. However, at higher salinity (associated with small volumes), a small evaporative loss has a large effect on the salinity concentration. The rate of evaporation will also decrease with increasing salinity. Conversely, a small amount of water added to a small volume with high salinity can result in a large drop in salinity, and *vice versa*. It is important to remember that if the volume of water is halved, the salinity is doubled. For example, if the salinity is 4 PSU and the volume is halved, then salinity becomes 8 PSU. These relatively low concentrations (<10 PSU) affect few of the estuarine species. However, if the salinity starts at 40 PSU and then increases to 80 PSU from a halving of the volume, the change can have a profound effect on much of the biota.

Since the changes in salinity concentration are directly proportional to the change in lake volume, a water balance model was developed to evaluate the compartmentalisation of the lake and the changes in lake level. The water balance model derives estimates of the water gained and lost from each of the southern compartments of Lake St Lucia during a drought period when the mouth is closed (no inflow/outflow of marine water with its attendant salt loads) and drought conditions lead to the cessation of river inflow from the north. The model calculates the water balance for each of the southern compartments and, based on the dimensions of that compartment, was able to simulate changes in water level and salinity.

The model is driven by inflow and outflow that regulate the volume and water level. When the level drops below a certain elevation (parameter), the lake becomes compartmentalised.

Conversely, the compartments join together when the overflow from one compartment is able to fill both compartments.

In addition to the understanding of how each compartment behaves, we needed to know the water level at which the compartments link to each other. When this happens, water spills over from the compartment with the higher water level into that with the lower water level. This adds water to the receiving compartment until both compartments have the same water level, after which they can be considered as a single compartment.

Mass balance model of the system

The model simulates the change in the water balance for three compartments that become isolated under severe drought conditions (The Narrows, Makakatana and Catalina Bay). Separating each compartment is a sand ridge that acts as a spillway (Figure 6). When the water volume (level) in the Narrows exceeds a specified value, it overflows into Makakatana and the volumes are partitioned according to the combined volumes. When their combined levels exceed a specified volume, they are combined in a similar manner with Catalina Bay. When the combined volumes of all three compartments exceed a specified value, it is assumed that the whole of the system has been recharged and the combined volume is partitioned between the three compartments with no outflow to the north. Consequently, the model is limited to simulating the water level and salinity changes in the southern part of St Lucia when the mouth is closed and when lake levels are so low that there is minimal or no connection northwards from Catalina Bay.

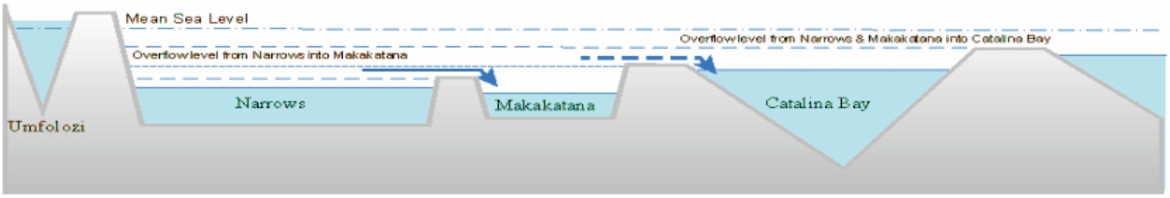

Figure 6. Schematic illustration of the model.

As water flows into the Narrows from the Mfolozi Link Canal, it will first spill over into Makakatana. The water level will then rise in both compartments until it spills over into the Catalina Bay. For the canal to be ecologically effective there is no need for the water level to be raised to that of the combined Narrows/Makakatana basin; all that is required is for the salinity to be diluted enough to remain below about 70 PSU.

The first step in the model development was to describe the relationship between water level and surface area, and water level and volume for each basin. This was based on existing bathymetry surveys. Then for each compartment the daily water balance was computed based on measured rainfall, average monthly evaporation figures from the exposed surface area, simulated groundwater inputs, measured inflows from the Mpate River and simulated inflows from the Nkazana Stream. This model was designed to run on a daily time-step for the period from January 2002 (the mouth closed in June 2002) to March 2005.

The simulated water levels and salinity were then compared to measured salinity and water levels. Only when reasonable correlations were obtained, was the model used to simulate the effects of different quantities of water being injected into the system from the Mfolozi.

The simulated salinity series for various transfer rates of water from the Mfolozi to the Narrows for the period from January 2002 to May 2005 are shown in Figure 7. The model indicated that a daily transfer of 10 000 m^3 of water from the Mfolozi into the Narrows would have prevented the high build-up of salt in Catalina Bay that was experienced in both January 2004 and in January 2005. These simulations (Table 1) show how peak salinity (in January 2003) would have been reduced by the addition of fresh water.

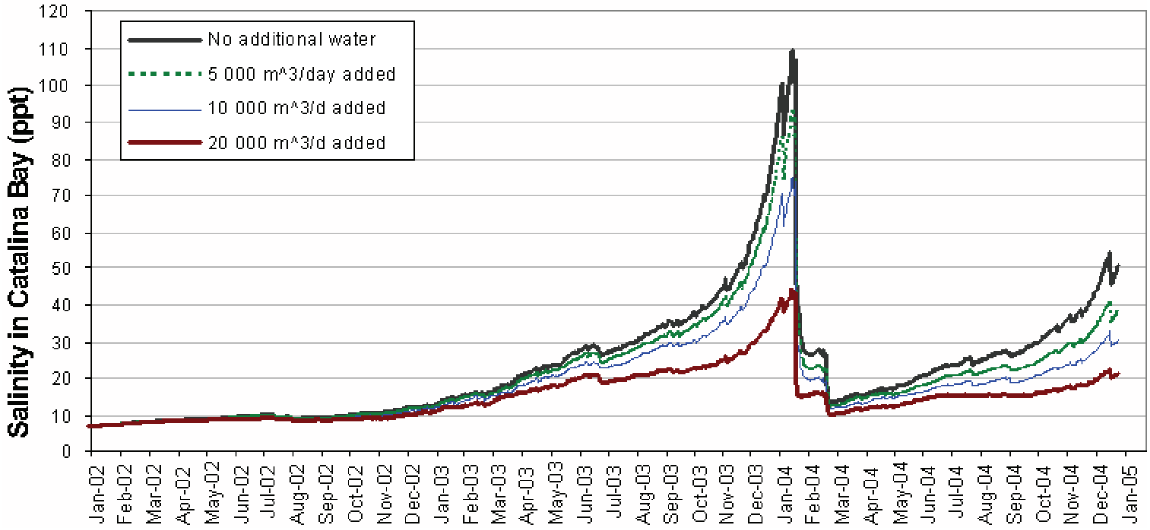

Figure 7. Simulations for the period January 2002 to December 2004 showing salinity levels without the addition of any water from the Mfolozi Link Canal, and additions of 5000, 10 000 and 20 000 m^3 day^{-1}.

Water added from the Mfolozi (m^3 day^{-1}) since January 2002	*Simulated peak salinity in January 2004*
0	**110**
5 000	**93**
10 000	**74**
20 000	**44**

Table 1. Simulated peak salinity levels for different transfer rates of water from the Mfolozi to the Narrows for January 2004.

Impact assessment of the overtopping

Figure 2 shows the frequency of different daily flow rates in the Mfolozi River compared to the combined inflow to St Lucia from all the rivers. These data were provided by DWAF who have a measuring station about 5 km downstream of Monzi and below where water is abstracted for irrigation, but above the point where water is abstracted by Richards Bay Minerals (RBM). The RBM abstractions are unlikely to have much influence, as they have a permit to abstract water only when flows are above 5 m^3 s^{-1}. However, large flood events (above 800 $m^3 s^{-1}$) are partially diverted to the Msunduzi channel via an off-take weir in the upper reaches of the flood plain. Consequently, the DWAF data for large floods is an underestimate. Since the flow regime associated with overflow to Lake St Lucia specifically excludes these large events it is unlikely to impact on this study.

There is a correlation between flow rates and sediment loads in the Mfolozi (Grenfell and Ellery, 2009); the greater the flow, the greater the quantity of sediment per unit volume of water. Most of this sediment is in the silt fraction and is carried as suspended load. As it is silt, not clay, the sediment does settle rapidly when there is no water movement. This is an important feature, as the size of the settling basin does not have to be excessively large. For management purposes it still has to be determined what sediment loads become unacceptably high for transfer to the lake.

Model Summary

The model can still be refined, but at this stage the simulated levels and salinity values during the three-year severe drought are adequate for the evaluation of the impact of inflow from the Mfolozi. One of the weaknesses comes from not having certain monitoring and survey data, e.g. the bathymetry used for Catalina Bay is from a survey done in the early 1970s and we do not know if there have been changes in the lake morphology since then. What is particularly important for the model is the height of the spillways between each of the compartments. These levels were inferred from field observations at various lake levels and through the model calibrations. Another problem was the failure in the DWAF water level recorder at Charters Creek (Catalina Bay compartment) during part of the drought period when its sensor was exposed by low lake levels.

The groundwater seepage rates were derived from coarse simulations studies for lake full conditions. These rates need to be reassessed under low lake conditions. The evaporation rates are based on seasonal values that have been adjusted during calibrations for each compartment where it is assumed that the rates for the Narrows are relatively lower than the corresponding rates for Makakatana and Catalina Bay.

The results of the model simulations indicate that the minimum daily flow in the Mfolozi River during the severe years of 2002 to 2005 would have been more than adequate to have had a significant impact on the salinity conditions of Catalina Bay in Lake St Lucia during this period. This leads to the second part of this contribution, namely to examine the hydrological conditions for returning the low flows directly into the lake.

DIVERTING MFOLOZI FLOW INTO ST LUCIA DURING MOUTH CLOSURE

The area of concern for this study is shown in Figure 8. When the combined Mfolozi/Msunduzi mouth closes, which often happens naturally during the low flow period in autumn/winter, the river runoff from both catchments is stored in the lower sections of the flood plain. As the storage increases in this area, the level of water rises and overflows through a channel into Lake St Lucia (Whitfield & Taylor, 2009). A photograph of the main outlet to the system under these conditions is shown in Figure 9.

This was the case in 2008 and again in April/May 2010. During the first period an estimated 17 x 10^6 m^3 of water were transferred into St Lucia and in the second instance 8 x 10^6 m^3. As the water had dropped its sediment load in the virtually static backed up water, it was sediment-free. Because it is likely that any future long-term solution for managing Lake St Lucia will involve the linking of the lower portion of the Mfolozi/Msunduzi swamp to the St Lucia estuary, this section investigated an approach for routing Mfolozi/Msunduzi flood water into Lake St Lucia during periods of mouth closure.

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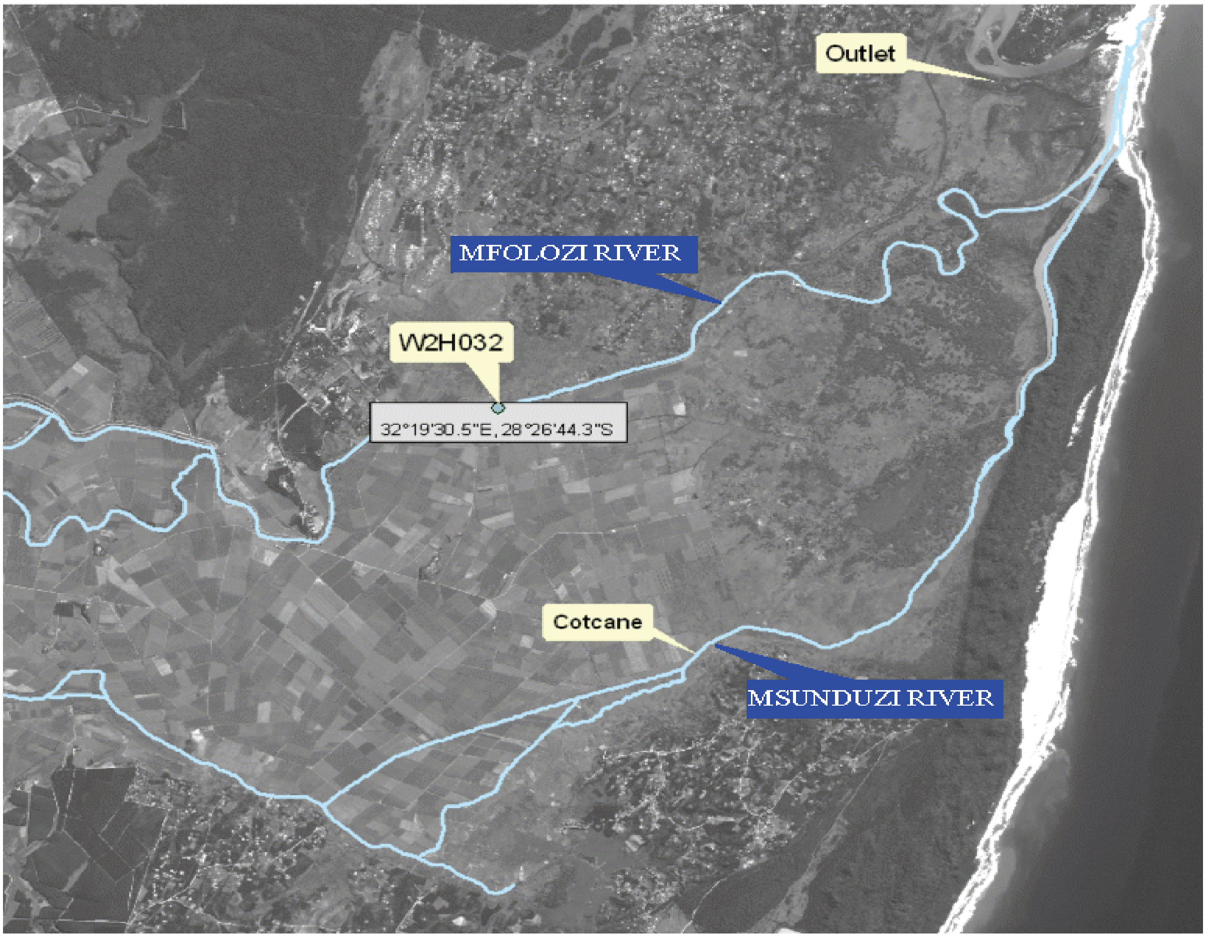

Figure 8. The area of concern for re-routing the low flow runoff from the Mfolozi/Msunduzi rivers into the St Lucia Estuary via the various outlets along the estuary banks.

METHODS

Treating the storage compartment of the swamp area as a reservoir with numerous terrestrial outcrops (islands under flood conditions) allows the application of simple reservoir routing methods for directing the inflow from the combined Mfolozi/Msunduzi river through the swamp and out via the overflow channel when the mouth is closed. This method is critically reliant on the following basic assumptions that need to be verified:

1. The rising flood waters in the swamp area maintain a horizontal surface that can be measured at a convenient position.
2. The storage within the river channels below mean sea level is insignificant if these channels are always at full capacity when the mouth closes and storage begins.
3. The groundwater seepage is negligible.

4. The exposed water surface evaporates at the potential rate.
5. The combined inflow from the Mfolozi and Msunduzi under low flow conditions is known.
6. The outflow configuration can be determined for the stage of the rising water in the swamp.

Figure 9. Surface flow from the Mangrove swamp into the St Lucia Estuary from the Mfolozi/Msunduzi storage zone when the mouth is closed.

Under these assumptions, the flow into the swamp storage area minus the outflow into Lake St Lucia will equate to the change in storage. If the inflow is measured what remains is to determine the change in storage and rate of outflow in relation to the change in stage of the storage zone. Both the storage and outflow will increase (or decrease) as the stage (h) rises (or falls).

Inflow measurements

At this stage of the study it is assumed that the inflow during the period of concern (low flow with mouth closed) can be determined from measurements and models. The inflow hydrograph for the Mfolozi is measured by DWAF at weir W2H032 and is illustrated for the period from 2000 to 2010 in Figure 10. The contribution from the Msunduzi catchment is not monitored and still needs to be simulated using appropriate models. The Msunduzi catchment area is several orders of magnitude smaller than the Mfolozi catchment and has been ignored in this preliminary model.

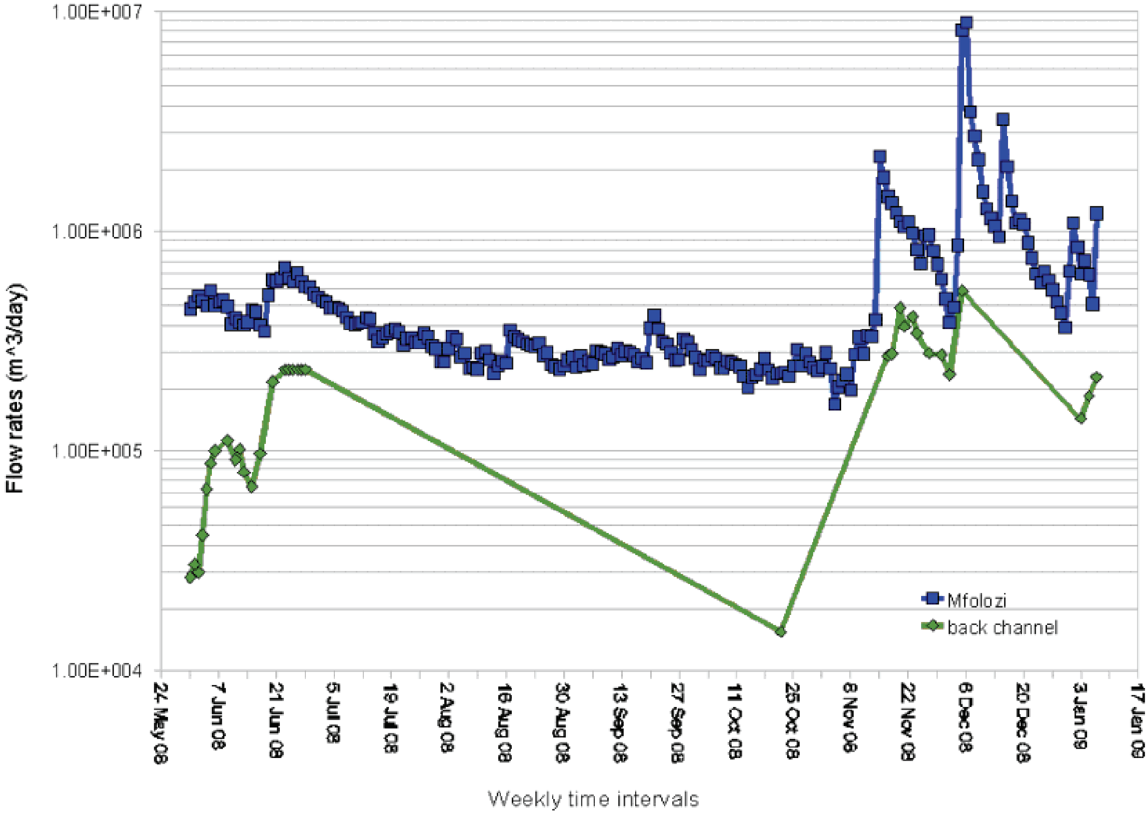

Figure 10. River discharge measurements (blue) for 2000-2010 at W2H032 gauging weir on the Mfolozi canal (data from DWAF) and the back channel discharge (green).

Outflow measurements

Outflow from the swamp area into Lake St Lucia occurs through the Back Channel, which is a canal that was dredged in the 1960s and subsequently closed off, but now opened to allow constricted flow. *Ad hoc* measurements were collected of the discharge rate through this Back Channel at the location shown in Figure 11. These measurements, which represent the only data for the discharge from the swamp, are shown in comparison to the flow in the Mfolozi in Figure 10. While the flow rates in the Back Channel are significantly lower than in the Mfolozi, it is important to note that the peak flow measured in November 2008 was considerably higher than the winter flow between July and November of the same year.

On occasions, overtopping into the Link Canal has occurred during flood conditions in the canalised part of the lower Mfolozi River. Under these conditions the canal is so full that it spills over into the Link Canal. These are conditions when the assumption that the water level is horizontal does not apply and there need not be simultaneous flooding in the downstream area, especially when the Mfolozi mouth is open. Because these conditions do not conform to the assumption of pool routing (horizontal flood surface), they are not considered in this study.

Figure 11. Outflow from the swamp area into the St Lucia Estuary where discharge measurements were conducted.

The level of the backed-up water in the swamp has not been high enough while the mouth has been closed for water to rise to the level that it can overtop the levee into the Link Canal. This requires a much higher beach berm than has been present in recent decades. It is likely that prior to this water level being attained, there would be sheet-flow over the wetlands north of the Mfolozi into St Lucia. However, future modification of the berm section between the Mfolozi and the Link Canal could allow flow into the canal under specified conditions.

Stage measurements of the swamp

If the bathymetry of the storage area (swamp) is known, then an estimate of the storage volume in the swamp at any particular stage could be determined. The rate of discharge from the swamp through the back channels is a function of stage that could be derived though suitable calibration against measured discharge rates.

Measurements of the water level have been taken on a regular basis by the sugar industry at Cotcane on the Msunduzi River. The measurements from 2007 to the present have been provided by Gerrit de Jager (UCOSP). Unfortunately instrument error and failures have left patches of missing data (Figure 12). The instrument was replaced in January 2010 and recalibrated. The earlier data had not been calibrated and showed a distinct increase in stage up to the time the sensor failed. Consequently, the periods when the mouth was open and the measurements indicated a tidal range was used to adjust the values to match the tidal range in 2010. The final adjusted data are shown in Figure 12 superimposed on the Durban tidal range.

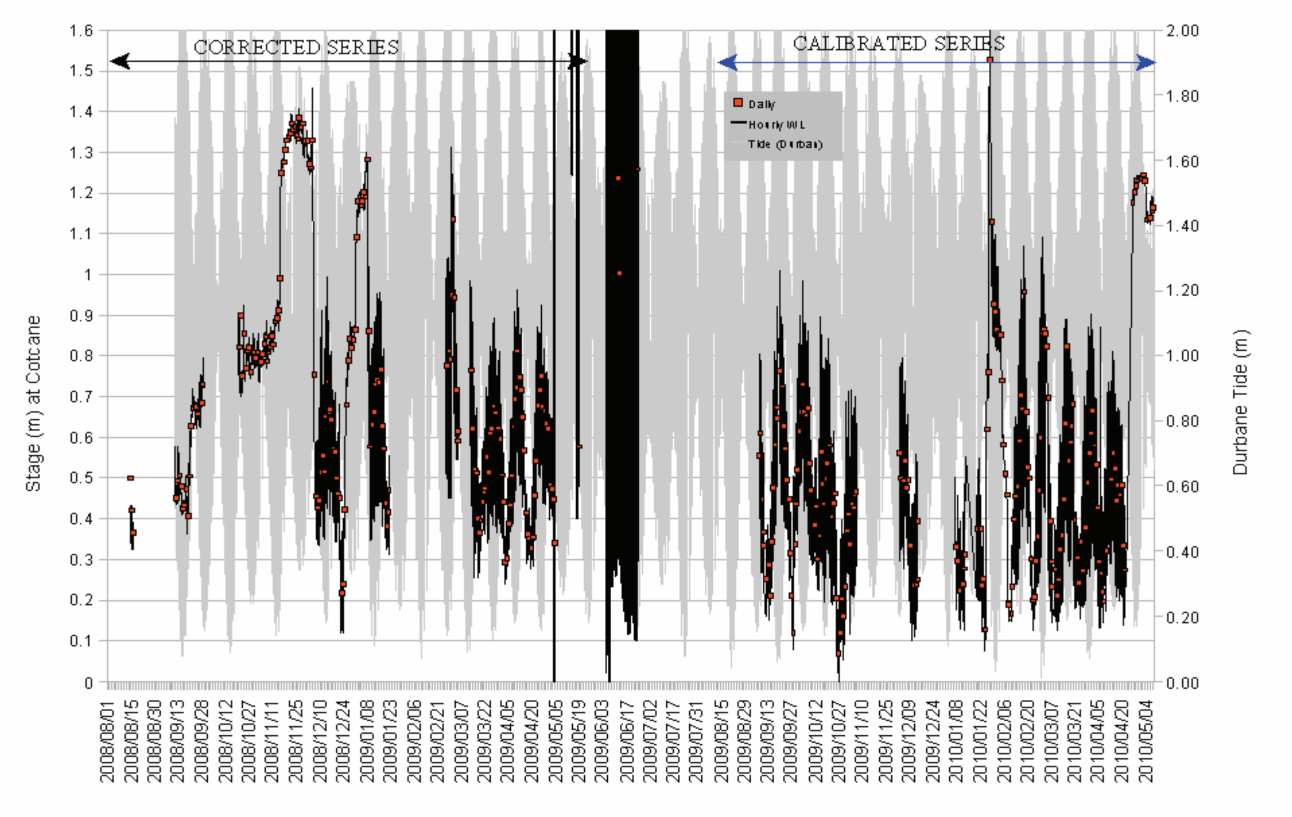

Figure 12. Stage measurements at Cotcane gauge on the Msundusi River. Background shows the Durban tidal range for the same period. Data from Gerrit de Jager (UCOSP).

The relationship between the water level elevation in the storage zone (swamp) as measured by UCOSP at Cotcane and the outflow measurements from the swamp into the St Lucia Estuary via the back channel is shown in Figure 13. This relationship gives the rate of discharge out of the storage zone of the swamp in relation to the water level in the swamp.

Swamp storage

It is still necessary to derive a suitably accurate bathymetry of the swamp in the form of a Digital Elevation Model (DEM) to establish the rate and volume of river storage during the period of mouth closure in response to varying inflow rates. The topographic surface profile defines the base elevation of the storage zone in the swamp area. All available elevation data have been examined to derive the best estimate of the DEM in the area of interest. Several sources of data with varying levels of accuracy were examined, namely;

The 5 m and 20 m elevation contour data from the National Department of Survey and Mapping in the Department of the Interior. The available contours supplied freely by this organization for the study area are shown in Figure 14. Unfortunately, this data set is not adequate for the creation of the DEM at the required vertical resolution for this study.

The raster elevation data from the Shuttle Radar Topography Mission (STRM) flown by NASA and available freely online at a spatial resolution of 90 x 90 m. These data were derived from a 10 orbit mission to map the elevation of the earth using 5.6 cm (C Band) radar that was validated against GPS reading measured along roads across all continents.

While the estimated vertical resolution of the SRTM data is better than 6 m, the surface features that are measured do not always coincide with the terrestrial surface. Carabajal & Harding (2006) describe the radar derived effective height as the height determined by the phase of the complex vector sum of all returned signals. For areas with little vegetation, the radar return gives the height of the terrestrial surface. However, with extensive vegetation, the radar return is a function of the vegetation height, structure and density. However, the C-Band radar can penetrate significantly into the vegetation canopy making it difficult to extract vegetation height to derive terrestrial heights (Carabajal & Harding, 2006). The SRTM for the study area is shown in Figure 15.

The satellite imagery utilised and disseminated through Google Earth provides point source data for the location (latitude and longitude together with the elevation) (Figure 16). However, unlike the 90 x 90 m spatial resolution of the SRTM images, this finer spatial resolution with satellite imagery enables more precise selection of points in relation to vegetation and water features, thereby reducing the error associated with deep vegetation.

High resolution data can be derived using Light Detection and Ranging (LiDAR) technology with a vertical resolution of better than 24 cm under pine land cover (Hodgson *et al*., 2005). This method uses optical remote sensing technology to measure the properties of scattered light to find the range of a distant object. The wavelength of the source varies between applications from 500 nm (visible) to over 1500 nm depending on the application. Modern LiDAR offers great accuracy and an increased ability to avoid the vegetation issue and produce a bare earth DEM (Rubinstein *et al*., 2003). Systematic random errors can be removed through block correction using points of known elevation (Bowen & Waltermire, 2002).

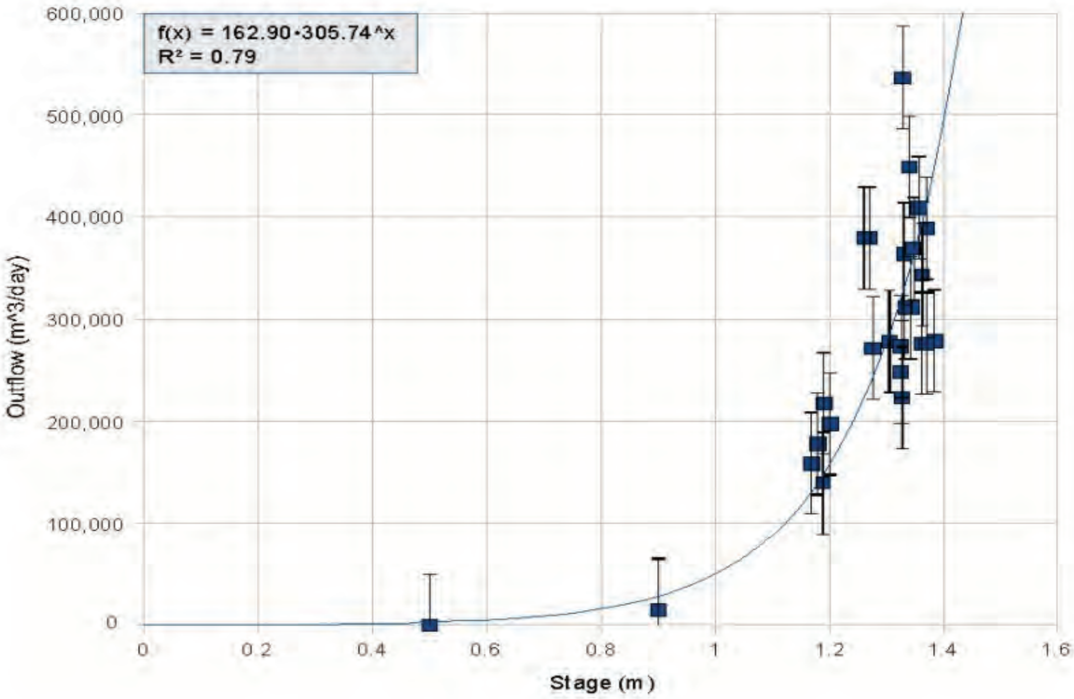

Figure 13. Plot of the Cotcane stage measurements against the corresponding outflow measurements from the back channel.

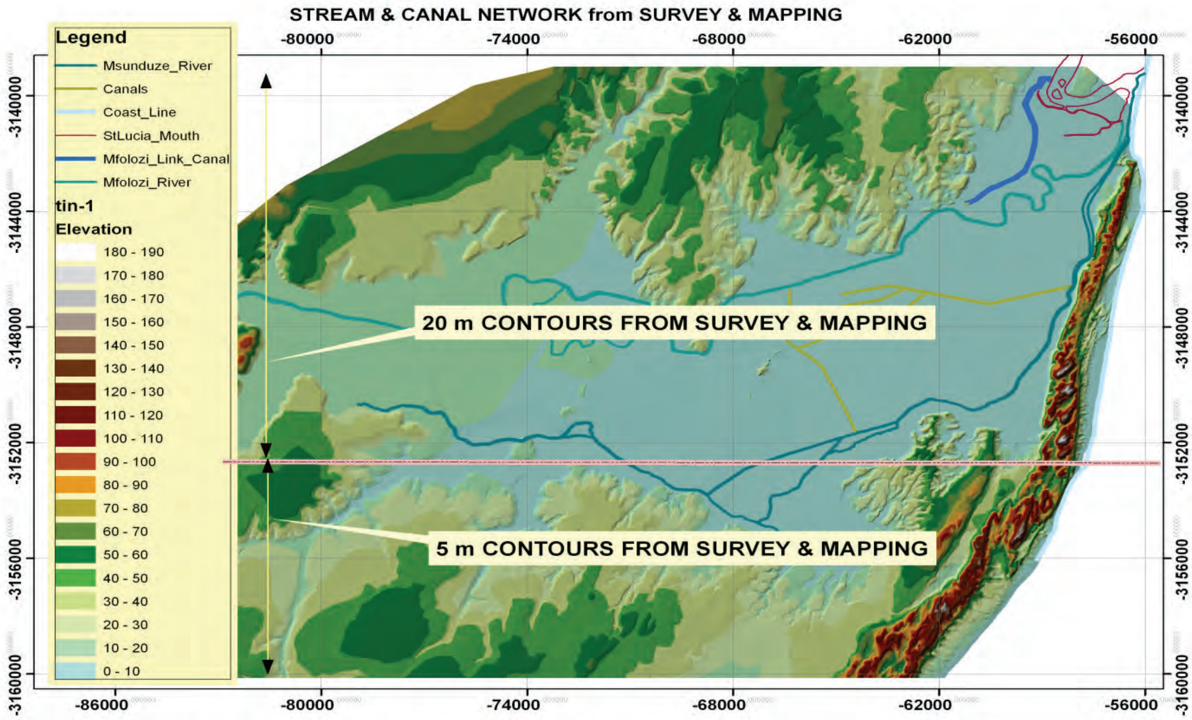

Figure 14. The DEM derived from elevation contours distributed by National Department of Survey and Mapping, Mowbray, Cape Town.

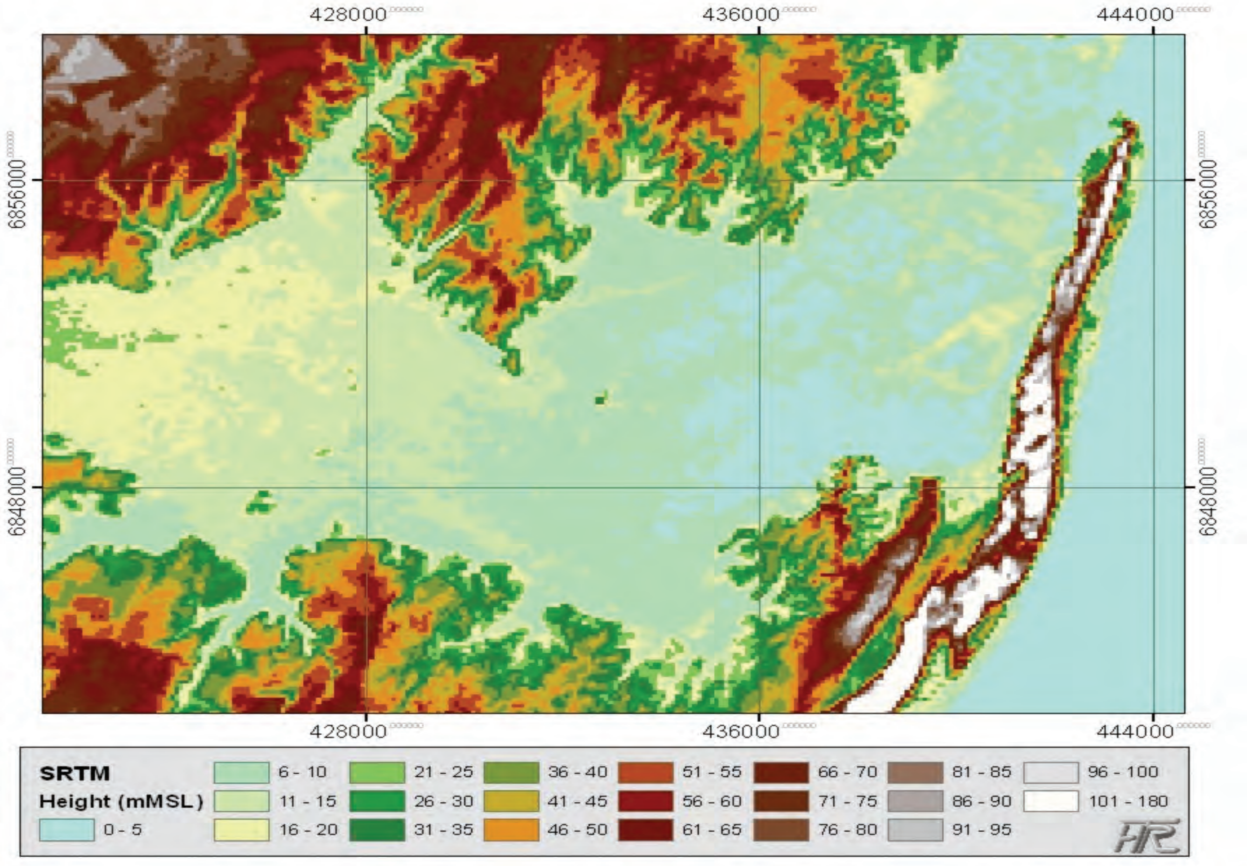

Figure 15. The SRTM DEM of the Mfolozi study area supplied by NASA.

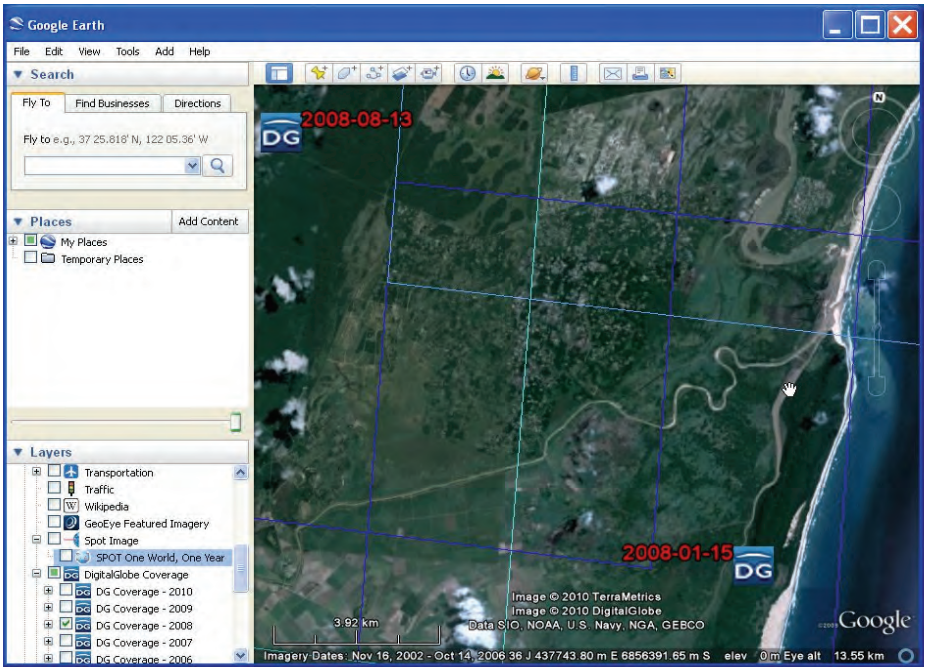

Figure 16. Example of the satellite image frames by Digital Globe for the study area and the information available from Google Earth utilised in this study.

The modern LiDAR methods use multiple returns from the same propagating laser pulse. In this configuration, a fraction of the pulse will return from the vegetation canopy, a fraction from within the canopy and the rest from the ground below. By taking the last returns from a pulse, the elevation can be reasonably assumed to represent the point ground elevation (Harding, 2000). LiDAR data donated to this study by Richards Bay Minerals (RBM) covers a section along the southern high dunes and part of the flood plain (Figure 17). The available data are insufficient to derive the desired DEM but would supplement the selected data format and enable the evaluation of the accuracy of the resultant DEM.

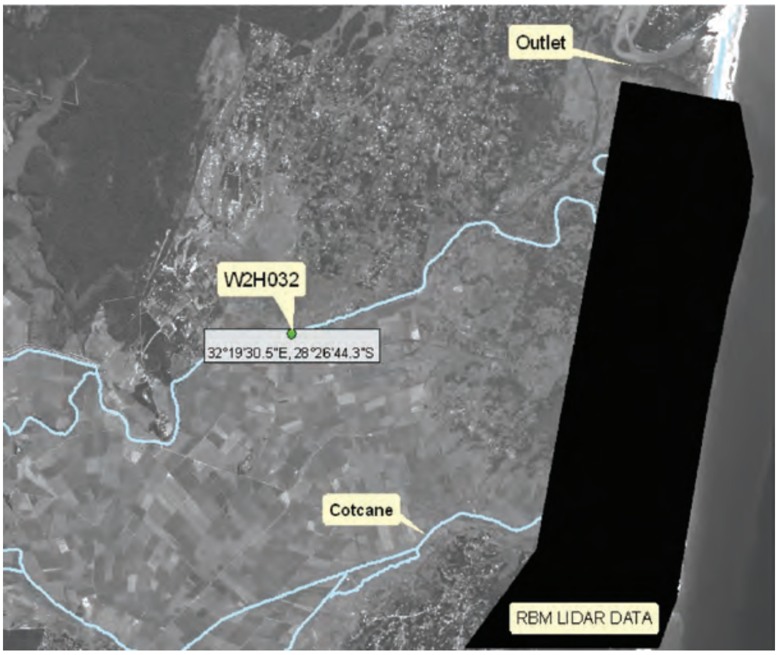

Figure 17. The data points for available LiDAR coverage of the study area donated by RBM.

Terrain model accuracy

The STRM data for the study area was compared directly to the LiDAR data by rasterizing the LiDAR data to the same spatial resolution as the STRM image and then subtracting the elevation values for each pixel (Figure 18). The resultant image showed residual errors exceeding 20 m. The image also indicated a spatial bias that suggests the need to align the original images. The positive errors occurred along the western section of the high Mapalane dune ridge while all the large negative errors occurred along the eastern slopes. The cause of this discrepancy is unknown so the decision was taken to translate (transpose) the LiDAR image by 90 m to the west. The resultant difference is shown in Figure 19 where the differences are generally within -10 m and +20 m. The cause of the large positive errors in the translated image is considered to be due to the lack of penetration into the vegetation by the Radar data in the STRM image.

The relationship between the vegetation and elevation error are illustrated in Figure 20. The areas with little vegetation or short vegetation correspond closely with the residual errors in the range -2 m to +2 m. All the areas with the taller vegetation indicate a residual error exceeding 10 m.

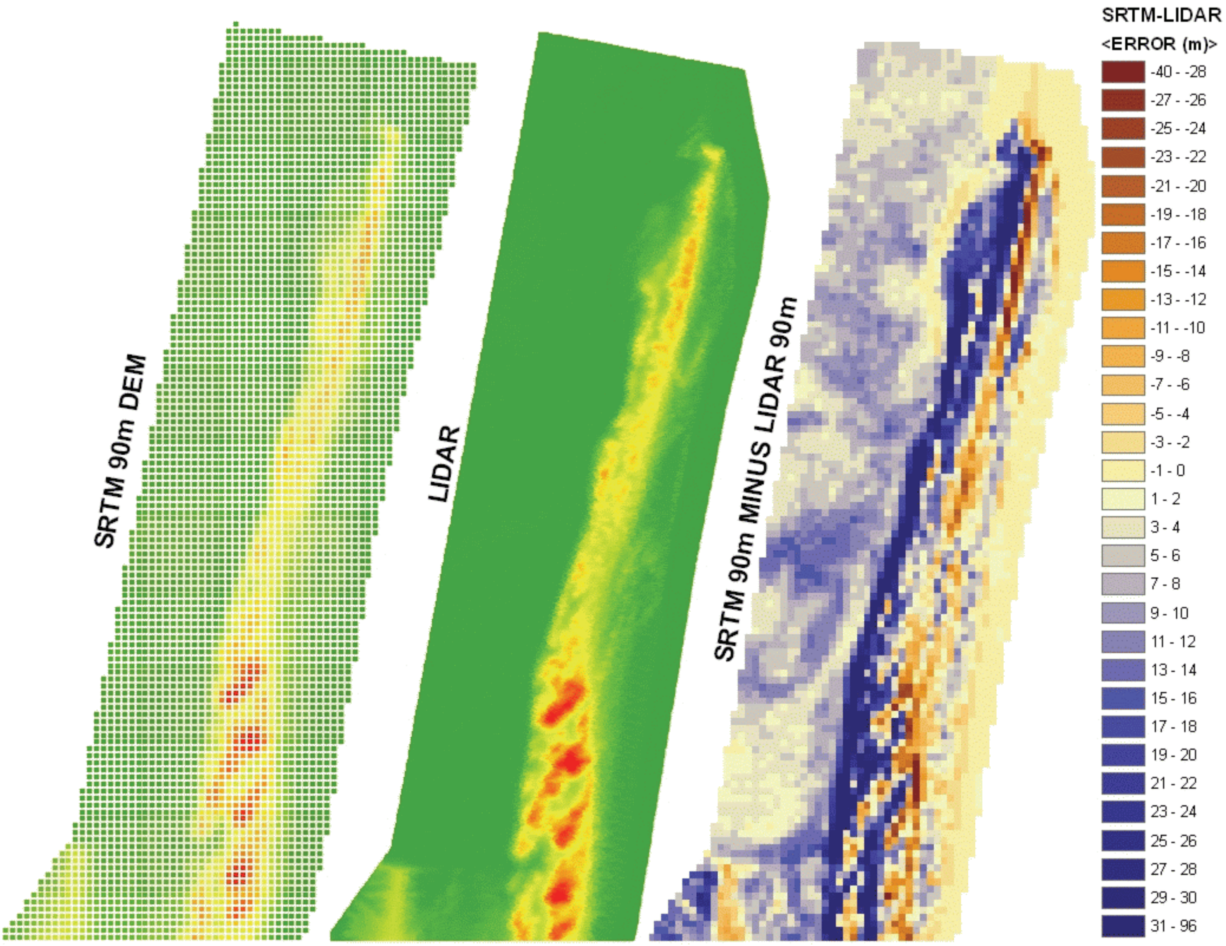

Figure 18. The relationship between the SRTM 90m data and the LiDAR coverage

Satellite data points from Google Earth

The ability to extract individual (x,y,z) points along the edge of topographic features using Google Earth was used by Magagula (2009) to create a DEM. The digitisation of an initial grid of the Mfolozi/Msunduzi flood plain was followed by digitisation of specific features such as river banks, canals and infill of important wetland zones. Rivers and canals were subsequently digitized as linear features (lines and polygons) for the creation of a Triangular Irregular Network (TIN) of the study area. The digitised points are shown in Figure 21 in relation to the LiDAR data for all the coverage below the 20 m contour.

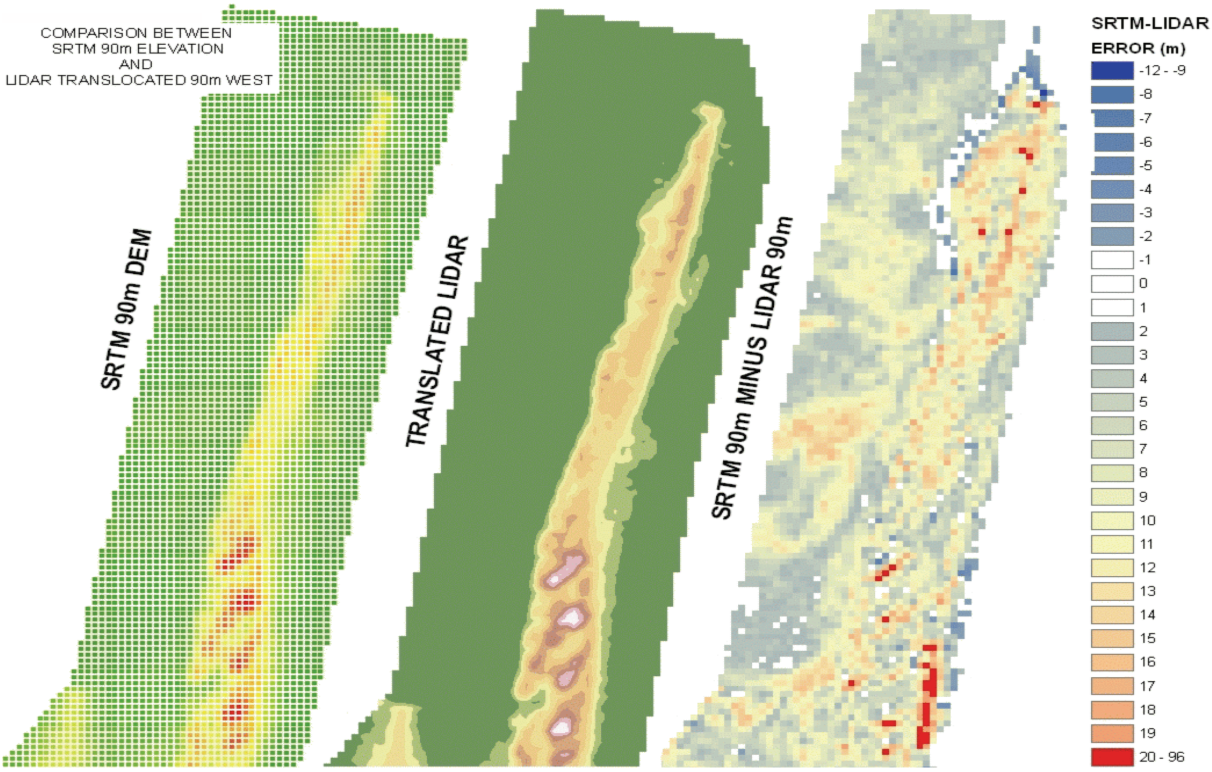

Figure 19. A comparison between SRTM and LiDAR after rectification.

While the satellite imagery in Google Earth has similar constraints and errors in the vertical measurements of the bare earth elevation, it provides a distinct advantage through the selection of specific features at a higher spatial resolution. This enables the selection of specific features such as river banks, wetland margins, bare earth and other features that are more closely aligned to the topographical surface and not the vegetation. The elevation of the points digitised by Magagula (2009) from Google Earth were compared with the interpolated values in SRTM raster and shown in Figure 22. There is a large scatter in the SRTM values due to either the linear interpolation between surrounding grid dells or the specified values for the specific features.

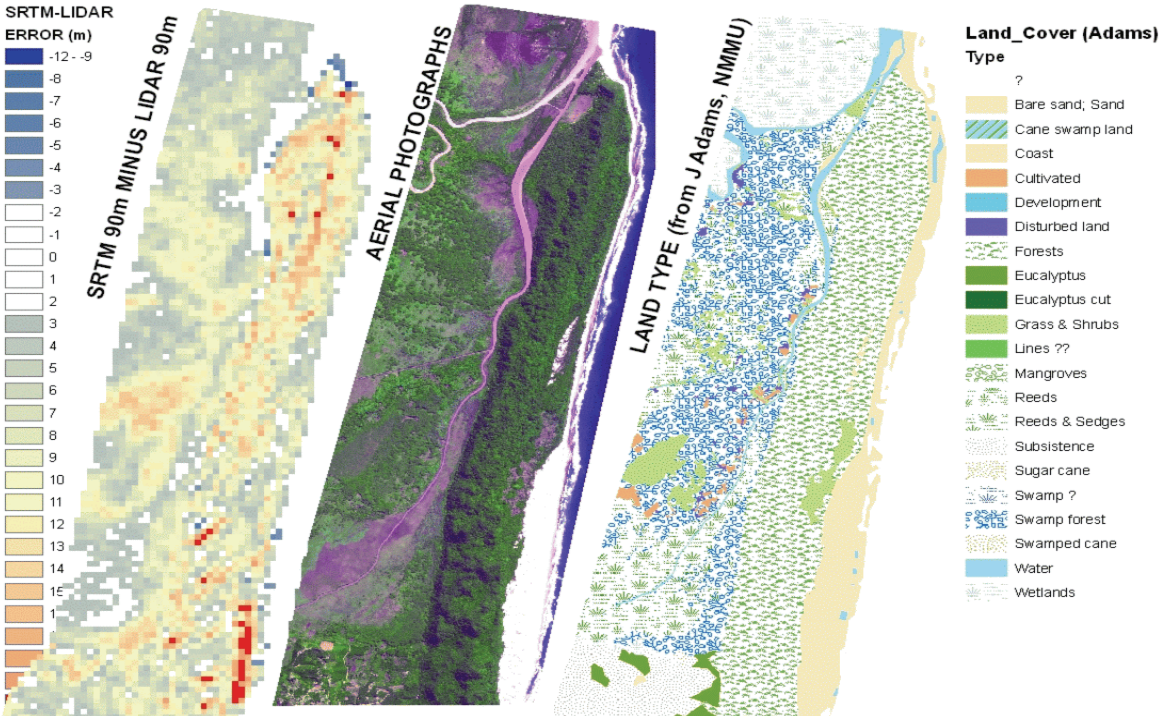

Figure 20. The SRTM error in relation to the vegetation types.

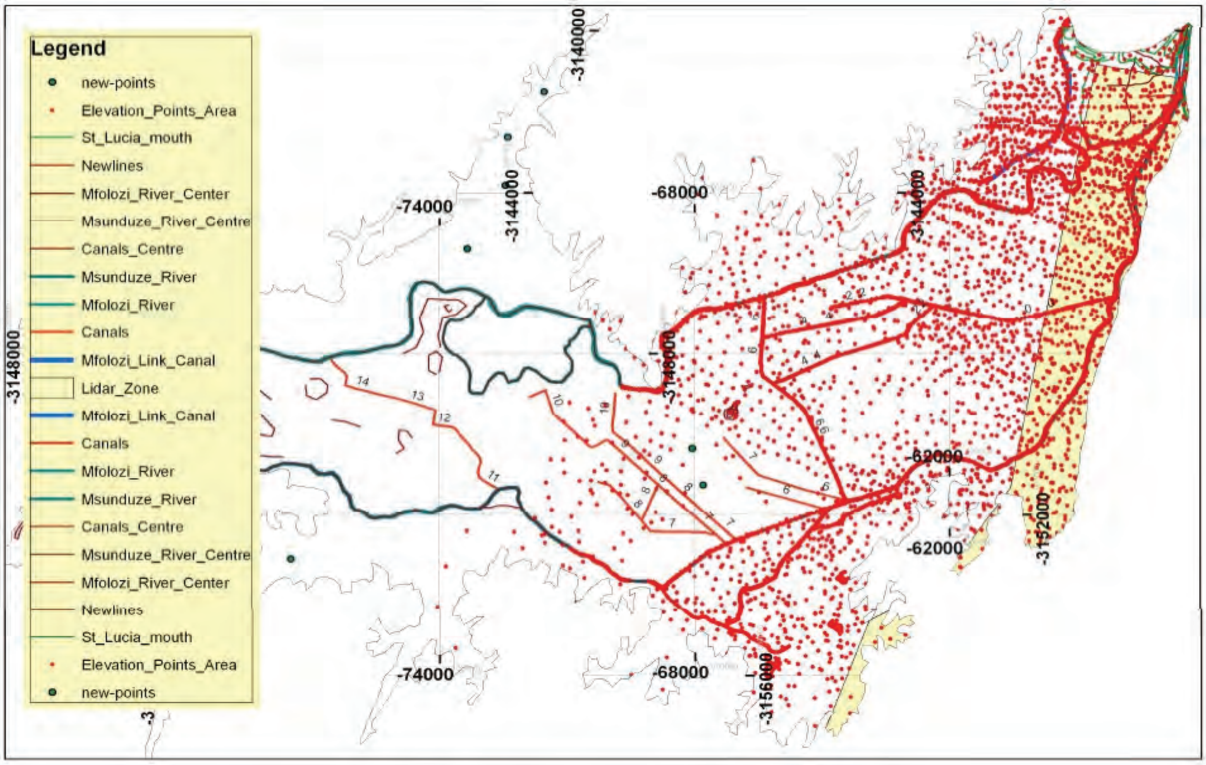

Figure 21. The (x,y,z) points digitised from Digital Globe satellite images in Google Earth by Magagula (2009).

The error associated with the digitised satellite points from Google Earth were also compared to the corresponding LiDAR point and shown in Figure 23. There were few LiDAR values greater than the digitised points. However, there were some large errors in the digitised points in some areas.

These errors indicate the limitation of the different data sets for creating a suitable DEM for the determination of the Stage-Storage Relationship. Nevertheless, a relationship was derived from the best estimate of the topographic profile and used in this initial model development. The best estimate of the DEM was derived by starting with the full coverage of the SRTM image, superimposing the digitised values from the Google Image and then superimposing the LiDAR coverage to give the final DEM shown in Figure 24.

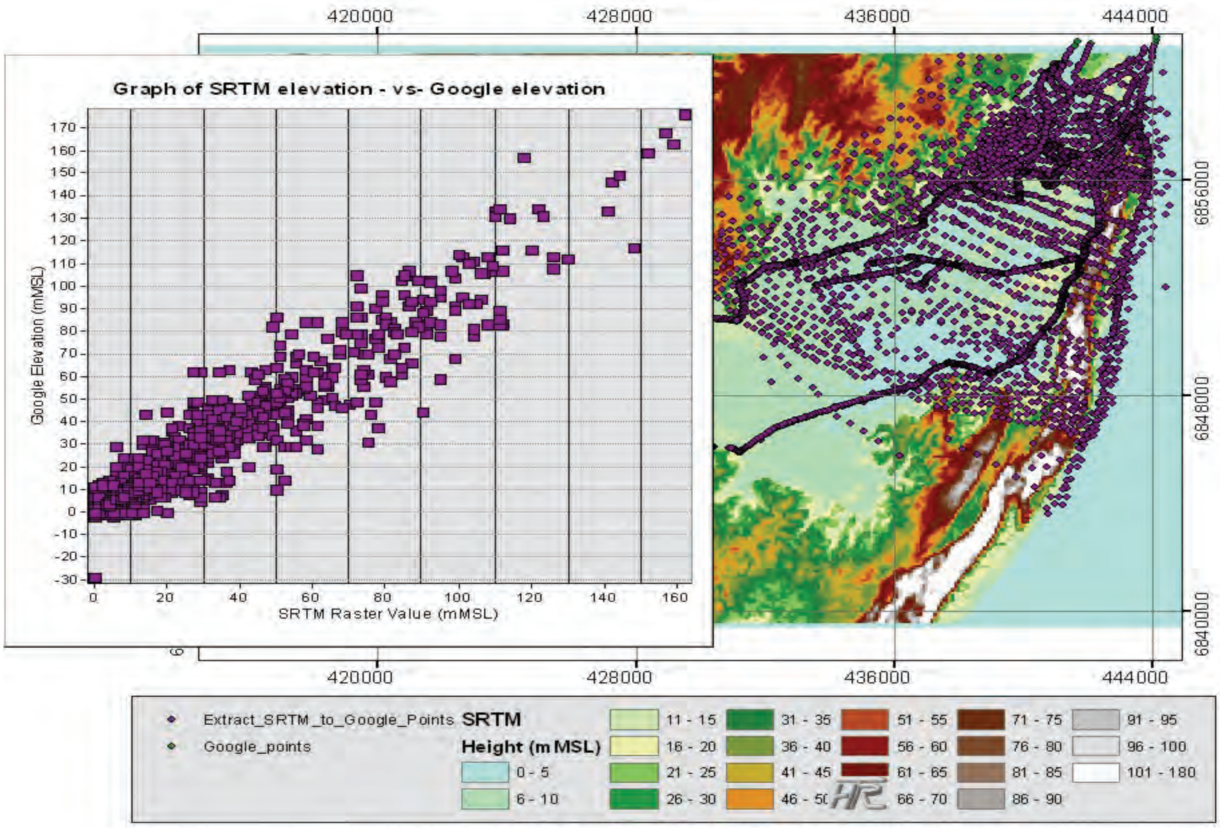

Figure 22. The location and scatter plot of the comparative points used to evaluate the errors in the Digitised points.

Stage storage relationships

The change in storage and surface area with an increase in stage (mMSL) was derived from the final version of the DEM described above. The derived relationship for the best estimate of the storage volume (Vol[LiDAR]) is shown in Figure 25. The best fit power equation up to a stage of 4 mMSL (Figure 25) is given by:

$Volume=76{,}000{,}000\mathbf{h}^{1.14}$ *(where* $\mathbf{h}$ *is the stage in mMSL)*

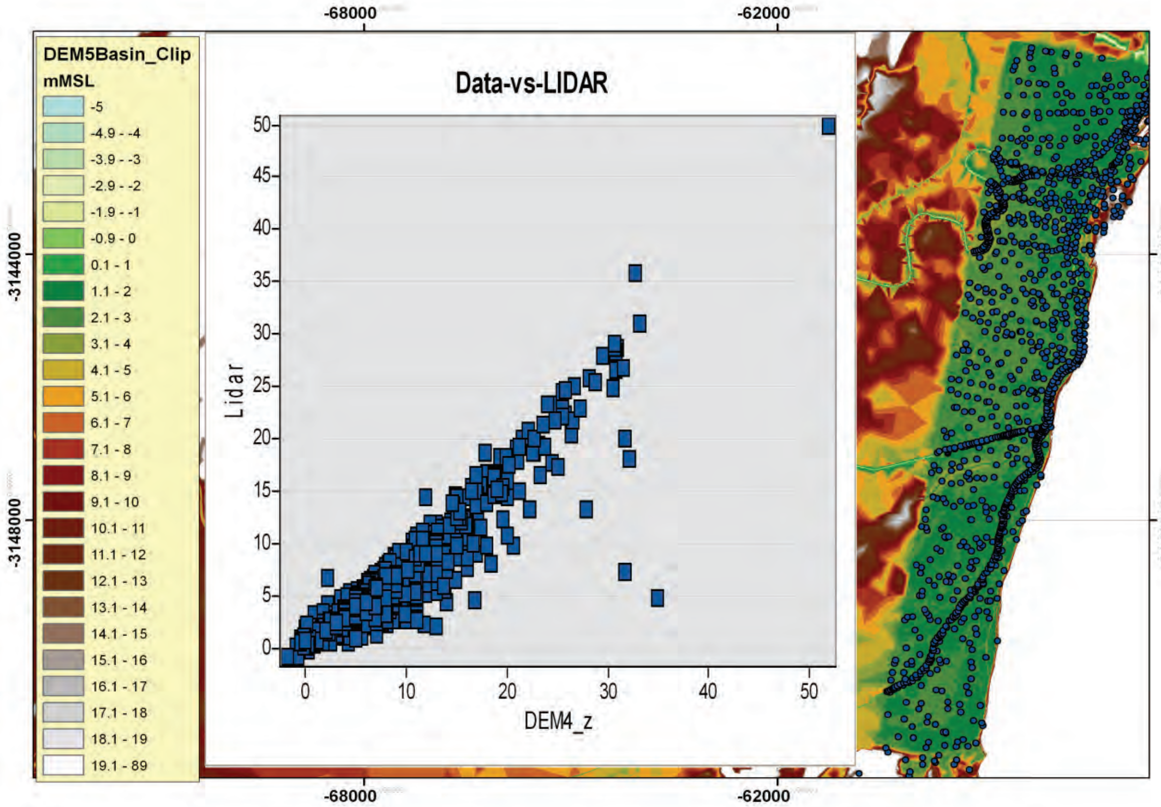

Figure 23. The scatter plot of SRTM vs. LiDar points in the study area shown in the background map.

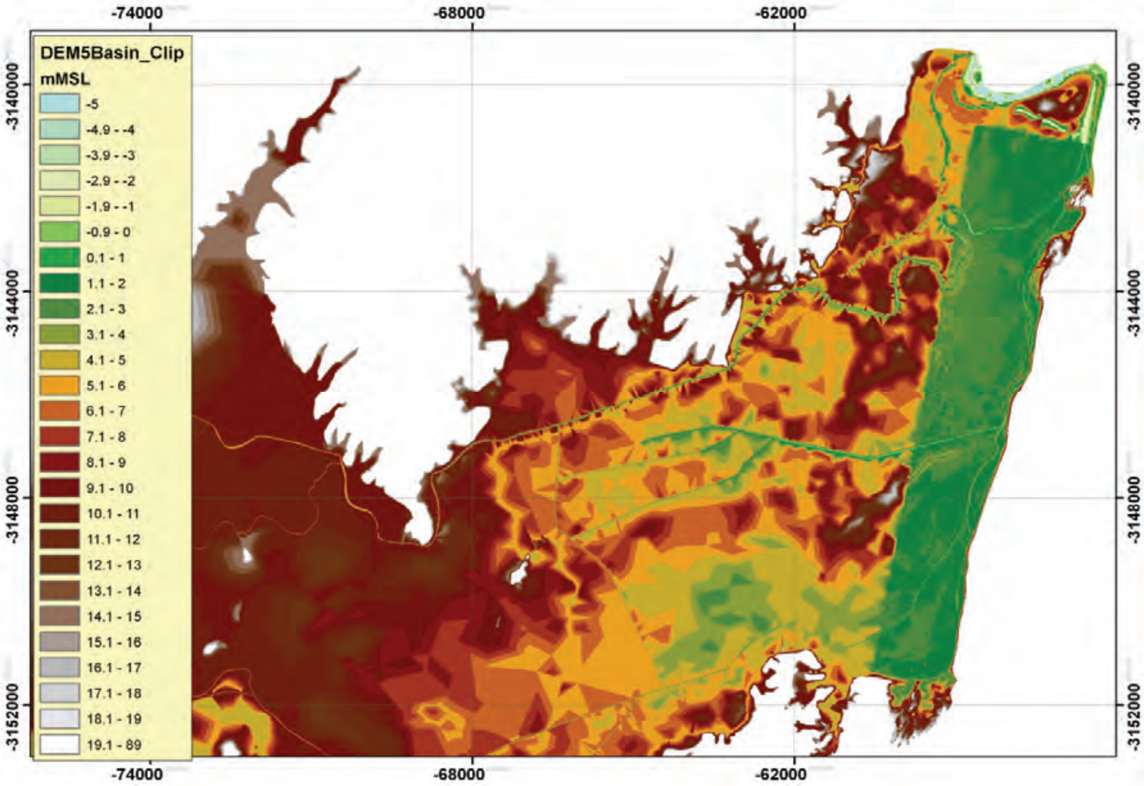

Figure 24. The derived DEM used to develop a stage-storage relationship described in the next section.

There is a close agreement in volume between the model and the derived values up to a stage of 1 m but the residual increases to over 4 000 000 m^3, but is again in close agreement at 3 m (Figure 25). This suggests that the relationship may be adequate for flow routing in this study when the mouth closes and the flood does not exceed 3 m above MSL. The dashed green line indicates a 10% error curve for volume with increase in stage.

It must be recognised that the major difference between the SRTM and other DEMs is the depth of the vegetation. This same vegetation also utilises some of the storage capacity of the swamp area and will need to be included in the final stage-storage relationship. For a 3D surface area of 50 000 000 m^2, it is estimated that the vegetation mass in the bottom metre is about 5% (see Figure 9) which is within the error margin shown in Figure 25.

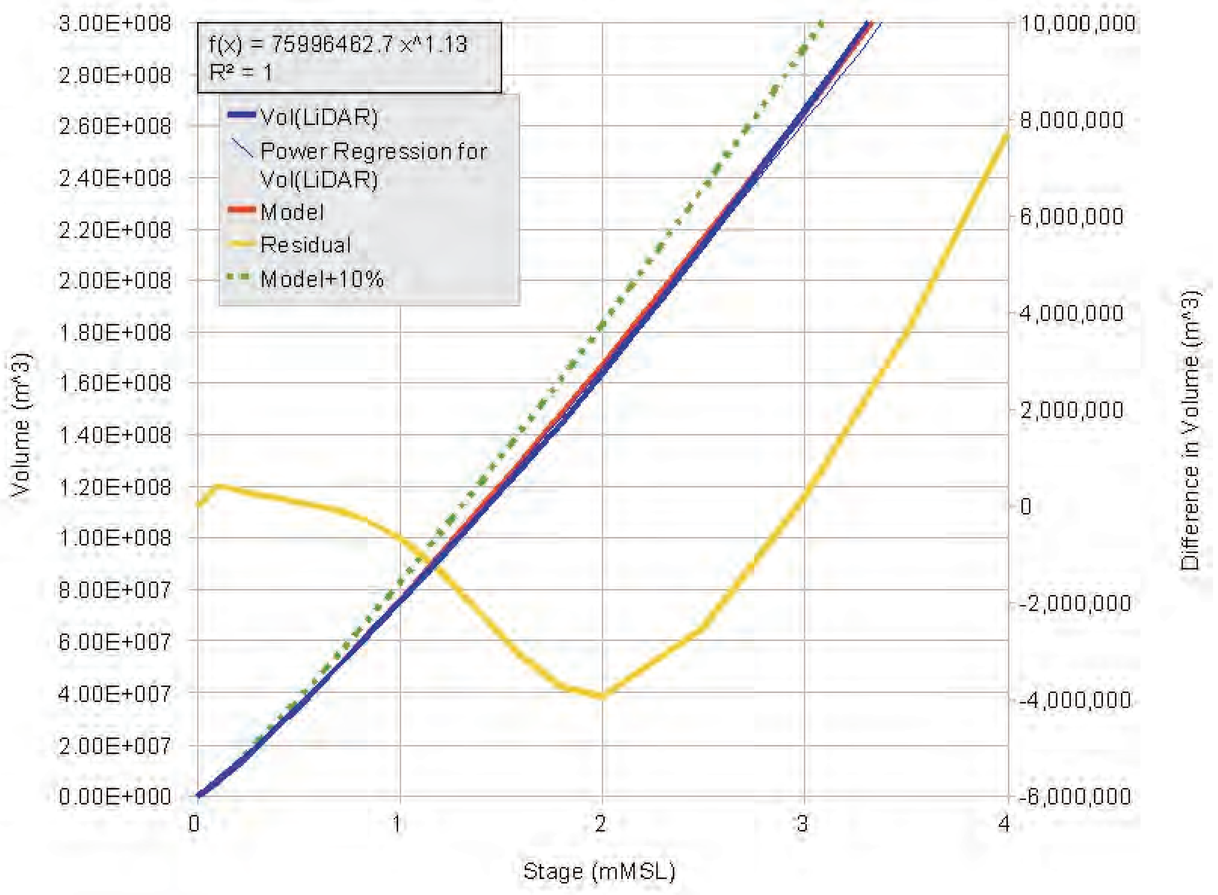

Figure 25. Plot of the derived stage (depth of water above Mean Sea Level) against the calculated volume of the swamp area. The yellow line shows the difference between the linear regression and the volume derived from the DEM.

Error analysis of the vegetation component

In the development of the flow routing model the stage-storage relationship is derived above a datum that represents the lowest elevation where overflow to Lake St Lucia can occur when the mouth first closes. The assumption is that this relates to the water level of the ocean and river channels when the mouth closes (assumed to be MSL) and that the water in the Mfolozi/Msunduzi channels below this level does not play a role in the flow routing model. Consequently, it is not important to determine the bathymetry below zero metres mean sea level (0 m MSL) for the estuary, river and canals in the study area. The storage component of prime relevance is between 0 m MSL and the stage (water level) of the estuary when it breaches the mouth and all storage is released to the sea. This is currently less than 4 m MSL, so the stage storage relation is restricted to this range (Figure 25).

While it is important to know mean sea level for the mouth, which is difficult to determine, it is more important to have the relative elevation of the sea and overflow points as they reflect the storage capacity. Also, it is unlikely that the mean water level in the estuary at closure will be at 0 m MSL as there is generally a head gradient creating outflow. However, this model assumes level pool routing and assumes these errors are negligible.

Spatial distribution of storage capacity

The spatial distribution of the derived storage capacity for the combined SRTM, Google Earth and LiDAR data sets is shown in Figure 26. The LiDAR points clearly suggest that the area (volume) at elevations below 3 m MSL is much more extensive than the SRTM and digitised data sets suggest. The spatial model indicates that much of the area covered by the LiDAR points lies below 3 m MSL which would contribute to the storage when the mouth was closed by a berm of this amplitude. The SRTM and Digital Google Earth data do not show many areas with elevations below 3 m MSL although there is a substantial region in the south west that lies below 4 m MSL. Without the expanded coverage of the area by LiDAR points it is assumed that the error in the DEM over half the area of interest is likely to underestimate the available storage below 4 mMSL by about 10%, giving a revised volume versus stage relationship of $V = 83\ 000\ 000h^{1.14}$. This is the model used for the rest of this contribution and is shown by the green dashed line in Figure 25.

The flow routing model used the mass balance approach where Inflow-Outflow equated to the change in storage. The change in storage is related to the stage through the relationship described above. The stage is also related to the discharge into the St Lucia estuary via the overflow channels also described above (Figure 13). In this model, the outflow is calculated through the following steps;

1. the INFLOW is derived on a daily basis from the Mfolozi runoff rate at W2H032 gauge,
2. the OUTFLOW is calculated from the stage of the storage (zero when the mouth is open,
3. the change in storage is calculated from the difference between the inflow and the previous days outflow,
4. the stage is calculated from the storage (assumed to be zero when the mouth is open).

The only inflow rates are the measured flow in the Mfolozi River at W2H032 weir. Unfortunately this does not include the flow in the Msunduzi River which also has the flow from the diverted Mfolozi River that happens under high flow conditions. The flow in the Msunduzi River is unknown and assumed to be negligible for this initial study.

An evaporation component has been included in the model. It is assumed that the evaporation rate is constant at approximately 5 mm per day when the mouth is open and the water surface is exposed to the atmosphere. This increases as the swamp fills up after the mouth closes. The rate of evaporation is assumed to be directly related to the surface area of the flooded section. The flooded area has been derived as a function of the stage (Figure 27).

The exact proportion of the Mfolozi Weir measurements, evaporation rates, mouth breach rates were all adjusted to achieve the best fit to the observed overflow rates described above. The resulting best fit graph is shown in Figure 28. The model indicates that a total discharge of over 20 000 000 m^3 to the lake occurred during the 2008 year, which would have made a significant contribution to the lake water balance under extreme drought conditions.

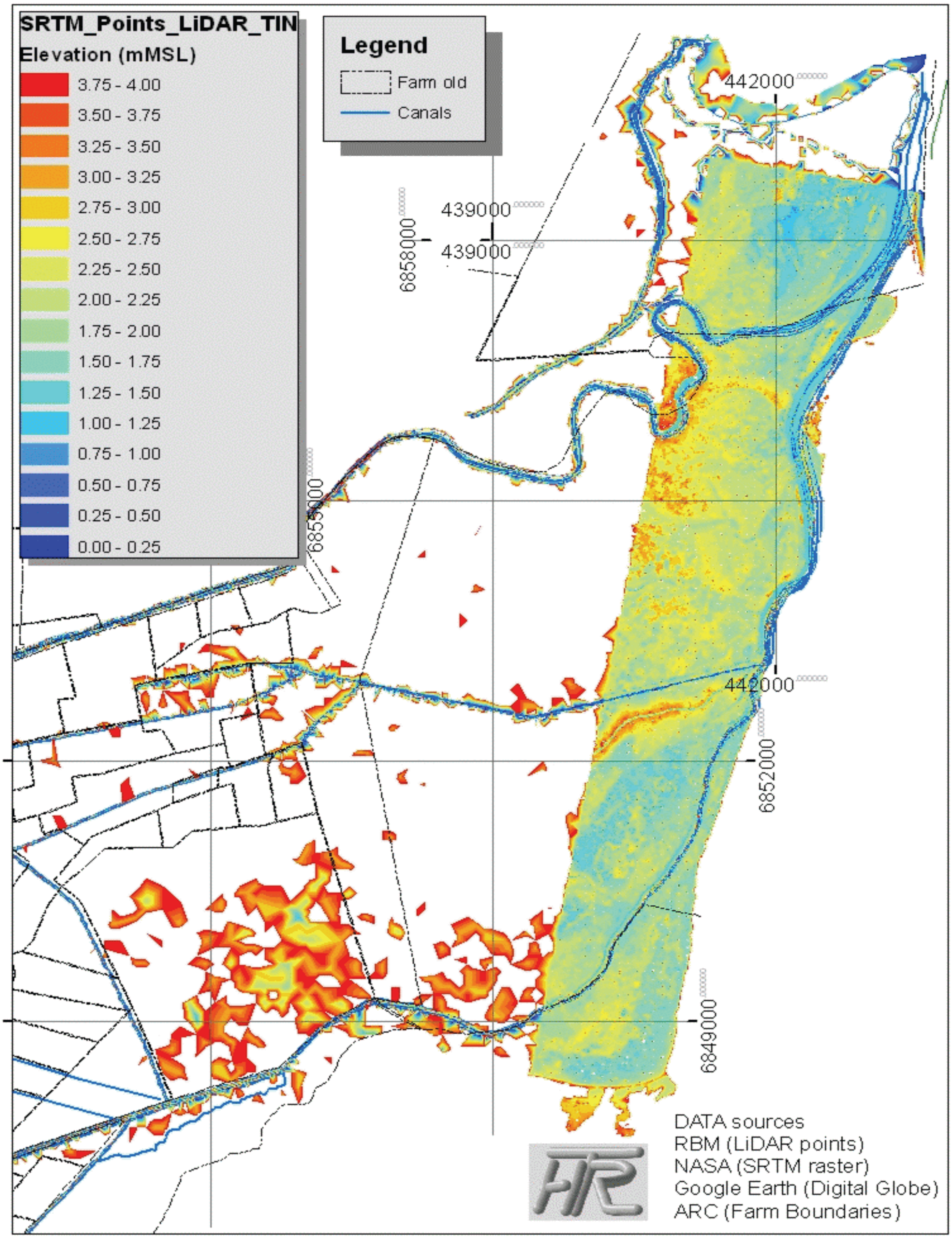

Figure 26. The DEM of the combined data set for all elevations below 4 mMSL.

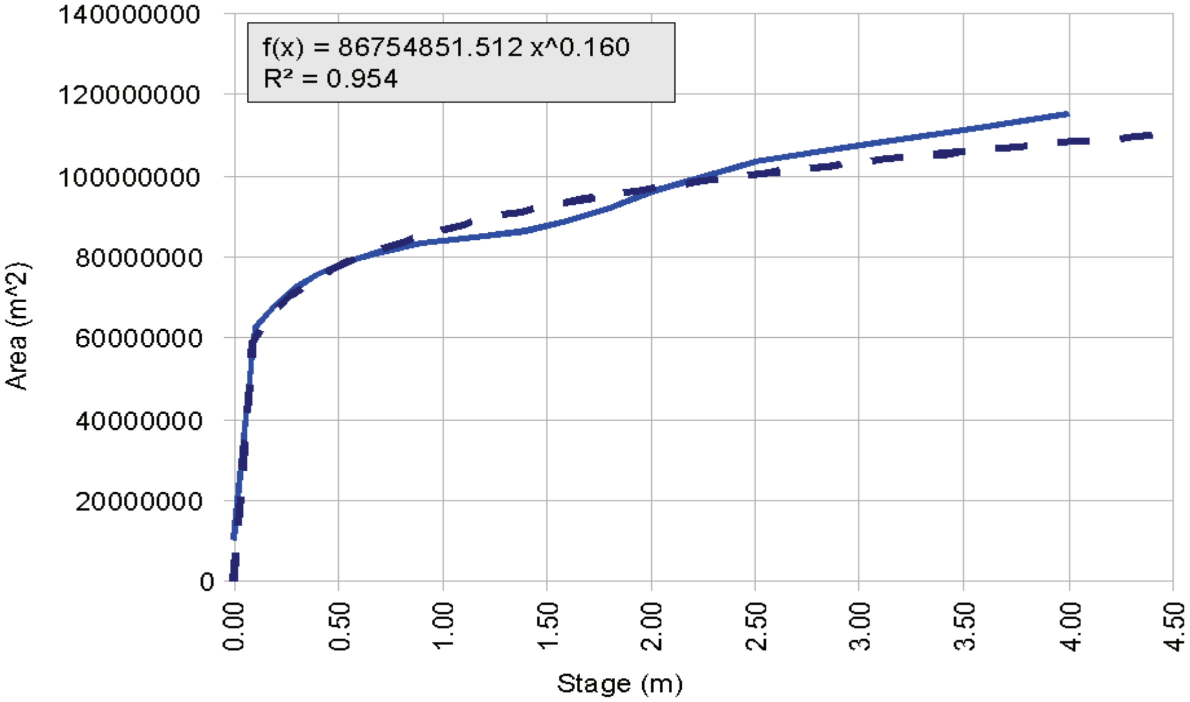

Figure 27. The stage-vs.-Area function used to estimate the evaporation rate. The dashed line is the best fit power function used to calculate the area from stage for evapotranspiration calculations.

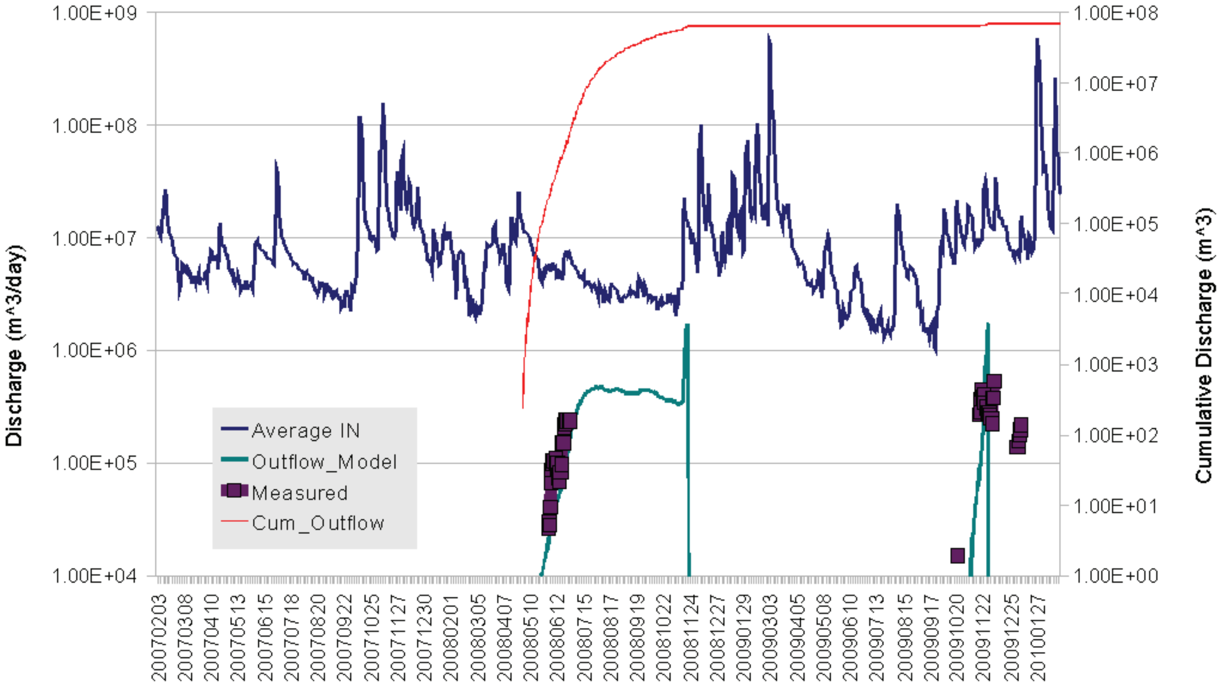

Figure 28. The measured runoff from the Mfolozi Canal (W2H032) together with the measured and simulated outflow through the Back Channels.

DISCUSSION

The need to reconnect the Mfolozi into Lake St Lucia led to the development of the Link Canal in the late 1970s and early 1980s. However, the canal and its inlet works were damaged by sediment during flooding and it was realized that the sediment-laden runoff of the Mfolozi could not be diverted directly into St Lucia without causing possible serious problems. Consequently, the Link Canal has never been used and other methods of directing the flow into the lake need to be examined. It is understood that prior to the separation of the mouths, the sediments from the Mfolozi that had not been trapped in the floodplain area, would have been deposited in the large basin linking the estuaries, before the water flowed northwards into the St Lucia system.

With the separation of the mouths and their dynamic nature, various options of linking the river estuaries are being investigated by Chrystal and Stretch (this report). However, the mouth of the Mfolozi/Msunduzi estuary often closes, causing flooding of the surrounding Low-lying sugar cane farms. During flooding, this large area will still the water and lead to substantial sediment deposition, effectively cleaning the Mfolozi runoff. This study has examined these conditions as a means for re-linking the Mfolozi/Msunduzi system to Lake St Lucia without the risk of damage from excessive sediment.

The Mfolozi/Msunduzi inflow to Lake St Lucia is not particularly important during wet conditions with high inflow from the St Lucia catchments or when the St Lucia mouth is open to the sea. It is of most importance during drought conditions when the mouth of St Lucia is most likely to close. This is also when the Mfolozi/Msunduzi mouth is also likely to close. This study has thus focused on the linkage between the two systems when both their mouths are closed under extremely dry conditions.

How important is the Mfolozi/Msunduzi water to St Lucia?

This study started by examining the importance of the flow diversion from the Mfolozi/Msunduzi river system into the St Lucia Estuary under extreme drought conditions. It focused on the situation when the mouths of both systems were closed and Lake St Lucia had shrunk to less than 20% of its full surface area creating separation of the water body into several lakes that were partially isolated from one another. Under these conditions the separated lake compartments experienced extremely low water levels (and volumes) leading to very high salinity. Under conditions of low volume and high salinity, a relatively small injection of fresh water into the compartments has a significant impact on the salinity. The mass balance model of the hydrological conditions during the extreme drought was used to evaluate the significance of the over-topping of the Mfolozi/Msunduzi into the highly stressed lake compartments in relation to the other more persistent influxes from streams and groundwater. The results illustrate the importance of these small injections of fresh water under extremely stressed conditions.

Is enough water available in the Mfolozi/Msunduzi rivers for it to be significant?

The study then attempted to evaluate the general conditions governing the routing of Mfolozi/Msunduzi flow into Lake St Lucia by assessing the relationships that regulate the inter-flow between the systems. Through a detailed evaluation of the available information and data, a flow routing mass balance model was developed that simulated the volume (and rate) of overflow from the Mfolozi/Msunduzi swamp area into St Lucia under low flow conditions when the mouth was closed. The model was calibrated against limited data and then applied to the period from January 2008 to 2010. The model indicated that flow rates of up to 1,000,000 m^3 day^{-1} could be sustained by allowing the Mfolozi/Msunduzi mouth to close during low flow periods (usually in winter). These are sufficient to alleviate the severe conditions described in the first half of the paper.

Characteristics of the floodplain storage area and the Back Channel bottleneck

The model development was based on limited data sources with many uncertainties that required corrections and conversions. The data need to be calibrated but the preliminary results indicate a reasonable level of agreement which suggests that the approach has merit and warrants further investigation. The model suggests that there is substantial storage capacity in the swamp area of the Mfolozi/Msunduzi flood plain that could be exploited to re-establish the link with St Lucia during periods of stress. The main restriction to flow into Lake St Lucia from the Mfolozi/Msunduzi swamp area is the single narrow outflow point through the Back Channel. This bottleneck needs to be enlarged to allow greater flows into the lake without raising the level of flooding in the swamp. A doubling of the Back Channel capacity would allow greater inflow with little increase in storage. However, the position and type of enlargement needs to be planned very carefully so that the benefit of using the swamp storage is not compromised.

A compound type weir (berm walls) that enables increased flow rates as the stage rises may be a suitable option to protect the level of storage (stage) and flooding. This is likely to be of most benefit if the flow is diverted into the lake via different routes at different stages.

From science to management

The purpose of this investigation has been to provide information that can be used by managers of the iSimangaliso Wetland Park World Heritage Site when they consider the various options for transferring Mfolozi River water to St Lucia. As an ongoing process we need to be continually reminded of the criteria needed for the management of the linkage of the Mfolozi to St Lucia.

Under the original condition, there was a common mouth for the Mfolozi and St Lucia estuaries, one that allowed intermittent diversion of the Mfolozi water into St Lucia. This would have occurred when the lake level dropped to below mean sea level. Some of the Mfolozi water was then deflected into St Lucia. Under these conditions it is likely that marine sediment would have accumulated in the mouth causing it to close naturally. After closure there would be no further tidal exchange and all the Mfolozi water would have been deflected into St Lucia until the mouth re-opened. The situation changed only after the mouth breached (by overtopping). Prior to breaching there would have been a rise in water level causing extensive flooding of the lower parts of the Mfolozi floodplain as well as the margins of the lake. Such a breaching would have been associated with scouring that removed accumulated sediment from the common mouth basin.

It is unlikely that the above process could be fully restored in the future, so any management action needs to identify the essential components of the process and to restore, or mitigate for, these. If the full floodplain is not restored (and sugar farming continues) then:

- It is probably necessary to maintain the two-mouth condition for St Lucia and the Mfolozi in which the flow of the Mfolozi water into St Lucia can only occur when the Mfolozi Mouth is closed and the lake level is low.
- A pool of static water is needed to act as a sediment trap and as a buffer area to accommodate flood-water (for small floods).
- There needs to be a controlling structure, such as a natural spillway, to maintain the water level in the lower floodplain so that it functions as a sediment trap. Without this, the river channel will just extend into St Lucia, transferring sediment as well as water. Such a structure is also necessary to prevent St Lucia water flowing in the other direction, i.e. into the Mfolozi, whenever the water level in St Lucia is higher than that in the Mfolozi. If this is not in place then the St Lucia channel will scour through the Back Channel so that its mouth will be *via* the Mfolozi mouth. In this way it will re-establish a common mouth. In effect, the spillway will enable managers to maintain a two mouth system where flood-waters flush directly out to sea, yet low flows can be diverted into St Lucia by allowing the Mfolozi mouth to close.
- The dimensions of the spillway (elevation and width) can be altered so that a sufficient volume of floodplain storage can be available to buffer the small flood spikes and prevent them from breaching the Mfolozi mouth. This spillway is best constructed using ‘soft’ structures such as sand bags.

Once investigations have determined the best elevation for this spillway (through modeling and empirical measurement), it will be possible to create a staged weir structure that does the following:

- Allows a low flow of water through the Back Channel over a long duration to carry all the water flowing down the Mfolozi as base flow. Hopefully, it will be possible to divert all the low flow into St Lucia during times of drought.
- Allows an increasing volume to flow into St Lucia as the floodplain fills up.
- Allows the Back Channel to be closed with sand-bags if necessary.

Protection is required from back-flooding for the lower farms. This is best accomplished by the farmers developing a polder system. However, there are problems associated with a polder system since this would necessitate pumping to remove irrigation and rainwater that accumulates in the fields.

RECONNECTION OF THE MFOLOZI RIVER TO ST LUCIA

The reservoir that acts as a storage area is the lower portion of the Mfolozi/Msunduzi swamps which back-floods as it fills up with Mfolozi River water whenever the Mfolozi mouth closes. This study provides information on how much water is stored at different levels of flooding. This knowledge allows management to consider possible ways of linking the Mfolozi to St Lucia to use this water.

At present, the management of St Lucia during times of drought is to either manage the system with the mouth closed, which effectively prevents biotic recruitment and emigrations from the system and results in extreme water level fluctuations; or to manage the system with the mouth open, which results in a very large mass of salt building up in the system as seawater flows in to replace water lost to evaporation. There has been no middle way, nor any way of alleviating the main problem, that of freshwater starvation by introducing Mfolozi water which does not carry an excessive sediment load.

This section is a proposal is a scheme that uses existing knowledge to achieve this middle-road. The problems that need to be overcome are:

- St Lucia needs additional freshwater during times of drought and the obvious place to obtain this is from the Mfolozi River.
- To maintain estuarine fauna it is necessary to allow recruitment from the sea and allow for the exodus of fauna from the estuary to the sea. To a lesser extent similar biological connectivity is needed between St Lucia and the Mfolozi, especially for *Macrobrachium* prawns from the Mfolozi into St Lucia.
- Water introduced from the Mfolozi needs to be relatively sediment-free.

Reconnection proposal

The current outflow through the end section of the Back Channel is across a flat horizontal section that is approximately 50 m wide where it drops down (Figure 9) to the outflow monitoring section shown in Figure 11. This section of sheet flow extends back to the canal section over several hundred metres which is overgrown with mangroves. It makes sense to seek other sections within the area for an expansion of the linkage between the swamp (the storage area) and the St Lucia estuary.

The concept of allowing a variable rate of interchange of water between the Mfolozi/Msunduze system and the St Lucia Estuary that is controlled by the level of either system is proposed. A 'v'-shaped notch in the berm wall separating the two systems will allow the exchange of small volumes during period of low flow but this will increase rapidly at a rate that is controlled by the relative difference in water surface elevation between the two systems and the angle of the notch (Figure 29). For the extreme situation where there is a substantial difference in water surface elevation, the flow rate would be defined by a relationship of the form given in Figure 29 where C_D is a coefficient derived by empirical methods and H refers to the head difference.

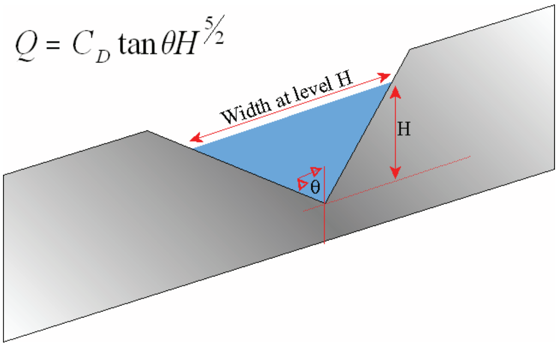

Figure 29. Conceptual form of the control structure between the Mfolozi/Msunduzi and St Lucia system showing how the exchange rate will change according to differences in water level elevation.

The most important component of this scheme is a new channel excavated at point ‘A’ in Figure 29 which has a ‘v’-notch spillway that allows Mfolozi water into St Lucia, but in a controllable manner. The ‘v’-notch will allow an increasing amount of water to flow as the water level in the Mfolozi/Msunduzi swamp storage area rises in responses to increases in flow in the Mfolozi River. And then it allows this storage area to slowly drain once the Mfolozi water flow subsides. By allowing this storage area to drain it ‘resets’ the storage basin so that it has the space to accommodate the next pulse of Mfolozi water. This channel at 'A' is cheap and easy to excavate. It should be lined with sandbags and the dimensions of the ‘v’ notch, although based on modelling, would be adjusted empirically. This is a completely reversible action as the channel could be closed at any time to return the system to its current conditions.

The main component is to construct a channel (‘A’ in Figure 29) which has a ‘v’-notch spillway within a section of the channel that allows Mfolozi flooding to mimic the way water flows from the Mfolozi into St Lucia, but in a controllable manner. The ‘v’-notch will allow an increasing amount of water to flow as the water level in the Mfolozi/Msunduzi reservoir (swamp) rises in responses to increases in flow in the Mfolozi River. The control section could be built of natural material to mimic the end section of the Back Channel but with a specific cross-sectional profile that will allow variable flow rates in relation to relative water levels. This section at 'A' could be closed at any time to return the system to its current conditions.

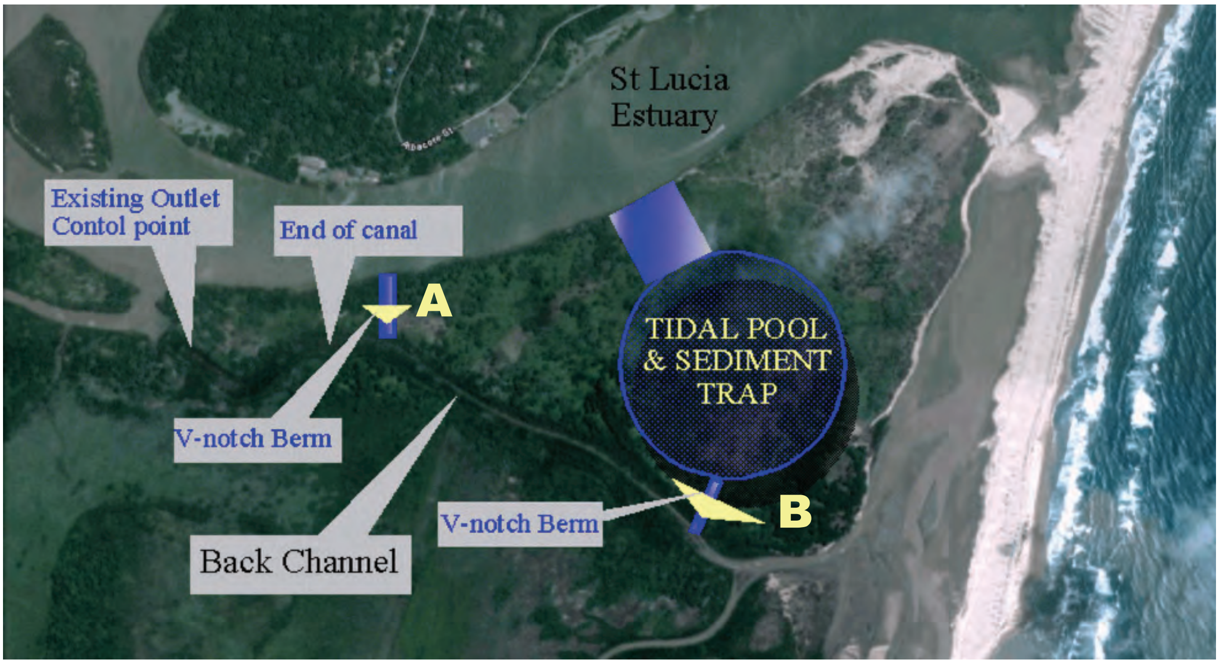

Figure 30. Conceptual linkages between the Mfolozi/Msunduzi Back Channel and the St Lucia Estuary described in the text.

The Mfolozi River is characterized by low flow periods punctuated by an occasional spate of short duration in which the water rises very rapidly, followed by a rapid drop in water level. The problem with this type of spate is that it can cause the mouth to the sea to breach and thereby loose the accumulated storage in the swamp area.

The Mfolozi/Msunduzi reservoir or storage area

The proposed system allows the water level in the Mfolozi/Msunduzi swamp to be a storage area to accommodate a considerable amount of water where it will drop its sediment load. This water is then diverted relatively slowly into St Lucia. As the water level in the reservoir rises (and the reservoir area expands) so the volume of water flowing into St Lucia will increase (through the ‘v’-notch spillway). As the reservoir increases in size, so the sediment-receiving capability is also increased. The holding of the water in the large shallow reservoir also has important consequences for floodplain swamp maintenance and rehabilitation.

The channel

This will allow the controlled flow of water from the Mfolozi into St Lucia. A superficial investigation indicates that the best position for this channel is at ‘A’ in Figure 29. This provides a short route in a low-lying area. It is far enough up into the Back Channel that the canal section can carry the water, but is not large enough to allow a flood to pass through. However, a detailed topographic survey is needed to confirm whether this is the most suitable site.

The ‘V’-notch spillway

This needs to be designed so that optimal levels are maintained in the reservoir. It would be best to have the base of the ‘V’ at about MSL, so that when the Mfolozi mouth is open, then seawater can flow into St Lucia, to promote recruitment, but this should not be excessive. This level should also be designed so that the flow from the Mfolozi/Msunduzi reservoir is not too rapid. It must allow for a slow-release of accumulated water into St Lucia. When the Mfolozi and St Lucia systems are at the same elevation there will be little movement across the 'V' notch.

The angle of the ‘V’ also needs to be considered because this controls the rate that water at different elevations will enter St Lucia. The angle should not be too large because large floods should not pass through this channel, but should be deflected seawards. It is envisaged that the ‘V’-notch be constructed of natural material but stabilised by ‘soft’ materials, such as sandbags, which can be modified or closed off easily. The cost of implementing this system is not high.

The beach-berm

The level of the beach berm near Maphelane needs to be carefully maintained so that it is not excessively high. The level needs to be maintained at the level that acts as a ‘weak link’ where breaching occurs to release the larger floods exceeding a specified magnitude.

The sugar farms

These need to be protected against flooding as the water in the Mfolozi/Msunduzi reservoir rises. This will involve the construction of levees to create polders in those areas where the fields are not protected. Once this is done, all excess water (rainfall or excess irrigation water) will have to be pumped out of the polders.

Mouth open-closed scenarios

The system must be designed to cope with the various scenarios shown in Table 2.

Table 2. The combination of mouth configurations to be considered in the conceptual development of a linkage between the Mfolozi and St Lucia systems.

	ST LUCIA MOUTH STATUS		
MFOLOZI MOUTH STATUS		OPEN	CLOSED
	OPEN	Scenario 1	Scenario 2
	CLOSED	Scenario 3	Scenario 4

Scenario 1: Both mouths open

This is a scenario that occurs during wet periods Under these conditions both systems are tidal but we do not know if the tides are synchronized because the delays of water moving up the Narrows are different from those moving up the Mfolozi/Msunduzi. This effect may also be over-ridden by wind action. The result is a variable amount of connection between the two systems, driven by the level of the high tide as well as the wind. Water will flow across the 'V' notch whenever the sea is above MSL (if this is the level that the bottom of the ‘V’-notch is set to be at) and wind direction is likely to dictate in which direction the water will flow.

Scenario 2: St Lucia mouth closed, Mfolozi mouth open

This is the scenario that often occurs during a persistent drought. It allows little freshwater from the Mfolozi to enter St Lucia. With the ‘V’-notch level at MSL, it will allow some recruitment at high tides, but only when the water level in St Lucia is below that of MSL. Under this scenario, the channel is important to maintain biological connectivity and not aimed at introducing freshwater from the Mfolozi River. If the St Lucia water level is above MSL, there will be a net outflow of water from St Lucia to the sea via the Mfolozi mouth.

Scenario 3: St Lucia mouth open, Mfolozi mouth closed

This is a scenario that will not occur frequently. It will only occur during short-term dry spells. Should the Mfolozi River come down in spate, this will flood the swamp storage reservoir, and there will be water movement from the Mfolozi into St Lucia. Once in St Lucia this water will not be of great significance as most of it will move out to sea with tidal exchange. The importance of this scenario is that the Mfolozi/Msunduzi floodplain swamps (the reservoir area) will be rejuvenated by being flooded. This situation will occur whether the channel is open or not.

Scenario 4: Both mouths closed

This is the situation described above and the one that occurs most often during drought periods. Hence the scenario is one when the movement of water from the Mfolozi into St Lucia is of greatest value. Mfolozi water will partially replace water evaporated from St Lucia. The swamp storage reservoir will act as described and will provide a slow-release of water and it will allow sediment to settle before entering St Lucia. Its buffering effect will prevent breaching of the Mfolozi mouth. In addition this flooding will rejuvenate the floodplain swamplands.

Expansion of the linkage to accommodate larger flows from the Mfolozi River

Once the proposed channel with the ‘V’-notch spillway is functioning, it may be worthwhile to go further and design an additional and larger channel to cope with much greater volumes of Mfolozi water. The specifications for this should be based on the quantities of sediment carried in floods of different sizes, as well as the extent of the reservoir needed to settle out the sediment, and the quantities of sediment deemed to be acceptable in St Lucia

The proposal is to establish a much wider channel at point ‘B’ (shown in Figure 29) with a spillway at a fairly high level (possibly above that of the extreme high tidal level and considerably higher than the level of channel ‘A’). The level of this spillway will be above the level catered for t at point ‘A’. This will allow floodwater to enter St Lucia without having to pass through the constricted Back Channel. Its purpose is to prevent breaching of the beach berm by all but the largest of floods and even when the Mfolozi/Msunduzi storage reservoir is filled to capacity.

The topographic elevation of the area where this channel is proposed is such that a considerable amount of excavation will be necessary in its construction. By dredging a basin of about 5 ha that will be fully connected to St Luciathis will increase the size of the St Lucia estuary tidal prism and hence increase the likelihood of the St Lucia mouth remaining open.

Management of the lower Mfolozi River

The Mfolozi River is contained within artificial levees until it is downstream of the Link Canal Intake Works. After this point the river should be encouraged, during flood conditions, to spill over its banks in a southwards direction so that the water enters the reservoir. It will also be advantageous to allow the river to permanently switch its channel at this point and flow southwards. This will maximize the effectiveness of the sediment trapping in the storage reservoir because it will be in the main path of flow rather than acting as an off-channel reservoir. The longer-term objective is to get the Mfolozi to switch channels near Riverview (as recommended by Van Heerden, this report) because this will shunt the water down the lowest portion of the floodplain and sediment can be trapped in suitable reservoir basins *en route*.

CONCLUSIONS

This proposal makes use of recent knowledge relating to flood routing processes and how partial reconnection of the Mfolozi to the St Lucia system may be facilitated. It is possible to implement the proposal for reconnection in stages, with the initial stages being cheap and having a large positive impact on the St Lucia system. The Mfolozi/St Lucia linkage is a process where we can learn by doing, i.e. an ideal adaptive management approach because any action taken is reversible. Further refinement will be possible if there is a sufficiently accurate DEM of the floodplain area to allow storage volumes at different stages to be calculated.

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ON THE ROLE OF THE MFOLOZI IN THE FUNCTIONING OF ST LUCIA: WATER BALANCE AND HYDRODYNAMICS

Robynne Lawrie, Clinton Chrystal & Derek Stretch*

Affiliation: School of Civil Engineering, University of KwaZulu-Natal, Durban
**Email: stretchd@ukzn.ac.za*

INTRODUCTION

The role of the Mfolozi in the functioning of the St Lucia lake and estuary system has become entrenched in historical narratives concerning changes to the system driven by human activities, *e.g.* Taylor (2006), Whitfield & Taylor (2009). The Mfolozi River historically provided a source of fresh water inflow that contributed to the lake water balance during drought periods, thus supporting the ecosystem. Since the separation of St Lucia Estuary from the Mfolozi in the 1950s the St Lucia inlet has been actively managed, *e.g.* by artificially maintaining an open estuary mouth using dredging, hard engineering and artificial breaching. These actions were thought to be necessary in order to maintain a biological pathway between the sea and the lake. The tendency for the separate St Lucia inlet to close, and to remain so except during large flood events, was apparently a largely unforeseen consequence of the management decision to intervene in the natural functioning of the Mfolozi/St Lucia inlet configuration. Overall it is apparent that the detailed effects of the Mfolozi on the St Lucia water balance and its role in the stability of the St Lucia Estuary mouth are complex and are not yet fully understood. This section presents a summary of some key recent findings from ongoing research (*e.g.* see Appendix 1 on page 265) concerning the crucial role of the Mfolozi in the functioning the St Lucia system, with a particular focus on the water balance and inlet hydrodynamics.

Some of the key questions or issues underpinning our current research concerning the St Lucia lake/estuary system and its link to the Mfolozi/Msunduzi estuary are:

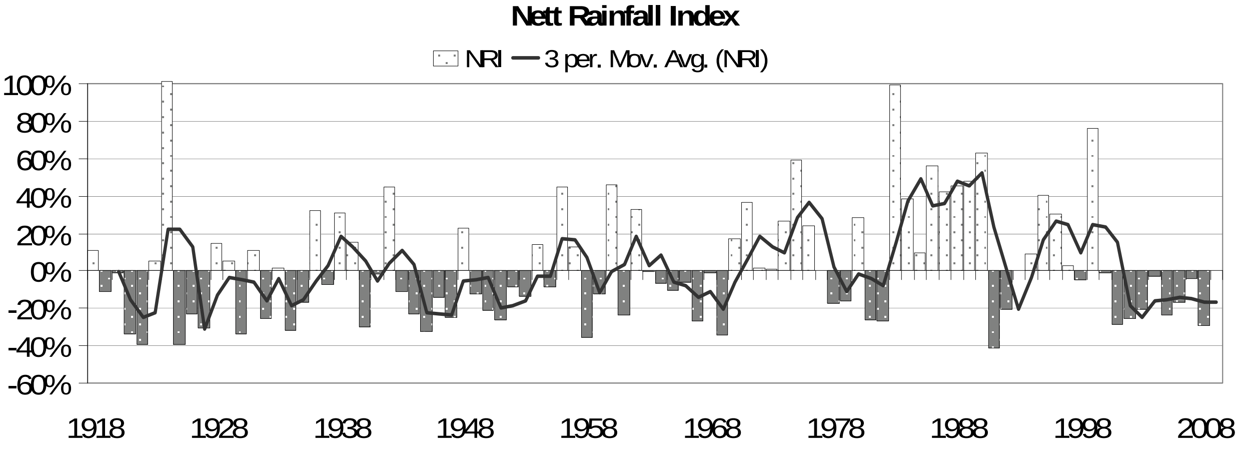
- What can a water balance model teach us about the impacts of past management decisions and the best options for the future?
- How do the inlet dynamics vary with different estuary configurations *i.e.* for separate or combined inlets, and what are the implications for Lake St Lucia?
- Is there any evidence of significant deposition of Mfolozi sediments within the St Lucia lake basins and upper estuary system? This issue has been widely cited as a reason for keeping the Mfolozi separated from St Lucia.

In this section we give an overview of recent research activities that address these issues and summarise some of the key findings.

SUMMARY OF KEY FINDINGS

Water balance

St Lucia has a mean annual rainfall (MAP) of 890 mm and mean annual evaporation (MAE) of 1470 mm (Hutchison & Pitman, 1973). The large surface area to depth ratio of the lake means that the water balance of Lake St Lucia is sensitive to direct rainfall gains and evaporative losses. The net rainfall index (the difference between the ratios of actual to average monthly rainfall and evaporation) and the accumulated net rainfall index give an indication of historical wet/dry patterns in the area (Figure 1). They show the presence of approximately decadal cycles of wet and dry periods. Extended drought periods are known to occur in the area (*e.g.* 1967 until 1972), however the current dry period seems to have had more severe effects on the system with extensive desiccation of up to 90% of the surface area in 2005/6. Nevertheless, the time history of net rainfall index indicates that the present extended dry period is not (yet) the worst on record and was preceded by a substantial wet period during the 1980s and 1990s. This suggests that loss of freshwater from the system and/or alterations to the mouth functioning have worsened the impacts of droughts on the system, and may have undermined its resilience and ability to recover during subsequent wet periods.



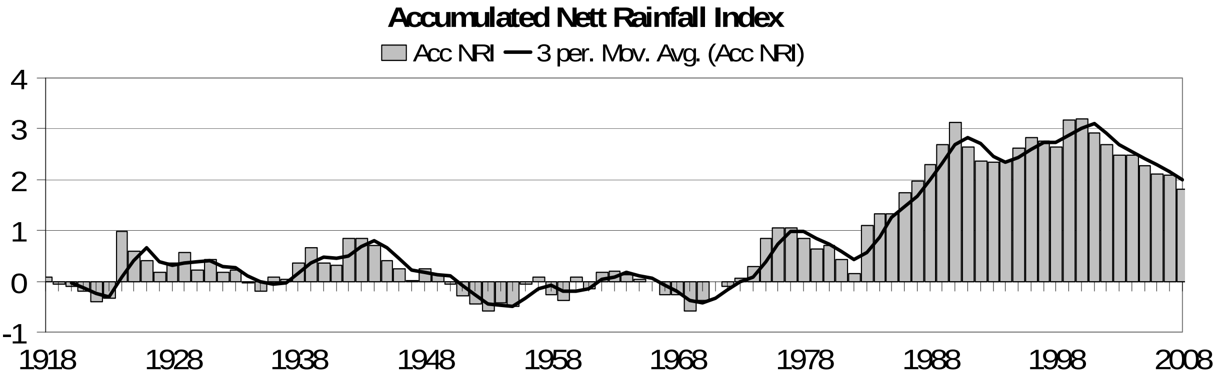


Figure 1. Net rainfall index and accumulated net rainfall index for Lake St Lucia over the 90 year period 1918-2008 (data courtesy from SA Weather Services).

A water balance model of the St Lucia lake/estuary system with the capability to simulate average lake water level, salinity and mouth state has been developed by Lawrie & Stretch (2010). The model has been used to simulate the following four scenarios for the 90-year period from 1920-2010.

Simulation Scenario 1 – Separate inlets with mouth manipulation: (the status during the period 1952-2002)

The management strategy from 1952 until 2002 was to keep the St Lucia inlet separated from that of the Mfolozi and to maintain it in a permanently open state to allow for the movement of fish and other aquatic biota into and out of the estuary (Whitfield & Taylor, 2009). At the onset of a dry period, an influx of sea water would occur when the lake level dropped below estuary mean water level (EMWL) due to evaporative losses. The water level thus remained near EMWL throughout dry periods and desiccation was not a concern. However, the salt load increased with the influx of sea water and hypersaline conditions would typically follow (particularly in the northern parts of the lake). Measurements of lake salinity are available for this period and provide an opportunity to validate the water/salt balance model. The simulated average lake salinity is compared with measured monthly lake salinities in Figure 2. It is evident that the model simulates average lake salinity characteristics accurately.

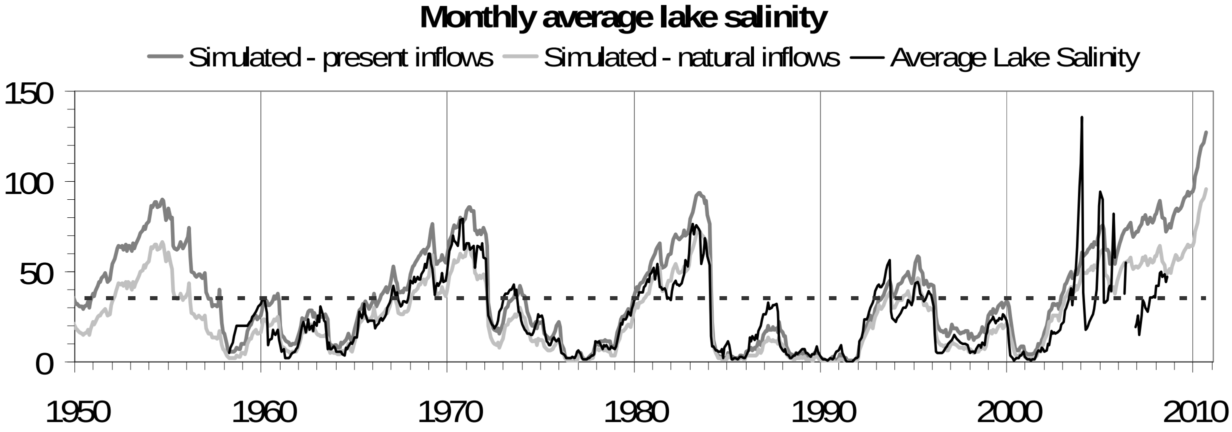


Figure 2. Measured and simulated monthly average lake salinity (data courtesy of EKZN Wildlife).

Simulation Scenario 2 – Separated inlets, no artificial mouth manipulation: (the status since 2002)

In 2002 the management strategy was changed, mouth manipulation ceased and the mouth closed naturally. Model simulations allow us to investigate the long term implications of this new mouth management policy.

With an estimated mean annual contribution of 165 Mm^3 the Mfolozi River was once an important source of fresh water to St Lucia when their combined inlet was closed. Simulations without the Mfolozi link, and without mouth manipulation (Figure 3), indicate that the system would be predominantly closed (88% of the time) in this scenario. Moreover average salinities in the lake would be low since the brief open mouth periods coincide with large flood events when no sea water influxes occur. With the reduced fresh water input into the system and the diversion of the Mfolozi, mouth outflows are not sufficient to overcome mouth closure mechanisms. The mouth would remain closed for about 10 years at a time and the lake level and salinity would fluctuate depending on fresh water input and evaporation. A one in ten year flood would typically be required to "naturally" breach the mouth under these conditions and the mouth would then stay open only for relatively brief periods of about 1 year. Salt load remains constant (and relatively low) during closed mouth conditions. Under these circumstances lake salinity is directly linked to water level (or volume): salinity increases exponentially as water levels drop during dry cycles from evaporation, but decreases when there is a net fresh water input. Desiccation (with associated hypersaline conditions) is probable during severe drought conditions in this scenario.

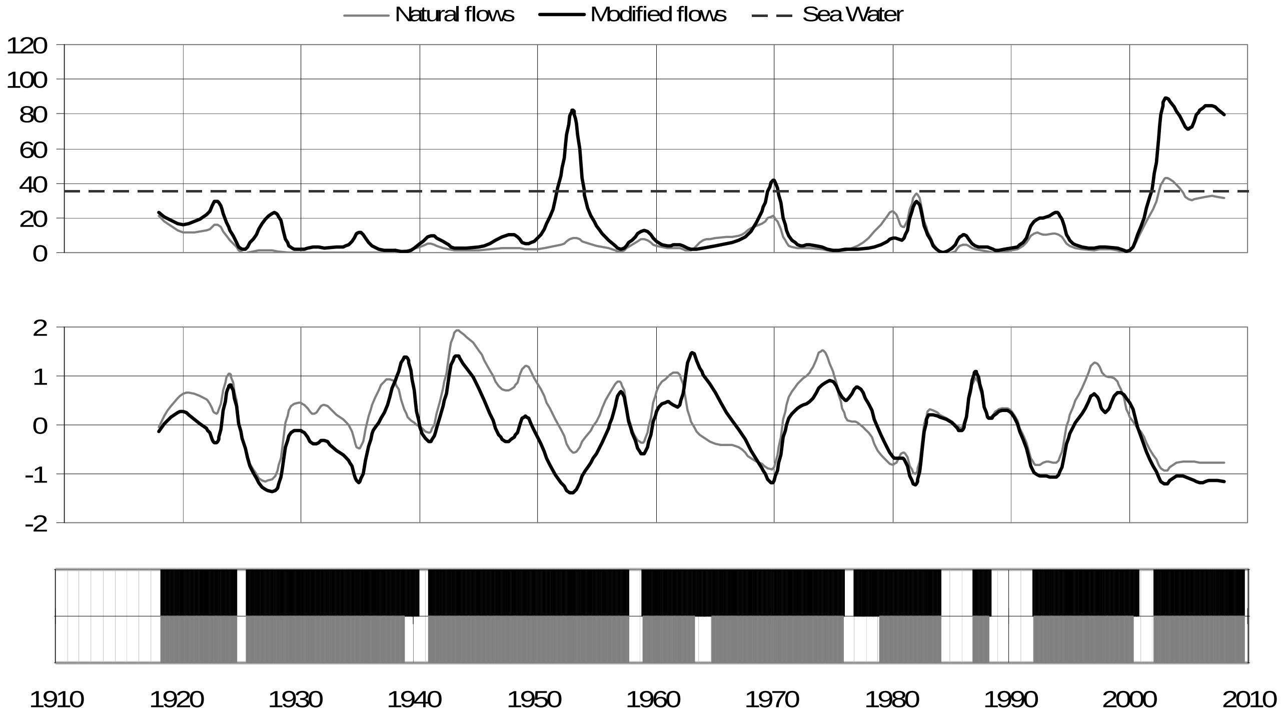


Figure 3. Simulated annual average salinity (top), water level (middle) and mouth state (bottom) for Scenario 2. Shaded areas indicate closed mouth conditions.

Simulation Scenario 3 – Combined mouth, no artificial mouth manipulation: (the status before 1952)

This scenario was simulated to depict a case with minimal human impacts. It is believed that prior to 1950, during dry conditions, the combined St Lucia/Mfolozi mouth would occasionally close and that the Mfolozi would flow into St Lucia replenishing water lost to evaporation and diluting salinity (Whitfield & Taylor, 2009). Simulations suggest that with a combined Mfolozi/St Lucia mouth, the mouth would be predominantly open (about 70% of the time – Figure 4). At the onset of a drought, sea water influx would maintain lake level at or near EMWL and salinity would slowly increase (approximately linearly in time). The mouth would eventually close if dry conditions persisted and the Mfolozi River flow would then be diverted into St Lucia thus maintaining or increasing the water level and lowering the salinity. The model indicates that a one in three year flood would typically breach the system naturally under these conditions. This scenario is predicted to produce a higher average salinity than Scenario 2 with hypersaline conditions occurring mainly during open mouth phases (as for Scenario 1). Salinity during closed mouth conditions is generally low due to dilution by fresh water inflow from the Mfolozi River. Compared with scenario 2, reinstating the combined mouth with the Mfolozi changes the system from a predominantly closed, fresh water system with a highly variable water level, to a predominantly open estuarine system with a more stable water level.

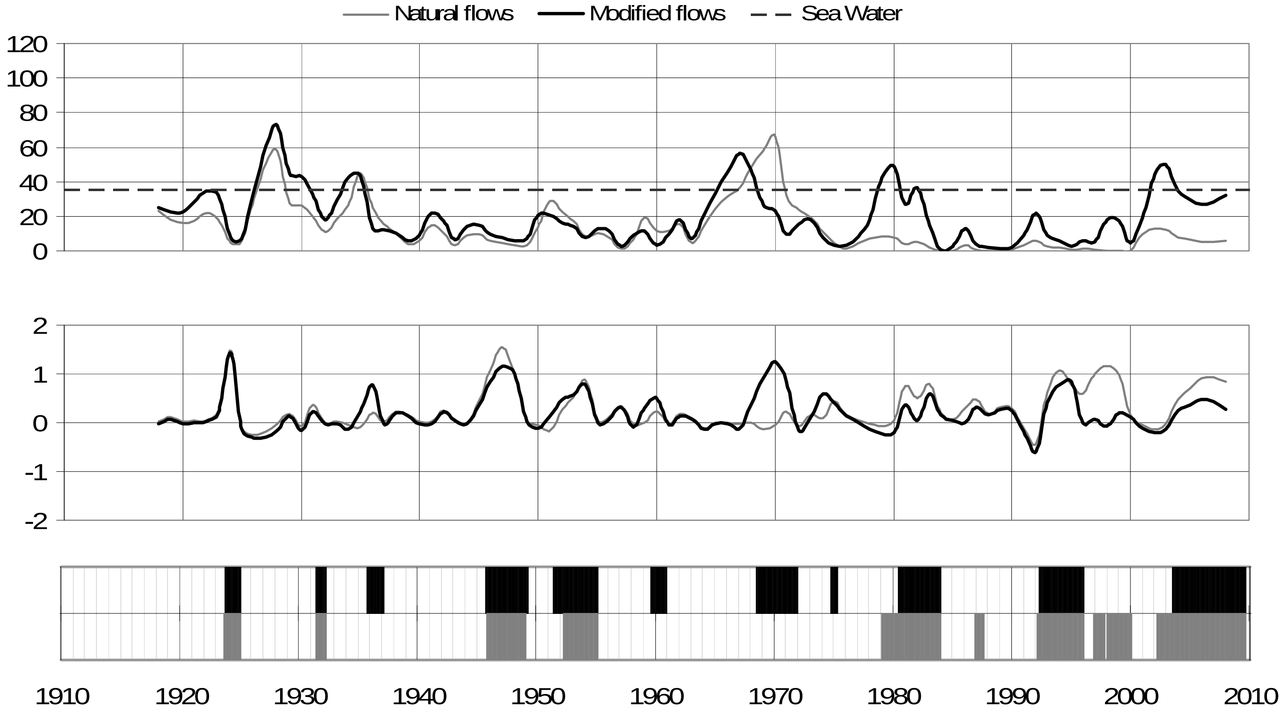


Figure 4. Simulated annual average salinity (top), water level (middle) and mouth state (bottom) for Scenario 3. Shaded areas indicate closed mouth conditions.

Simulation Scenario 4 – Separate inlets but with fresh water transferred into St Lucia via a link canal (Back Channel)

This scenario is similar to Scenario 2, but with additional fresh water imported into St Lucia via a Back Channel from the Mfolozi River (or some other source), but with the St Lucia and Mfolozi inlets maintained in a separate state. If we were to assume an additional fresh water inflow of 5 Mm^3 per month, which is equal to the estimated reduction in flows from the lake catchments due to water abstractions, the model predicts (Figure 5) that the mouth would still remain predominantly closed (83% of the time). The additional fresh water would, however, maintain the salinity below 35 and thus mitigate the effects of dry conditions. However, desiccation and associated hypersaline conditions would still occur (Figure 5). Water levels and salinities follow the same general trends as for Scenario 2, but are less variable.

The model predicts that the modest increase in fresh water supply would have no influence on the mouth state of the St Lucia Estuary. This emphasizes the significant role that the Mfolozi River plays in the functioning of a combined mouth. Note that the role of the Mfolozi in the functioning of St Lucia is not limited only to providing a source of fresh water during drought periods, but is also important for stabilizing the mouth dynamics. This has an indirect but significant influence on the overall water/salinity balance of the lake.

FUNCTIONING OF THE BACK CHANNEL

Additional fresh water via the Back-Channel would alleviate the effect of drought conditions (*i.e*. high salinity and falling water level). The mouth configuration and water level of the St Lucia and Mfolozi estuaries play a significant role in the functioning and success of the Back Channel (see Appendix 1 for more details). Note that to accurately quantify the functioning of the Back Channel a water budget for the Mfolozi basin is required. A detailed review of the effects of the Back Channel freshwater link is given by Lawrie & Stretch (2008).

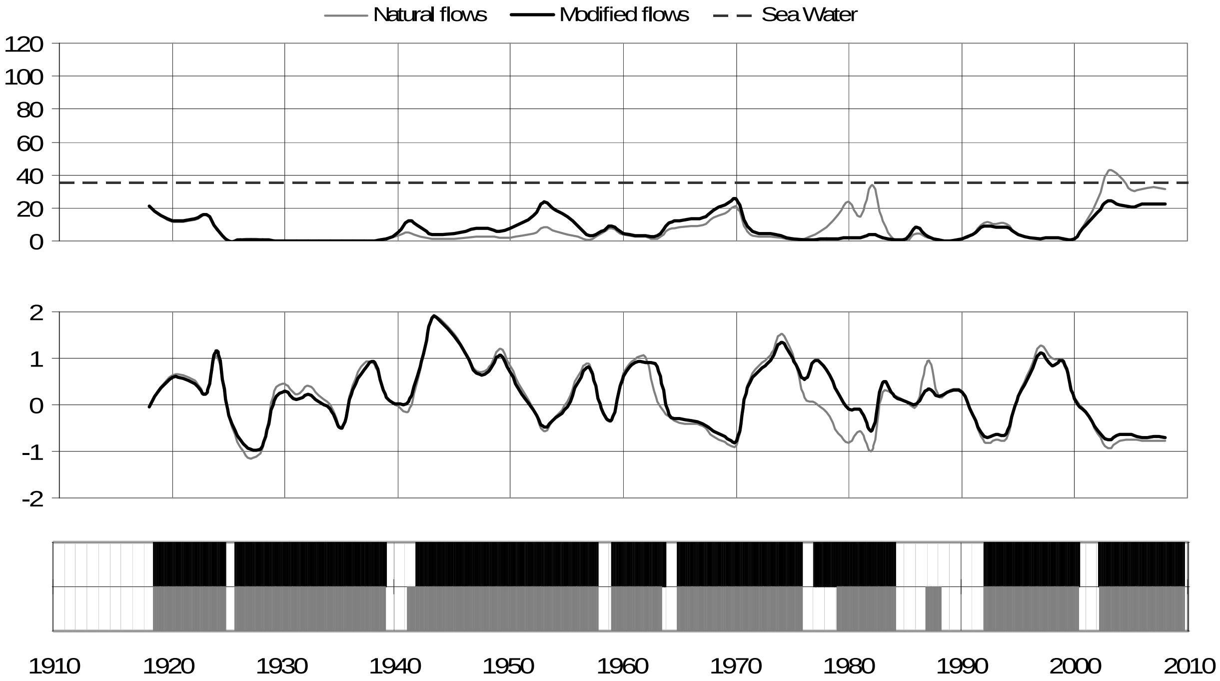


Figure 5. Simulated annual average salinity (top), water level (middle) and mouth state (bottom) for Scenario 4. Shaded areas indicate closed mouth conditions.

Mouth configuration

When both the Mfolozi and St Lucia mouths are open, both estuaries would be dominated by tidal exchange flow. When the mouth was open in 2007, Chrystal & Stretch (2010) measured an average exchange flow of about 650 000 m^3 per tidal cycle and measurements in the tidal reaches of the Mfolozi have yielded an average flow of about 500 000 m^3 per tidal cycle (Lindsay *et al*., 1996). Under these conditions the Back Channel would not be effective in providing any significant fresh water flow between the Mfolozi and St Lucia estuaries and the average water level in each estuary would be approximately the same.

In the case where one of the mouths is open and the other closed, the functioning of the Back Channel depends on the crest level of the hydraulic control that governs the outflow at the downstream end of the channel. For example, when St Lucia inlet is closed and the Mfolozi inlet is open, depending on the water level in St Lucia, saline water from the tidally influenced Mfolozi could flow into the closed St Lucia system. Flow in the opposite direction could occur during ebb-tides if the water level in St Lucia was above the crest of the Back Channel weir. It is evident that the Back Channel would not be effective in providing a significant fresh water flow into St Lucia in this scenario.

In the case of the Mfolozi mouth being closed concurrently with the St Lucia mouth, water levels in both systems would be dependent on terrestrial river inflow. Fresh water would flow into the lake via the Back Channel provided the water level in the Mfolozi is higher than that in St Lucia. Flow duration analysis of Mfolozi flows indicates that the likelihood of the Mfolozi remaining closed for extended periods beyond the low flow season from June to September is, however, very small.

In summary, the supply of water via the Back Channel could dampen the effect of drought conditions in terms of lake salinity and water level (Appendix 1). However the configuration of the two mouths plays a major role in the functioning of this scenario.

Water level

A hydraulic gradient is required to drive a flow of fresh water from the Mfolozi into the lake. There is a balance required between the levels of the Mfolozi and St Lucia berms and the water levels in the estuaries for the Back Channel to function effectively (refer Figure 6). For example, the crest of the Back Channel hydraulic control point (BCWL in Figure 6) needs to be high enough to avoid the loss of water from St Lucia to the Mfolozi when the water level in the Mfolozi is lower than that in St Lucia, and high enough to avoid sea water from entering St Lucia during spring high tides when the Mfolozi mouth is open. If MFBL is increased further, the flow via the Back Channel could be increased, but the MFBL level should be limited to prevent inundation of adjacent farmland. This does not leave much allowance for flow through the Back Channel before a breaching event would occur in the Mfolozi. The St Lucia breaching level (SLBL) is shown in Figure 6 and has been indicated as 2 m above EMWL (3 m on the gauge plate), which corresponds approximately to observed natural berm levels at this location.

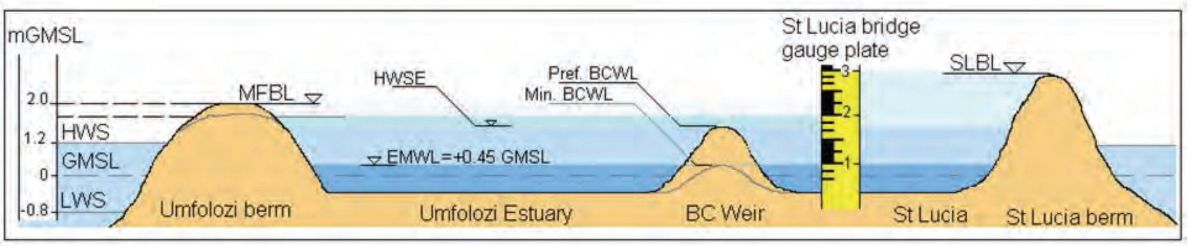


Figure 6. Schematic showing key levels required for the functioning of the Back Channel (not drawn to scale). BCWL is the Back Channel Weir Level; MFBL/STBL are the Mfolozi and St Lucia Breaching Levels respectively; HWSE is the Spring High Tide Water Level in the estuary when the mouth is open; HWS and LWS are the Spring High Tide and Low Tide Water Levels in the sea, respectively.

INLET HYDRODYNAMICS

The dynamics controlling the inlet functioning of the St Lucia and Mfolozi systems (separate or combined) plays a major role in their overall biophysical functioning. The Mfolozi and St Lucia estuaries are classified as temporarily open/closed or seasonally open estuaries. Inlet instability leads to closure of the mouth because of variable seasonal freshwater inflow, high energy wave climate, micro-tidal range, and a high rate of longshore sediment transport (Ranasinghe *et al.*, 1999; Parkinson & Stretch, 2007). The complex behaviour of inlets is illustrated in Figure 7, for both separate and combined inlets. Note the well-developed flood delta and meandering mouth configuration in Figure 7a. The northward migration of the spit due to longshore sediment transport and the formation of a flood delta within the estuary mouth are illustrated in Figure 7b.

Field measurements during a 6-month period in 2007 (when the St Lucia berm was breached by storm waves), together with data collected by Hutchison (1974), indicate that the St Lucia estuary has a tidal prism of approximately 500 000 to 1 500 000 m^3, depending on the tide cycle and mouth constriction. An empirical method for evaluating inlet stability in terms of the ratio of tidal prism P to annual littoral transport M is described by Bruun (1978). In the absence of significant terrestrial flow into the tidal reach, the P/M ratio provides an indication of whether an inlet functions in a stable or unstable regime, i.e. if it would tend to remain open or tend towards closure. The St Lucia inlet with P/M ratios of less than 2 based on an annual littoral drift of 850 000 m^3, falls well within the unstable regime and would thus tend towards mouth closure if terrestrial flows are negligible (see Table 1).

(a) (b)

Figure 7. (a) A combined St Lucia and Mfolozi system, illustrating the complex dynamics at the estuary inlet and the formation of flood deltas. (b) An artificially separated St Lucia mouth configuration illustrating the spit migration due to long shore transport and the formation of a flood delta due to the influx of sediment into the estuary (pictures courtesy of R. Taylor).

When the Mfolozi and St Lucia estuaries share a common mouth the influence of the additional storage area/volume of the Mfolozi does not significantly change the P/M ratio for the inlet. Figure 8 shows the change in water level fluctuations, measured in the St Lucia Estuary for separate and combined inlets. There is a 40% reduction in the estuary tidal range when the inlets are combined, but this is compensated for by the increased tidal area of the combined systems, so that the tidal prism through the inlet remains approximately unchanged.

Table 1. Inlet stability characteristics as a function P/M ratio following Bruun (1978).

P / M	Description
> 100	inlet fairly stable in open state
50 to 100	offshore spits develop - inlet open
< 50	shallow spits develop - inlet unstable

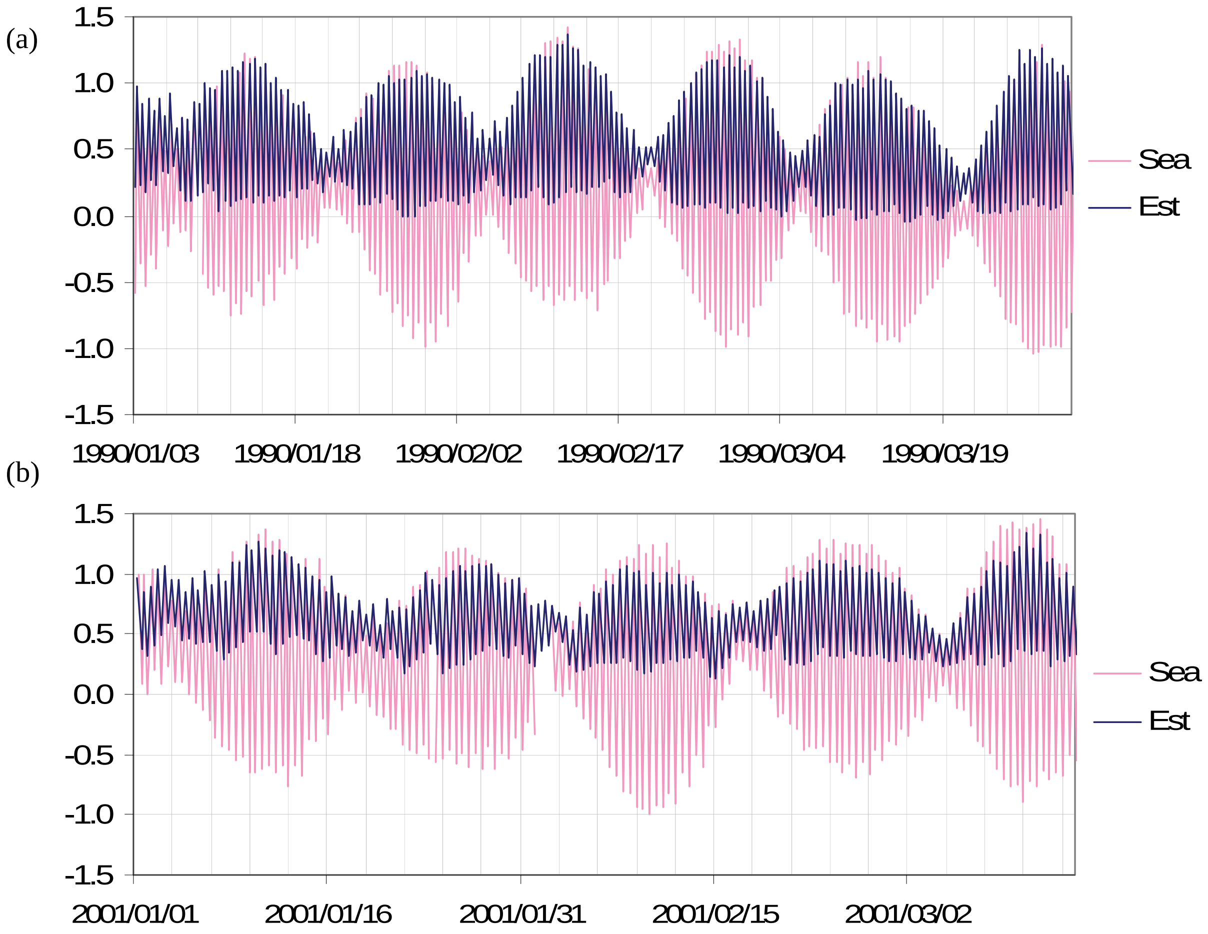


Figure 8. St Lucia Estuary water level plots for a separate system (a) and a combined system (b). The water levels are reduced to geodetic mean sea level (GMSL) (m).

Historical observations (Hutchison, 1976; Taylor, 2006) suggest that the inlet of the combined system (prior to 1952) was predominantly open. Hydraulic modelling of the system (Chrystal & Stretch, 2010) suggests that an ebb dominant system can be created by sufficient terrestrial inflow despite the low P/M ratio. The conclusion is therefore that it is the persistent baseflow of the Mfolozi that stabilises the mouth state when the Mfolozi and St Lucia estuaries have a combined inlet. The water balance model by Lawrie & Stretch (2010) is based on this concept and uses a threshold flow rate to drive the mouth state and indicates that the mouth state of the St Lucia Estuary moves from a predominantly closed (closed 88% of the time) to a predominantly open regime (open 70% of the time) when the Mfolozi and St Lucia estuaries have a combined estuary mouth.

SEDIMENT TRANSPORT (SILT DYNAMICS)

There are two main concerns regarding the silt dynamics of a combined system that have influenced management decisions. Firstly, during an open mouth state, there are concerns regarding the transport and fate of silt from the Mfolozi and the efficacy of tidal flushing through the inlet. Secondly, during a closed mouth state, there are concerns regarding silt deposition and propagation up the St Lucia Narrows and into the main lake basin.

During open mouth periods, marine sediment influx through the inlet will result in the formation of flood deltas and partial infilling near the inlet. These sediments are too coarse to be transported very far from the inlet as is evident in Figure 7a. The fine alluvial sediments carried into the mouth area by the Mfolozi are easily suspended and require longer settling times. Under some circumstances, for example if a combined inlet closes and a flood event occurs in the Mfolozi catchment, it is conceivable that high silt loads could be carried further into the St Lucia Estuary, and perhaps be deposited in the lake basins. This scenario seems to underpin much of the justification for keeping the Mfolozi and St Lucia inlets separate.

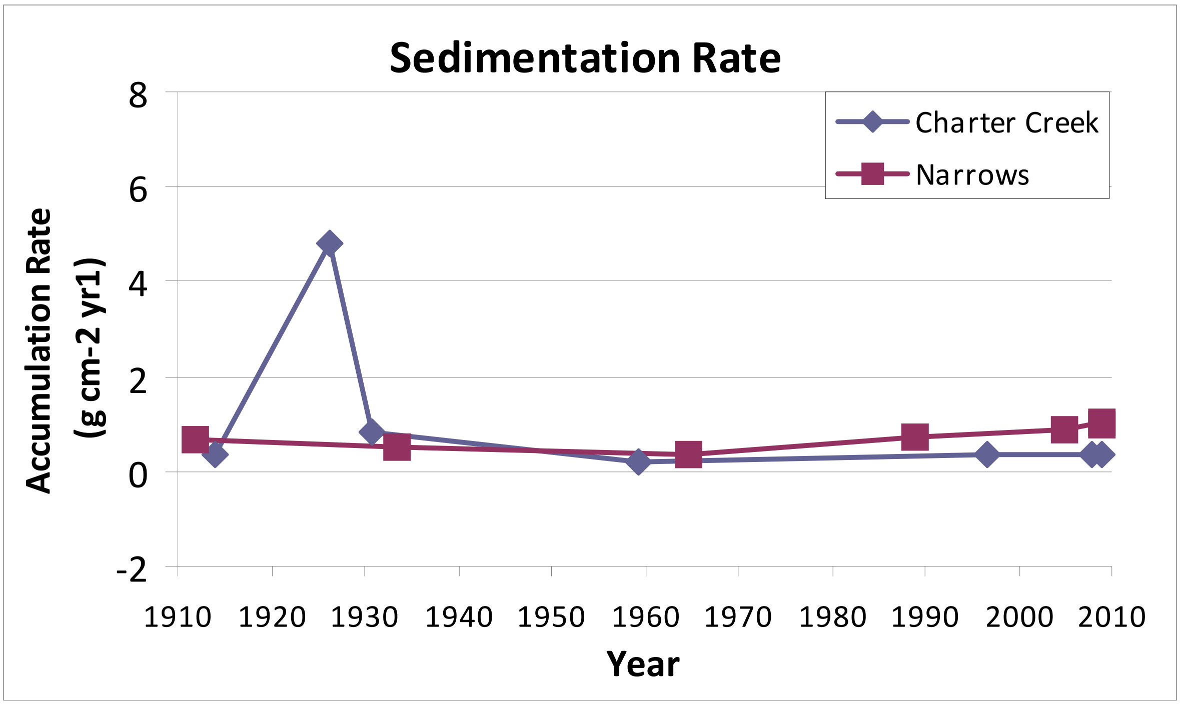


Figure 9. Sedimentation rates for Charters Creek and Esengeni (Narrows) cores dated using Pb-210 dating techniques.

A core sampling program has been undertaken to test the conjecture that the deposition of fine sediments has contributed significantly to lake sedimentation in the past. Core samples were obtained from several locations using vibra-core techniques (typically 2 m depths) and samples were dated using Pb-210 isotopes to obtain a chronology. Sedimentation rates for Charters Creek and Esengeni in the Narrows show no significant changes during the last century (see Figure 9). In the Charters Creek core sample there is evidence of an exceptional depositional event in the 1920s – this seems to be linked to the very large floods in 1924/5. Preliminary results therefore suggest that the separation of the Mfolozi from the St Lucia

Estuary has made no difference to the sedimentation rates in the upper Narrows and in South Lake. This further suggests that historically the Mfolozi has not been a significant source for the siltation of the lake basins. Hydraulic modelling is currently being used to further investigate this issue.

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LAKE ST LUCIA: OPTIONS TO SECURE FRESH WATER INFLOWS AS SUGGESTED BY REPRESENTATIVES FOR THE MFOLOZI FLOODPLAIN SUGAR INDUSTRY

AM Knox[1*], G de Jager[2*] and AT Wynne[3*]

Affiliations: [1] Stemele Bosch Africa (SBA), Durban; [2]UCOSP (Pty) Ltd, Riverview; [3]Umfolozi Sugar Mill (Pty) Ltd, Mtubatuba
**Email: KnoxA@sbadbn.co.za; gerrit@ucosp.co.za; awynne@usm.co.za.*

INTRODUCTION

The Mfolozi/Msunduzi Indaba took place between 3rd and 5th May 2010 at the Ezemvelo KZN Wildlife Auditorium in St Lucia, hosted by the Consortium for Estuarine Research and Management (CERM) and sponsored by the Water Research Commission (WRC). The context of the Indaba was that Lake St Lucia over recent years has not had sufficient fresh water to maintain its fragile ecosystem to the point that the system's sustainability may be compromised going forward (in the absence of any intervention or restoration).

The purpose of the Indaba was primarily to bring together researchers to develop a description of the Mfolozi/Msunduzi estuarine system, its process and dynamics (biotic and physical components) with the objective of identifying knowledge gaps that will focus future research to foster the sustainability of the system. As interested and affected stakeholders, the sugar industry were invited to attend, comprising UCOSP (Pty) Ltd representing the farmers and the Umfolozi Sugar Mill (Pty) Ltd (USM) representing the agro-processor. UCOSP and USM jointly made a presentation on Day 2 of the Indaba based on a report compiled by Stemele Bosch Africa (SBA), a firm of consulting engineers that has vast experience in the area. This paper provides a written version of that presentation for the purposes of producing a WRC report that documents the proceedings of the Indaba intended for publication.

Problem statement and mitigation process

The representatives of the sugar industry recognise the environmental problem of anthropogenically reduced fresh, clean water entering Lake St Lucia, particularly during extended periods of drought. In these circumstances, the salinity of the lake system increases to such an extent that portions of the lake become extremely hypersaline or dry up altogether. This is particularly prevalent in the northern lake areas, which can become isolated from the estuarine system during prolonged periods of drought.

Representatives of the sugar industry endorse the international best practice principle of sustainability that necessitates the reconciliation of environmental, social and economic demands and in this regard support focused scientific research to better understand the problem and potential mitigation measures. Consequently, the representatives of the sugar industry indicated their commitment to implementing appropriate win/win sustainable mitigation measures. In this regard, it was suggested that the causes of the problem be further investigated in an attempt to better understand what possible mitigation measures are available.

PROBABLE CAUSES OF INSUFFICIENT FRESHWATER ENTERING ST LUCIA

Extensive research has been conducted on the probable causes of insufficient fresh, clean water entering Lake St Lucia and it is widely acknowledged that the St Lucia lake system is large and highly complex. Although the Indaba has focused on the Mfolozi/Msunduzi estuary, the larger system should be further investigated (as a whole). In this regard, it is suggested that there are four principle causes of the problem, which are detailed below:

Reduction of freshwater inflow

Changes in catchment land use over the last century have changed the volume and distribution of fresh water inflow of all rivers entering the lake system. The rivers having the most significant influence will be those entering the head of the lake system such as the Mkuze and Hluhluwe rivers. Both these rivers are currently stressed and have virtually no flow during the dry winter months, even in an average rainfall year. Furthermore, the change in land use has also impacted on water quality during low flow periods.

Sedimentation

Sediment accumulation in the lake is a natural phenomenon. However, with the degradation of the catchments feeding the lake system there is reputed to have been an acceleration of this phenomenon, resulting in a shallower lake, higher average water temperatures and resultant higher evaporation rates. Sedimentation also creates dynamic bed forms, altering lake circulation patterns, developing dead zones which can become zones of stagnant, poor quality water.

Change of climatic conditions

The change in climatic conditions over the last century has possibly resulted in more extreme weather conditions, with high intensity short duration storms, accelerating catchment erosion and transport and more significantly, more frequent long duration droughts.

Rise in sea level

While not significant, the gradual rise in sea level will probably result in an increased volume of sea water penetrating the lake when the mouth is open.

OPTIONS FOR SECURING FRESHWATER INFLOW INTO LAKE ST LUCIA

Although more research is required in terms of the probable causes of insufficient fresh, clean water entering Lake St Lucia, available information enables the compilation of a list of possible mitigation measures. A number of these mitigation measures are described below in no specific order, and additional options may emerge as further research findings become available.

Transfer water from Pongolapoort Dam

There is currently infrastructure in place that will allow the release of Pongolapoort Dam water from the Makatini Flats canal system into the Mkuze River catchment, entering the lake system at the head of the north lake. The exact capacity of the system is not known, but could be in the order of 1 $m^3 s^{-1}$. It should be possible to increase this capacity at relatively low cost, compared to anticipated costs of other options.

The advantages of such a system are that some flow can be diverted almost immediately at virtually no cost. The system will be controllable, will carry little sediment and will be discharging fresh water into the worst affected parts of the lake.

The disadvantages are that flow, initially, will be low and that it involves an inter-basin transfer. This is generally environmentally unacceptable. However the impact of not getting fresh water into the upper reaches of the lake vs. potential environmental effects of transfer needs to be established. Particularly as inter basin transfer is already occurring for irrigation in and around Mkuze. Further research is required as to how the potential environmental effects can be mitigated.

The availability of water from Pongolapoort is currently under review by the Department of Water Affairs. Now will be an opportune time to establish availability and make an application for an allocation.

Rehabilitate and complete Mfolozi – St Lucia Link Canal

This was a link that was started in the early 1980s to transfer water from the Mfolozi River to the St Lucia Estuary that had an off-take from the Mfolozi River, some 3 km up-stream of the mouth and which discharged water near the start of the narrows of the St Lucia Estuary. The first stage of the canal was virtually complete, when it was severely damaged by the Demoina floods of 1984. The intakes and portions of the canal are still in existence, but in poor condition and will require significant work to re-instate and make improvements.

With modification to the intake to create better diversion conditions and better silt exclusion, plus the inclusion of a sedimentation bay behind it, it is believed that such a canal will be able to transfer relatively clean water from the Mfolozi River into the estuary of St Lucia during times of medium to low flows. In times of high flow, the canal system will need to be isolated at the intake and possibly at an intermediate point to prevent a large intake of sediment and back-flooding from the Mfolozi River, downstream of the intake.

Such a scheme will have an advantage over any system transferring water from the Mfolozi mouth area, as it will have additional hydraulic head to deliver the fresh water higher up in the St Lucia Estuary, providing a better chance of fresh water reaching further into the lake system. Such a scheme will also leave the current farming activities on the Mfolozi Flats virtually untouched, as the farms on the flats can drain to the Msinduzi River in the south and east, which will still be able to drain to the sea in the vicinity of Maphelane. However it will be questionable whether the reduced flow at the mouth will be sufficient to maintain an open mouth condition.

A major draw-back of this option is that in times of drought, the Mfolozi River catchment also experiences drought, where flows in the river are regularly less than 3 $m^3 s^{-1}$. This, and the fact that water can only be delivered in relatively small quantities close to the estuary mouth, makes it an unlikely solution to the high salinity problems of the North Lake and False Bay. Additional concerns of the iSimangaliso Wetland Park Authority of the Mfolozi River breaking through into the canal on one of the river bends downstream of the intake is very real and can happen even without the reinstatement of the canal link. With engineered protection measures this can be prevented.

Rehabilitate a portion of the Mfolozi floodplain

Rehabilitate that portion of the Mfolozi floodplain that becomes inundated when the mouth of the Mfolozi River is closed. This would probably include all areas up to about level 2.0 m amsl with consequent impacts on areas, possibly in excess of 3 m amsl. It is expected that in this instance the mouth will be left to breach under natural causes. Water will be allowed to enter St Lucia via the “Back Channel”, which could be increased in size to allow an increased flow rate. This option will obviously affect farms on the lower areas of the flats.

The filtering of water will be done by the backup of water in the lower Mfolozi and Msunduzi River floodplains where most sediments would be deposited and the slow movement of water through the “Back Channel”. Consequently, there is limited risk of large volumes of sediment being deposited into the estuary if the mouth joined the St Lucia Estuary without breaching; provided major river flooding and associated sediments could be designed to by-pass the estuary. This could be facilitated by creating and maintaining a weak link at the mouth. It is not expected that the rehabilitated farms through the establishment of wetlands and the maintenance thereof would provide a meaningful “filtering” under major flood conditions but further research is required in this regard.

The drawback of this option is the low level of flow in the Mfolozi River during drought and an even longer drainage path for the transfer system than that of the link canal. This would mean less chance of fresh water penetrating further into the lake. Other drawbacks include forced removals of subsistence farmers currently operating at the lower end of the flats. Economic drawbacks include the loss of sugarcane supply from affected subsistence farmers, certain commercial farmers and the consequent reduced throughput at the Umfolozi Sugar Mill.

Review operating rules and Water Reserve allocation for Hluhluwe Dam

The Hluhluwe Dam currently supplies the town of Hluhluwe and about 1 000 ha of irrigation. It has a yield of about 12 million m^3 per annum, which indicates that there should be water available for release to Lake St Lucia in times of need. However, the dam seldom fills to capacity and in 2010 it only reached 50% capacity, a level that has not been reached for many years. It is therefore unlikely to have spare capacity to supply large volumes of water to the lake.

The use of water from the dam however appears excessive and it would make sense that the operating rules for the dam and water extraction from it are reviewed. There does not appear to be any scope for raising the dam wall.

Construct a Dam on the Mfolozi River

The construction of a dam on the Mfolozi River is probably the most feasible and advantageous of all the options, but it would be the most expensive and the longest to develop. Ideally, such a dam would need to be constructed somewhere below the confluence of the Black and White Mfolozi Rivers. Water Affairs have conducted investigations into several sites on the Mfolozi River and it is believed that a suitable site has been identified in this area.

To make this option effective in getting fresh water into the central and northern areas of the lake, water will need to be transferred into the Nyalazi River, which discharges into False Bay. The challenges of this option will be the size of the floods that the dam will need to handle, high siltation, large storage volumes that are needed and social and environmental issues.

The positives of such an option are that Mtubatuba and surrounds will have a reliable source of water, there will be a level of flood control and if the dam is made big enough (greater than approx. 200 million m^3) there will be a high level of trap efficiency of silt and sediments, leading to cleaner water at the Mfolozi mouth. Other positives include (1) possible irrigation water for cane production to mitigate against any lost cane production through the rehabilitation of a portion of the Mfolozi/Msunduzi floodplain and (2) possible supply of potable water for the town of Mtubatuba.

The drawback of such a dam is that its life span will be short and there will be degradation of the river bed downstream of the dam, with the cutting off of downstream movement of sediments. This dam life span draw back could be mitigated if the sediment could be extracted and used to make blocks for the local building industry. Further research in this regard is required.

Construct a Dam on the Mkuze River

Issues around constructing a dam on the Mkuze River, will be similar to that of the Mfolozi River, the only difference is that its catchment is smaller and as such will not be able to support as large a dam as the Mfolozi. The converse is that floods and sediment loads will be smaller, potentially making it a cheaper option. The other advantage is that water will be provided at the head of the lake system. It is not known whether any large dam sites have been identified on the Mkuze River.

Rehabilitation of catchments

The rehabilitation of catchments is arguably the most logical and least environmentally invasive, but probably the most impractical. This would be a massive operation which would impact a large population, their livelihoods, their traditional way of living with the rehabilitation of damaged soils and vegetation. The success would be heavily influenced by the political will of the government of the day and support of the populations living in the catchments. It will not be a once-off operation, but will require ongoing management, control and maintenance. Given the inability to control much smaller areas such as the Dukuduku Forest, this is not considered a viable option on such a large scale. Greater efforts on the conservation of existing pristine areas will probably be more beneficial.

Construct a desalination plant

Because of the volumes of water required and cost of operation it is not considered an economically viable option. Desalination plants also come with their own environmental problems.

Rehabilitate the entire Mfolozi Floodplain

By removing all farming operations from the Mfolozi floodplain and establishing a mangrove/wetland area on the floodplain it is hoped that the Mfolozi River will flow into the head of the floodplain, deposit its sediments within the mangrove/wetland areas and flow out as clean water at the bottom end of the floodplain. There is no certainty that this outcome will transpire given the change to the flow regime of the river and the characteristics of its sediment load. It is likely that the upper end of the floodplain will become choked with heavy sediment, there will be a build-up of water and with medium to large floods, the river will break through, short circuiting the mangrove/wetland system and re-establishing a main river course. The evidence of numerous old river beds throughout the floodplain confirms this principle. Also given that floods of 1 000 $m^3 s^{-1}$ to 2 000 $m^3 s^{-1}$ are common on an annual basis, it is expected that a main river channel will always be maintained, even if the floodplain were to be returned to its natural state. Even with this system in place, the over-riding factor is that during a drought there is very little water in the Mfolozi River.

Unfortunately, the rehabilitation of the entire Mfolozi Floodplain would necessitate the forced removals of both subsistence farmers and a large number of commercial farmers The economic consequences for the district will be severe because the Umfolozi Sugar Mill would be rendered unviable, having a negative multiplier effect on other cane supplying areas and supporting industries.

Do nothing

The implications of this are self explanatory and undesirable.

OVERALL SYSTEM ANALYSIS AND ONGOING MANAGEMENT TOOLS

The mitigation options described above should not be viewed in isolation and any single option will in all likelihood not be the ultimate solution. A combination of options may be required to produce the best possible solution. Furthermore, one or a combination of options is expected to only provide levels of partial relief. It is therefore argued that a sustainability mitigation matrix needs to be compiled to better guide research efforts given that resources are limited. Furthermore, as and when research findings become available, it is necessary that this sustainability matrix approach be revisited; *i.e.* a continuous improvement approach.

Table 1 is a first attempt at constructing a sustainability matrix that endeavours to rank the various options with the objective of securing or regulating fresh water inflow into Lake St Lucia. No specific research has been undertaken in this regard and the options and ranking are purely based on the authors' knowledge of the system and experience gained in various engineering projects on the Mfolozi Flats and catchments of the Mfolozi, Hluhluwe and Mkuze rivers. Furthermore, the values used are not the collective views of all the stakeholders represented. The values in Table 1 should be interpreted as percentages, where high values are desirable and low values are undesirable. At this stage, Table 1 is intended for illustrative and discussion purposes only; the intention is that such a table or some alternative mechanism be developed over time to guide decision makers.

Table 1. Options for Securing or Regulating Fresh Water Inflow into Lake St Lucia, where Imp = impact in addressing the problem, Pro = probability of sustained impact largely in terms of climate related factors, Env = environmental impact, Soc = social impact, Eco = economic impact, # = success factor as a simple product of all other factors.

Description	**Imp**	**Pro**	**Env**	**Soc**	**Eco**	**#**
Rehabilitate main St Lucia catchments	40	5	100	10	20	0.4
Dam Mfolozi transfer via Nyalazi River	30	80	80	50	10	10
Water transfer from Pongolapoort Dam	20	80	40	90	50	29
Rehabilitate entire Mfolozi floodplain	20	20	100	20	20	2
Dam Mkhuze River, regulate flows	15	40	80	50	30	7
Review Hluhluwe Dam operating rules and Reserve	10	40	80	40	80	10
Rehabilitate Mfolozi-St Lucia Link Canal	7	80	50	90	80	20
Rehabilitate Mfolozi floodplain (<2 m amsl) and Back Channel	7	50	80	50	50	7
Construct a desalination plant	5	90	80	100	5	2
Do nothing	0	0	40	80	80	0

(**Important note from the editors of this WRC report**: The above table represents rating values from the perspective of the authors and a number of these allocated values are likely to be contested by other experts)

Table 1 ranks the various options in terms of their hypothetical impact in addressing the underlying problem. The success factor in the far right column (which is a simple product of all the other factors) provides a hypothetical ranking based on the international best practice principle of sustainability that necessitates the reconciliation of environmental, social and economic benefits. As already mentioned, a more robust approach is needed to populate the numbers in the table, which should be an outcome of further research. The preliminary sustainability mitigation matrix example of Table 1 suggests that research should initially focus on the following:

- Water transfer from Pongolapoort Dam
- Constructing a dam on the Mfolozi river
- Rehabilitating the Mfolozi link canal or similar alternative to transfer water from the Mfolozi/Msunduzi system into the St Lucia system
- Rehabilitating a portion of the Mfolozi flood plain.

Funding and research capacity is available. CERM and WRC need to be commended in this regard for their efforts to date and should be encouraged by interested and effected stakeholders to continue their support. The iSimangaliso Wetland Park Authority should also be commended for their efforts in raising support from the Global Environment Facility (GEF) in association with the World Bank regarding a current project that is also examining ways of securing fresh water inflow to Lake St. Lucia.

CONCLUSIONS

The St Lucia Lake system is large and highly complex, involving a number of river catchments, each with its own problems, a dune system between it and the sea, the surrounding lands bordering the western side of the lake and an estuary and mouth system which it shares with another two river catchments. An alteration to any of the catchments or elements of the system can have an influence on the overall system operation. The effects of any intervention cannot be evaluated without the correct tools and management information. In this regard, it seems logical to build a dynamic mathematical model of the entire system to underpin the sustainability mitigation matrix that will ultimately guide decision making. With current stochastic modelling, robust predictions can be made on river flow rates, water quality, sedimentation and weather patterns. Consequently, informed decisions can be made by modelling various circumstances or scenarios. It is suggested that such stochastic modelling be a key focus of the GEF project going forward and/or other research initiatives. Furthermore, the development of such a model should be designed specifically for local conditions by local personnel, where the model should include, but not be limited to:

- A topographical survey of entire area (lake and surrounds, including any adjoining flood plains, pans, wetlands etc.), including profiling of lake and estuary bottom.
- Catchment yield model (would include rainfall model).
- Catchment sediment yield model.
- Catchment water quality model.
- Ground water flow model.
- Hydraulic model of lake, estuary and mouth.
- Lake, estuary and floodplain sedimentation dispersion model.
- Lake, estuary and floodplain salinity model.
- Social impacts model.
- Environmental impacts model.
- Economic impacts model.

Each of the above fields will require specialist input and although it is onerous, it will provide the necessary base from which informed decisions can be made. This is important because the potential decisions may affect large sectors of the population, the local economy and the environment. There is a need to focus research to objectively evaluate the “better” interventions to ensure a reliable fresh water supply to Lake St. Lucia and the sustainability of the system, otherwise research could continue indefinitely without a coordinated and informed intervention. The development of such a model is the means of prioritising and coordinating the multidisciplinary research outcomes in an effort to facilitate meaningful, informed and timeous decision making. Doing nothing is an undesirable option.

KEY ROLE OF THE MFOLOZI RIVER IN THE GREATER ST LUCIA WATER REQUIREMENTS AND A PRELIMINARY HEALTH ASSESSMENT FOR THE SYSTEM

Lara van Niekerk[*] & Piet Huizinga[*]

Affiliation: Council for Scientific and Industrial Research, Stellenbosch
**Email: lvnieker@csir.co.za, p.huizinga@adept.co.za*

INTRODUCTION

This paper provides an overview of the CSIR's historical involvement in the St Lucia/Mfolozi system. It gives a brief summary of work done on the Mfolozi and Msunduzi estuaries in 1990, reviews the findings of the 2004 St Lucia Lakes Ecological Water Requirements (Reserve) study and concludes by listing the results of the 2009 national desktop health assessment done as part of the 2010 National Biodiversity Assessment.

SUMMARY OF HISTORICAL DATA ON THE MFOLOZI/MSUNDUZI ESTUARIES

The CSIR were commissioned in 1990 to undertake preliminary investigations into the feasibility of extracting water from the Mfolozi River at the Monzi Bridge (CSIR, 1990). This review extracts data and findings from that report which is one of the few historical physical data sets on the Mfolozi and Msunduzi estuaries (Figure 1).

Figure 1. The Mfolozi Estuary mouth (23 February 1989) showing the confluence of the Mfolozi and Msunduzi rivers in the centre of the picture, with the Msunduzi left and the Mfolozi on the right.

Hydrological data

The Mean Annual Runoff (MAR) of the Mfolozi is estimated at 940 x 10^6 m^3. The Mfolozi runoff shows significant variation between years with floods (*e.g*. 1983 with total runoff of 3996 x 10^6 m^3 or 420 % of MAR) and years with droughts (1982 hydrological year with 142 x 10 ^{6} m^3 or 14 % of MAR). Significant seasonal fluctuations also occur between the high summer runoff (~ 47 % of the runoff occurs between January and March) and low winter runoff (~ 7 % of the MAR occurs between June and August). Monthly flow volumes of 10 x 10^6 m^3 is exceeded about 80% of the time, while higher monthly flow volumes such as 100 x 10^6 m^3 are only exceeded for 15 % of the time (Figure 2). The MAR of the Msunduzi is estimated at 61 x 10^6 m^3 or about 7 % of that of the Mfolozi.

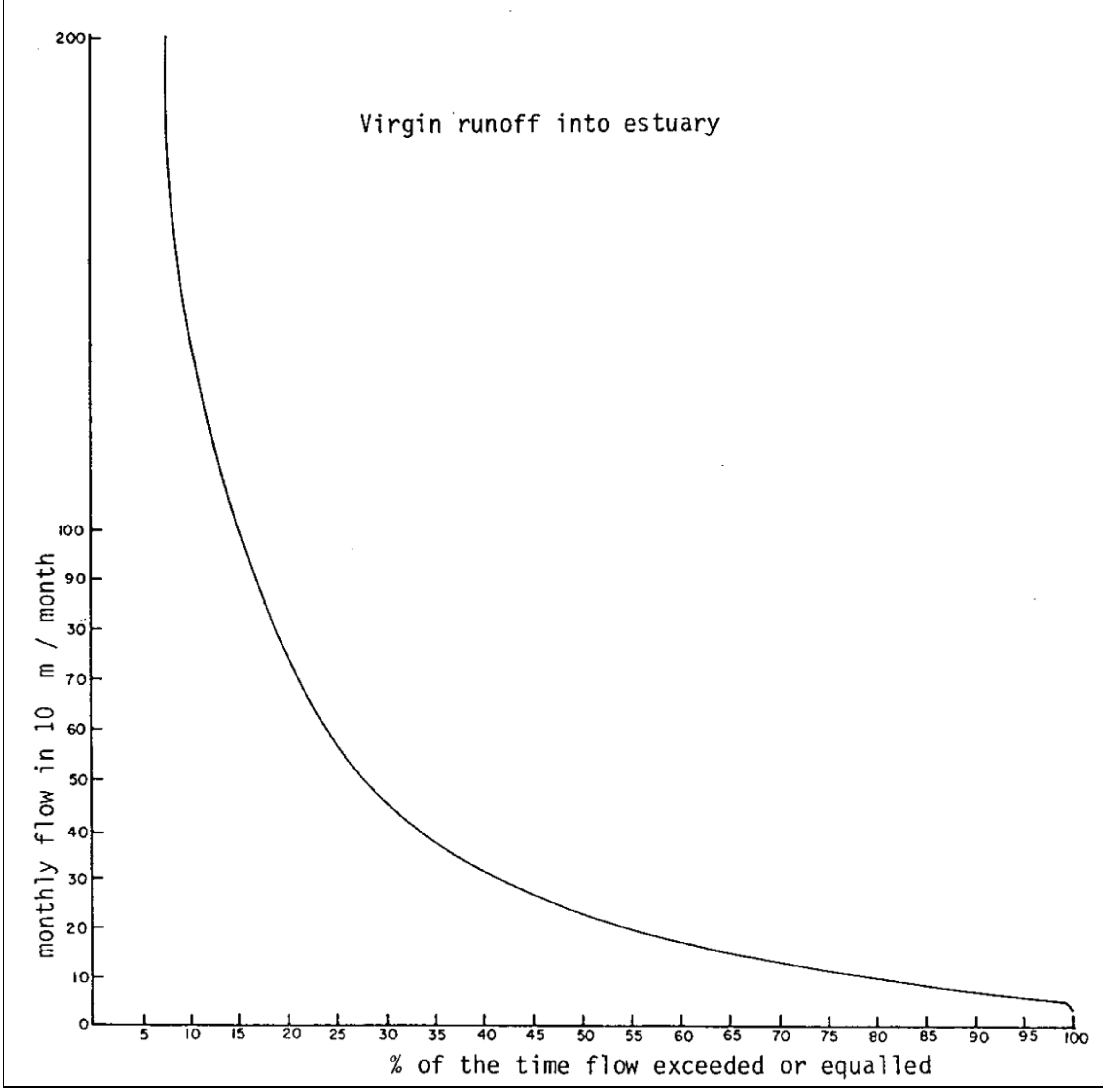

Figure 2. Probability of exceedance of the Mfolozi virgin monthly flow in 10^6 m^3 per month.

Salinity

The results of salinity data taken on a high tide at 12 stations (Figure 3) on 22 May 1990 are presented in Figure 4.

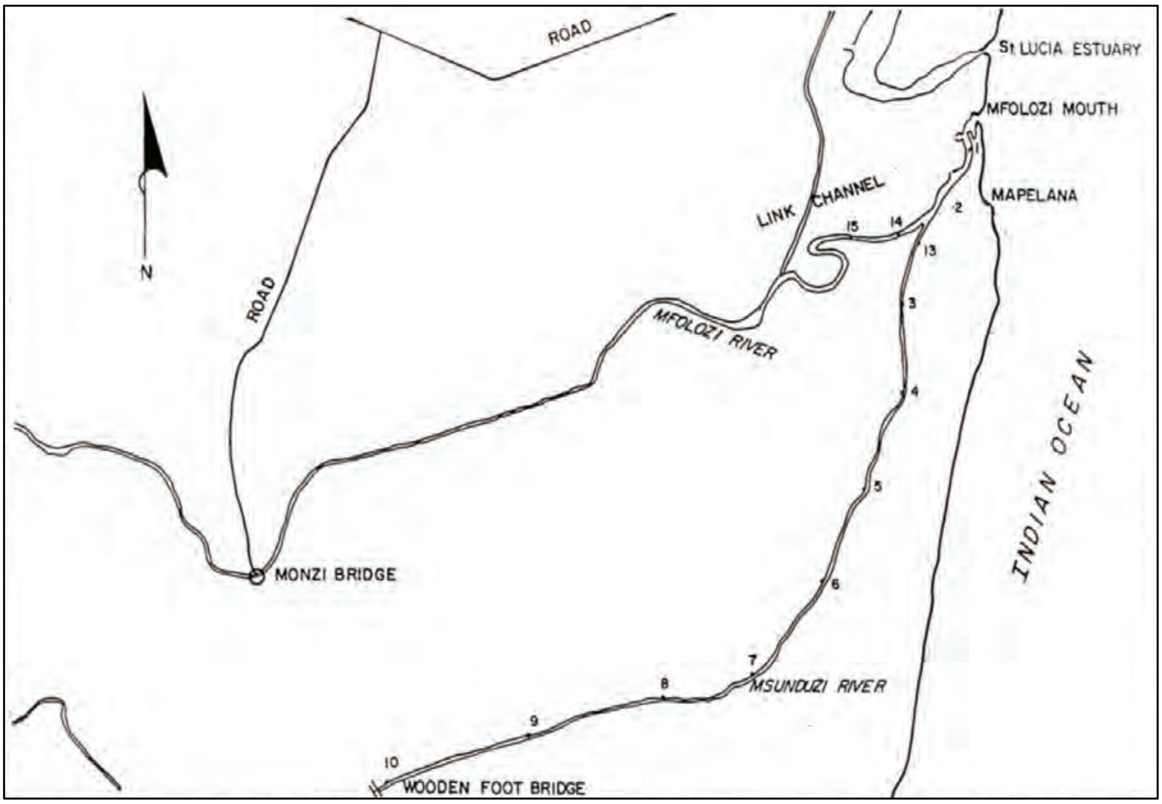

Figure 3. Sampling sites on the Mfolozi and Msunduzi estuaries.

The river flow into the system was estimated to be 15 $m^3 s^{-1}$ from the Mfolozi and 1 $m^3 s^{-1}$ from the Msunduzi. Salinity equivalent to seawater (35 PSU) was measured at the mouth (Station 1 and 2). From the confluence of the Msunduzi and Mfolozi to a distance of 9 km upstream, salinity values of 10 to 20 PSU were measured in the Msunduzi (Station 6 and 7). A salinity of 0.1 PSU was measured in the Msunduzi at the wooden foot bridge, 14 km upstream of the confluence (Station 10). While no further data were available it can be concluded from these results that the salinity in the Msunduzi is mainly determined by the flow in the river and the tidal flow through the mouth, with inflow from the Mfolozi having a moderating influence upon the salinity distribution upstream of the confluence.

Owing to the shallowness of the Mfolozi Estuary at the time of the survey only two positions were sampled on the high tide. Salinity values of 34.5 PSU were measured about 0.5 km upstream of the confluence throughout the water column (Station 14), whereas a further 1 km upstream (Station 15) there was significant stratification with a salinity of 13 PSU at the surface and 32 PSU at the bottom.

Anecdotal observations indicated that the tidal influence could sometimes be observed at the Monzi Bridge at high spring tide (Bails-Smith, Pers. com.). When river flow has been very low for a period of several months, saline intrusion could therefore occur as far as this bridge.

Mouth closure

The most important dynamic forces associated with estuary mouth closure are river flow, the tidal prism of an estuary (volume of water flowing in and out trough the mouth during one spring tidal cycle), wave climate and the river sediment load.

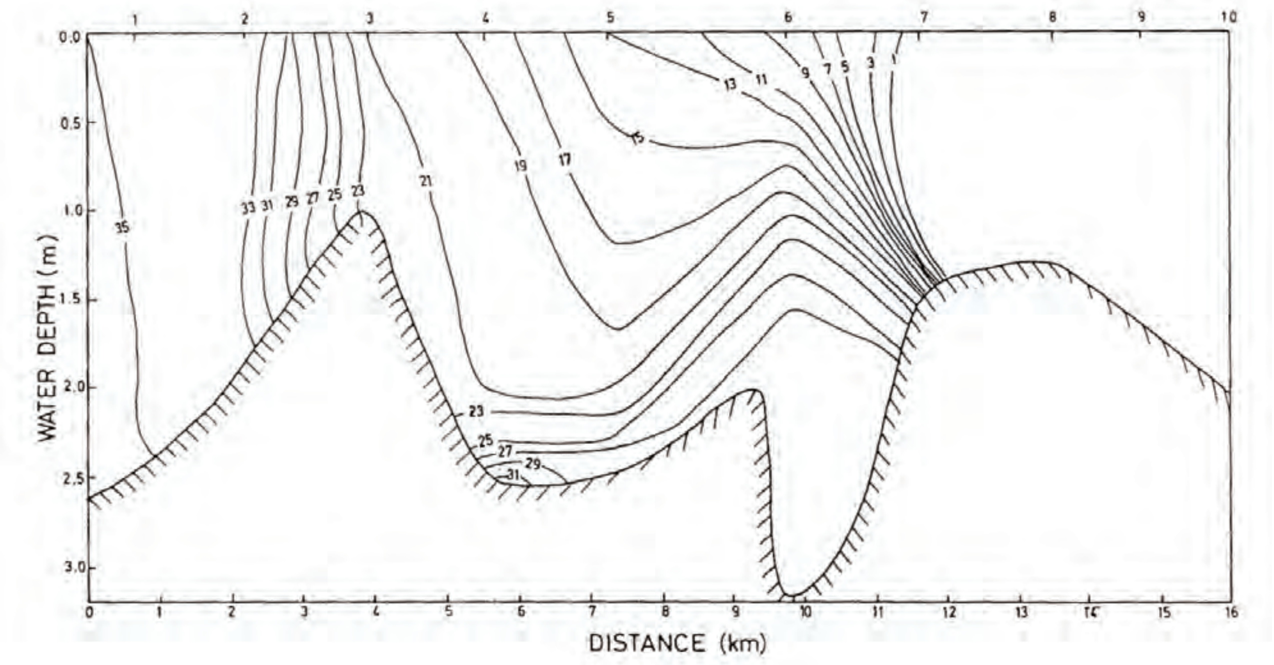

Figure 4. Salinity profile of the Msunduzi Estuary at high tide on 22 May 1990.

A reduction in river flow over an extended period will result in mouth closure (Note: there is normally a delay of weeks to months between the reduction in flow and actual mouth closure). The major closing force at an estuary mouth is wave climate.

The tidal prism of the Mfolozi Estuary was estimated at 3 x 10^6 m^3 and was deemed to play a significant role in maintaining an open mouth. Due to the significant tidal exchange, Mfolozi mouth closure would likely occur gradually over a period of a few months of sustained low flow. Summer flooding after the lower winter flow will result in scouring of sediment from the mouth which will reset the estuary to its normal open mouth state.

Based on the fact that the Mfolozi Estuary mouth had only closed a few times during the preceding decade (CSIR, 1990) and on an evaluation of the simulated runoff data generated in an earlier study, the following conclusions were drawn (Table 1):

- Mouth closure was deemed unlikely to occur at flow rates exceeding 5 m^3 s^{-1}.
- Closure could occur at between 3 and 5 m^3 s^{-1} but only for short periods before the sand bar at the mouth would be overtopped and breached.
- Mouth closure would occur at a prolonged river flow of less than 3 m^3 s^{-1}.

Table 1. River flow ranges at which mouth closure could occur in the Mfolozi Estuary.

Flow range	Mouth State
< 3 $m^3 s^{-1}$ for > 3 months	Closed
3-5 $m^3 s^{-1}$	Closed for short period (weeks to months)
> 5 $m^3 s^{-1}$	Closure not likely

Sediment loads

The Mfolozi River carries a very high silt load relative to other South African rivers. The average monthly silt loads based on data from the Mfolozi Co-operative Sugar Planters Ltd, measured during 1973-1975 are presented in Table 2. The data show a wide variation in silt content, with highest values during the months of the strongest flow, *i.e.* during summer. In general, the carrying capacity of the estuary water is dependent on the inflow and in the case of the Mfolozi the study assumed that the Mfolozi is always close to its carrying capacity.

Table 2. Average monthly sediment content measured in the Mfolosi River from 1973-1975 (mg l^{-1}).

Month	Sediment content (mg l^{-1})
Oct	320
Nov	2 753
Dec	2 803
Jan	2 990
Feb	1 285
Mar	2 600
Apr	1 065
May	440
Jun	75
Jul	90
Aug	70
Sep	280

Water level variation

The Msunduzi Estuary, as a result of its shallow gradient and roughly 10 km tidal reach, was estimated to have a tidal prism of about 1 x 10^6 m^3 and a tidal delay of about 30 minutes. This delay increases with distance from mouth. The Mfolozi tidal variation was about 1 m and 0.4 m at a spring and neap tide respectively (Figure 5).

An interesting phenomenon observed in the Mfolozi is the increase in minimum (low tide) and average water level over the spring tide. In certain instances the minimum water level during spring tide exceeded the maximum water level measured during neap tide. This is due to a combination of mouth constriction and a large tidal prism, resulting in a net retention of water over a spring tide (Figure 6).

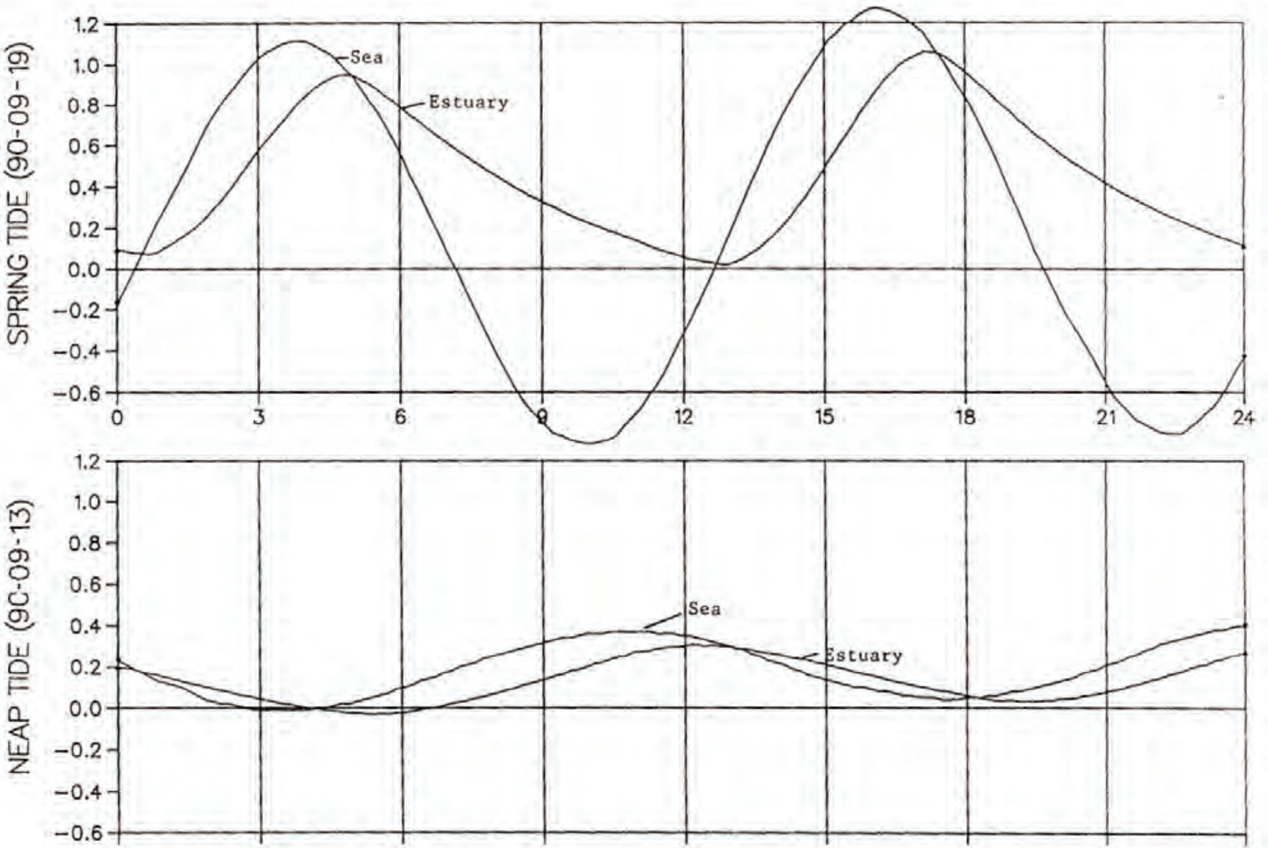

Figure 5. Water level variation in the Mfolozi Estuary at spring and neap tide Water level to MSL (m)

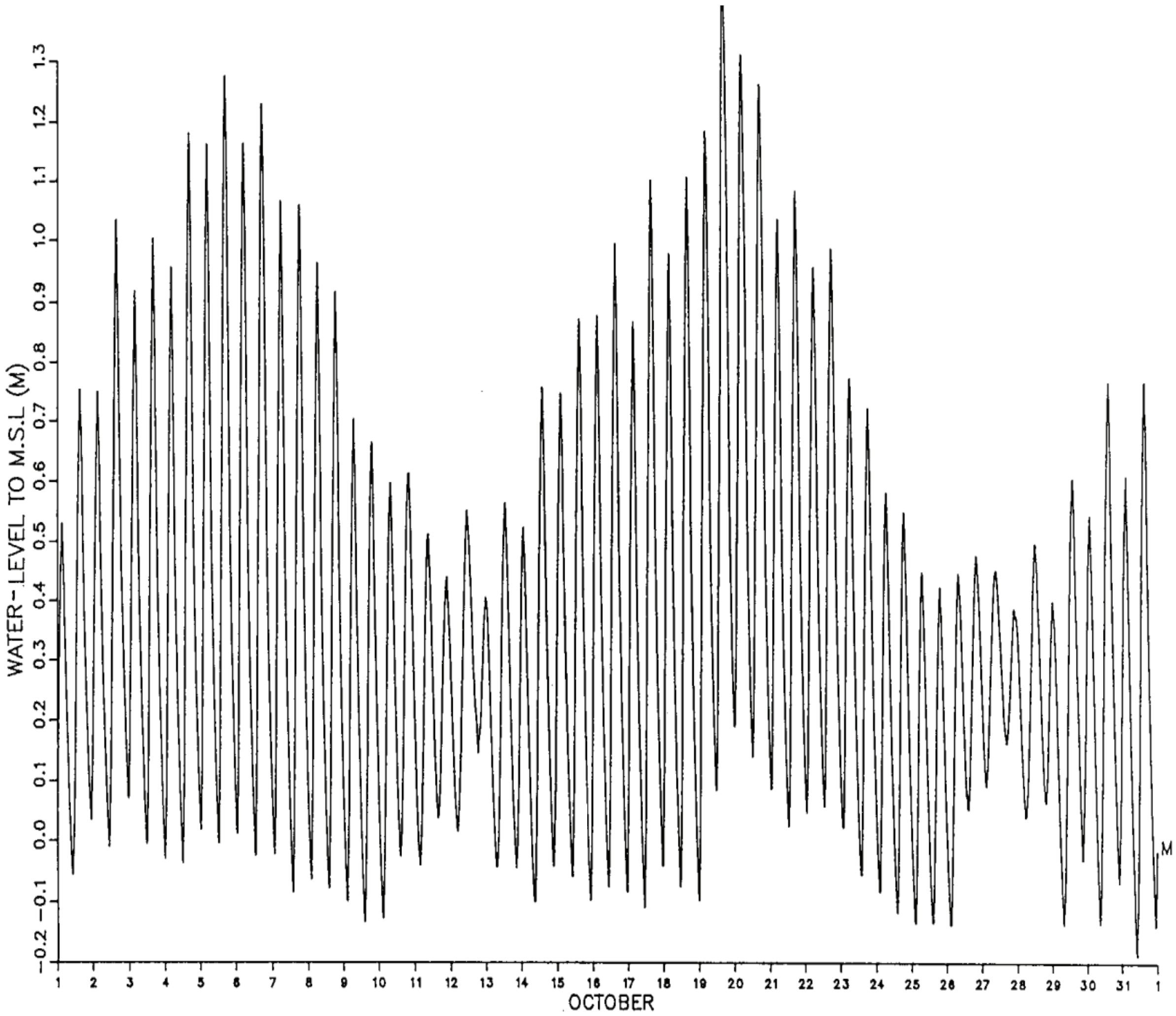

Figure 6. Water level variation in the Mfolozi Estuary from 1 October to 31 October 1990.

Figure 7. Maintenance dredging at the St Lucia mouth.

ST LUCIA'S ECOLOGICAL WATER REQUIREMENT (RESERVE) STUDY IN 2004

St Lucia – physical dynamics

Important background information on the physical dynamic processes of the St Lucia system can be obtained from an overview of the condition of the mouth over the past two hundred years. This information is listed in the report of the Commission of Inquiry into the alleged threat to animal plant life in St Lucia Lake from 1964 till 1966 (Table 3).

Table 3. Historical record of the St Lucia Lake mouth condition between 1823 and 1965 (Source: Commission of Enquiry St Lucia, 1966).

Date	Observation
1823	Mouth closed
1833	Mouth closed
1849	Mouth open, navigable channel
1851	Almost closed
1852	Mouth open
1853	Mouth open
1856	Mouth open after floods
1885 and 1895	Mouth usually completely blocked from September to November?
1902	Mouth could not be crossed (probably by boats)
1903	Mouth closed
1905	Mouth open
1911	Flood in Mfolozi
1918	Serious flood in Mfolozi
1922	Mouth closed, re-opened naturally in 1923.
1925	Serious flood in Mfolozi
1927	Drainage and canalization of Mfolozi swamp started
1932	Mouth closed and was re-opened artificially
1936	Completion of Warner's Drain in Mfolozi swamp
1952	Separate mouth cut for Mfolozi and Mfolozi and St Lucia Estuary separated
1951-1955	Mouth closed
1955	Flood
1956	Serious flood
1955-1961	Mouth closed and was re-opened artificially on three occasions
1963	Serious flood
1965	Mouth closed for a few days and was dredged open again

Important conclusions that can be drawn from this historical information are that:

- Mouth closure occurred regularly under natural conditions.
- The last recorded natural breaching occurred in 1923.
- Development in the Mfolozi floodplain and swamp was undertaken from the 1920s.
- The first artificial mouth breaching was undertaken in 1932.

The 1966 Commission of Enquiry report also highlighted that the closing of the mouth had been known to result in the trapping and death of numerous fish, including sharks. When the mouth was completely closed the flow in the Mfolozi would have entered the Narrows and even reached the Lake, thus assisting in stabilising the lake level and salinity. The report also noted that while the mouth was subjected to periodic closure, some earlier reports and maps give the impression that the estuary was at one time a large open sheet of water.

Siltation of the St Lucia estuary probably accelerated with development in the catchment of the Mfolozi. When the Mfolozi flats were opened up for sugar planting, recurrent flooding of the farms resulted in many attempts to canalise the river. This canalisation and also the drainage of the Mfolozi Swamp increased the sediment load that reached the estuary. Together with increasing soil erosion in the catchment area, this must have increased the tendency for the estuary to silt up. While the estuary was the main area affected by siltation, there was evidence that the Narrows had also silted up considerably, presumably as a result of the Mfolozi flowing up the Narrows towards the lake when the water level was low or the mouth closed. The channel connecting the lake to the sea was described as being “narrow” as early as 1904. In 1952 the Mfolozi was diverted to its present separate mouth and since then dredging in the St Lucia lagoon has greatly assisted in removing much of the silt.

Based on historical information the conclusion is that major changes to the St Lucia system were caused by:

- The development on the Mfolozi flood plain.
- The separation of the Mfolozi and the St Lucia systems.
- The efforts to keep the mouth open permanently.

Developments on the Mfolozi flood plain

One of the major impacts on the dynamics of the St Lucia system was the development of the Mfolozi flood plain, particularly for sugar cane cultivation. Impacts include:

- Artificial breaching undertaken at much lower water levels than at natural breaching, resulting in strongly reduced flushing of sediments, which in turn contributed to the perceived need to keep the mouth of the St Lucia system permanently open.
- The settling of sediments in the Mfolozi Swamp was greatly reduced, resulting in a big increase in the silt load downstream in the Mfolozi River and occasionally into the St Lucia system.
- The need to separate the Mfolozi River from the St Lucia system. This strongly reduced the river flow from the Mfolozi into St Lucia, resulting in far more severe hypersaline conditions in the lakes during drought periods.

The condition of the mouth has a major effect on the physical and biological dynamic processes of the St Lucia system. Mouth closure occurred regularly under natural conditions, but the management policy for many years was to keep the mouth of the estuary open artificially. This policy was changed more recently and at present no effort is made to keep the mouth open or to breach it again after closure.

Closure occurs normally when the water levels in the lakes are low and when a net inflow of seawater occurs through the mouth over the tidal cycle. The net inflow of seawater combined with wave action results in a net influx of marine sediments into the estuary. The ongoing build-up of sediments eventually results in the lower estuary becoming very shallow and the restriction of tidal flow. If the water level in the lake remains low and the influx of marine sediments continues, this will result in closure of the mouth. The available information indicates that closure of the mouth of the St Lucia Estuary normally occurs at a water level close to mean sea level.

Before development in the swamp area the mouth would naturally breach when the water level in the estuary exceeded the height of the berm, or when the water level was high enough to cause seepage through the berm, resulting in erosion and slumping of the barrier.

After closures, the berm at the mouth of an estuary along the KwaZulu-Natal coast normally builds up to levels of between +3.0 and +3.5 m above mean sea level and this was probably also the case at St Lucia. Breaching would then have occurred at water levels of approximately +3.0 m MSL or higher. Natural breaching would therefore have occurred after the St Lucia system including the surrounding flood plains, had filled up to about +3.0 m MSL. It is estimated that the water surface area of the lakes is approximately 300 km^2 at MSL. The surface area is probably considerably larger at +3.0 m MSL because of the flooding of the surrounding flood plains, including those of the lower Mfolozi. A preliminary estimate of the volume of water required to fill the estuary before a natural breaching would have occurred in the past is therefore approximately 1000 million m^3.

If 1 000 million m^3 were released during a natural breach it would have caused enormous scouring of the mouth and the estuary. Observations of natural breaching are unfortunately not available, but the outflow and scouring during a breaching probably would have been spectacular. Natural mouth breachings are very important for the long-term equilibrium of sedimentation and erosion in the estuary. Breaching at a much lower water level and attempting to maintain a permanently open mouth probably resulted in ongoing sedimentation in the estuary.

Separation of the Mfolozi and St Lucia systems

The flow of the Mfolozi River was a major contributor to the water balance of the lakes at low lake water levels and during closed mouth conditions. Separating the Mfolozi River therefore had a major effect on the salinity in the lakes. It is also the main cause of the very low water levels in the lakes.

Physical conditions under different management scenarios

There are four main management scenarios that can be distinguished for the St Lucia system:

1. Natural (pristine) conditions.
2. Recent past conditions; the mouth being kept open and major dredging being undertaken;
3. Present conditions; with the Mfolozi separated from St Lucia and the St Lucia mouth being allowed to stay closed;
4. Present conditions; Mfolozi again connected to St Lucia (allowing freshwater inflow to St Lucia at low lake levels and when the mouth is closed) and the common mouth being allowed to stay closed.

The physical conditions for each of these management scenarios are summarized in Table 4 based on the current understanding of the dynamics of the system.

Table 4. Summary of the physical conditions under each management scenario.

Scenario	**Physical conditions**
Natural: Pristine condition	• The Mfolozi was normally connected to the St Lucia Estuary • Mouth closures occurred regularly • The river flow from the Mfolozi at low lake levels and when the mouth was closed, prevented or at least strongly reduced the occurrence of severe hypersalinity and/or drying out of large parts of the lake. • The sediment supply to the lake from the Mfolozi was probably small, because of limited erosion in the catchment and because much of the sediment load of the Mfolozi was deposited on the floodplain of the lower Mfolozi. • Large amounts of sediments were flushed from the St Lucia Estuary when the mouth breached naturally. This probably occurred at a water level of approximately + 3.0 m MSL and more than 1 000 million m^3 would then have flowed out to the sea during a breaching. This is equivalent to, or probably even considerably more than, what would have flowed out during major floods. • Because of the high water level before natural breaching, large areas of the flood plains of St Lucia and the lower Mfolozi would have been flooded.
Recent past: Mfolozi separated from St Lucia. Mouth kept open or breached at low water levels.	• Preventing the flow from Mfolozi to St Lucia considerably changed the water balance of the system. • Strong inflow of seawater occurred for prolonged periods when the water level in the lake was low. • With ongoing evaporation there was an increase in hypersaline conditions in the lakes during drought periods. • Efforts to keep the mouth open resulted in a large influx of marine sediment into the lower estuary. Continuous dredging was undertaken to remove these sediments and to keep the mouth open. • When the mouth closed, breaching was undertaken at a very low water level. This resulted in a strong reduction in the flushing of sediment during mouth breaching. Indirectly, this probably resulted in severe ongoing sedimentation, necessitating the undertaking of comprehensive dredging.
Present: Mfolozi separated from St Lucia. Mouth allowed to close.	• Allowing the mouth to close and keeping the Mfolozi separated from St Lucia, resulted in far more severe hypersaline conditions and far longer mouth closure than occurred naturally in the system. The mouth could remain closed for five to ten years at a time. • Only after prolonged strong river flow is the natural breaching level reached. • The salinity in the lakes will gradually be reduced to lower levels when the water level in the lake is increased. • Only a much higher breaching level and a strong increase in flooding of the flood plains around St Lucia and along the lower Mfolozi will result in a flood similar to the natural conditions.
Mfolozi/St Lucia link restored with the mouth being allowed to stay closed.	• Mouth closure and salinity will return to the conditions that occurred naturally. • The influx of sediments from the Mfolozi into St Lucia could be considerably more than occurred naturally because of increased erosion in the Mfolozi catchment and the canalisation of the lower Mfolozi. This could cause serious sedimentation in the St Lucia system. • At a much higher breaching level a strong increase in flooding of the floodplain around St Lucia and along the lower Mfolozi will occur similar to what occurred under natural conditions.

The transition between the different states will not be instantaneous, but will take place gradually. It should be noted that due to the extensive surface area of the lake system (~300 km^2) the water level and salinity regime of the estuary are not immediately affected by the inflow rates (*i.e.* they are delayed) as the large basin area acts as a buffer and an increase in the flow rate does not normally directly relate to a rapid change in state. A simple basin model (Table 5) was therefore developed in which inflow from the five river systems (Mkuze, Mzinene, Nyalazi, Hluhluwe and Mpate), directly into the estuary, groundwater, direct rainfall, evaporation and the discharge to and from the sea were combined to estimate the water level of the St Lucia system. The lake level, in turn was used to evaluate probable mouth conditions and the salinity regime of the system for any particular month

Table 5. The components of the Lake St Lucia water balance model.

Inflows/Outflows	**Volume yr^{-1} (10^6 m^3)**
Rivers (5)	417 (Natural): 362 x 10^6 m^3 (Present, i.e. a 13.2 % reduction)
Groundwater	23
Rainfall	273
Evaporation	-420
Net Inflow	238
Mfolozi	920

For the reference condition it was also assumed that the Mfolozi and the St Lucia estuaries interacted at a water level below 0.1 m mean lake level, at which point the Lake St Lucia mouth could close. For the benefit of the evaluation, the monthly runoff from the Mfolozi (Reference MAR 920 x 10^6 m^3) was used to evaluate the effect of the additional Mfolozi runoff on the St Lucia mouth. The Mfolozi inflow was mainly considered when the St Lucia mouth was closed. The water balance model assumed that the St Lucia system breaches naturally at approximately 3.0 m above Mean Lake Level. The past management practices of artificially breaching the estuary at far lower than natural water levels were also evaluated, but the water balance model was not very sensitive to changes in the breaching level, *e.g.* lowering the breaching level to 2.0 m above Mean Lake Level only increased open mouth conditions by 5%. Therefore, in the Rapid Ecological Water Requirement study the mouth breaching level was taken as 3.0 m Mean Lake Level.

Based on the limited data available, three Abiotic States were derived for the St Lucia Estuary, the occurrence and duration of which depends on river inflow. These states are summarised in Table 6.

Table 6. Abiotic states of St Lucia Estuary linked to mouth condition and salinity level.

No.	State	Water level
1	Open, with marine influence	> 0.1 m
2	Closed, brackish	0.1-3.0 m
3	Closed, potentially hypersaline (*i.e.* salinity greater than 40 PSU)	< 0.1 m

The occurrence and duration of the different abiotic states during the Reference Condition and Present State are illustrated in the simulated monthly water levels tables (Tables 7 and 8). To provide a conceptual overview of the distribution of abiotic states under the Reference Condition, the total occurrence of the various states for the 53-year period were used to depict both the Reference Condition and the Present State (Figure 8). Note that a water level of less than 0.1 m Mean Lake Level was taken as indicative of months in which State 3: Closed, Hypersaline conditions can potentially develop.

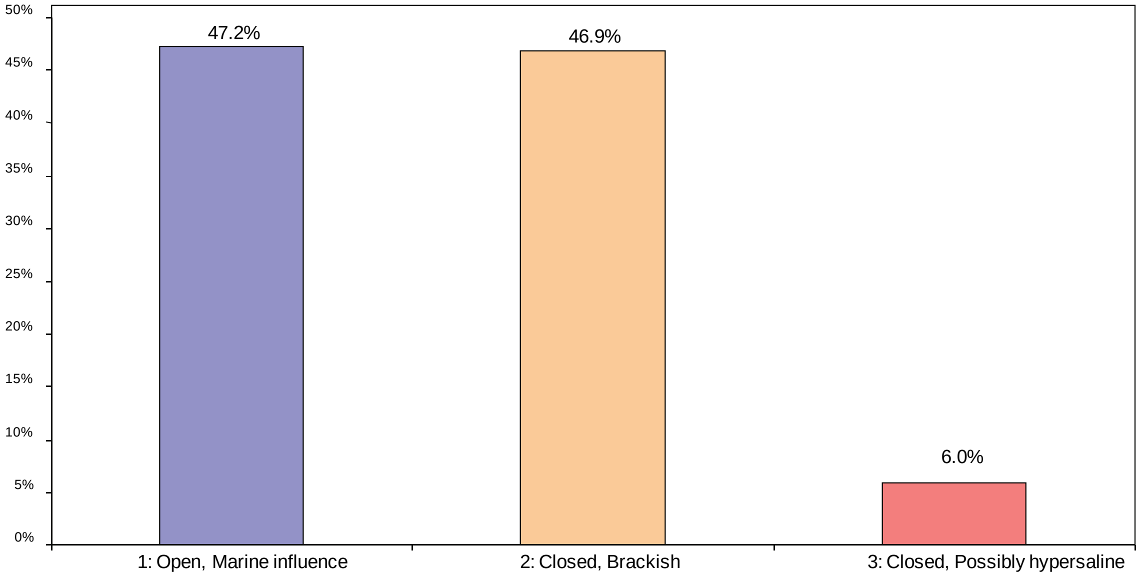

Figure 8. The occurrence and duration of different abiotic states under the Reference Condition (top) and Present State (bottom).

Table 7: Monthly water level data (m above or below Mean Lake Level) for the Reference Condition.

YEAR	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Closed	State 3
1926	0.32	0.26	0.20	0.16	0.20	0.28	0.25	0.21	0.18	0.22	0.17	0.16		
1927	0.23	0.24	0.24	0.38	0.33	0.25	0.24	0.21	0.19	0.17	0.16	0.18		
1928	0.17	0.14	0.13	0.20	0.20	0.61	0.48	0.32	0.30	0.26	0.23	0.28		
1929	0.29	0.25	0.22	0.74	0.58	0.44	0.32	0.25	0.21	0.19	0.17	0.16		
1930	0.15	0.20	0.18	0.16	0.14	0.15	0.15	0.15	0.15	0.15	0.12	0.11		
1931	0.08	0.23	0.19	0.09	0.53	0.49	0.52	0.47	0.36	0.27	0.21	0.18		
1932	0.14	0.19	0.36	0.37	0.36	0.30	0.23	0.18	0.16	0.18	0.14	0.13		
1933	0.12	0.29	0.47	0.53	0.42	0.33	0.30	0.26	0.24	0.23	0.23	0.18		
1934	0.15	0.15	0.27	0.23	0.20	0.17	0.15	0.17	0.17	0.16	0.13	0.08		
1935	0.02	-0.05	-0.12	0.78	1.66	2.90	0.55	0.41	0.31	0.26	0.19	0.16	6	3
1936	0.21	0.52	0.36	0.58	0.76	0.53	0.36	0.25	0.21	0.19	0.17	0.16		
1937	0.12	0.12	0.47	0.35	0.29	0.25	0.24	0.20	0.25	0.27	0.21	0.16		
1938	0.19	0.14	0.43	0.38	0.97	0.83	0.50	0.40	0.30	0.28	0.23	0.30		
1939	0.24	0.54	0.39	0.41	0.28	0.46	0.35	0.34	0.50	0.38	0.32	0.27		
1940	0.22	0.41	0.58	0.42	0.36	0.31	0.27	0.21	0.19	0.17	0.14	0.14		
1941	0.08	0.10	0.17	0.75	1.15	2.16	2.52	2.62	2.77	2.86	2.94	0.75	10	1
1942	0.40	0.41	0.58	0.36	0.38	0.79	0.93	0.64	0.41	0.41	0.43	0.32		
1943	0.33	0.37	0.42	0.30	0.48	0.36	0.25	0.20	0.31	0.26	0.19	0.24		
1944	0.21	0.20	0.14	0.17	0.28	0.48	0.38	0.29	0.23	0.19	0.14	0.10		
1945	0.11	0.03	0.03	1.39	2.00	2.27	2.37	2.40	2.42	2.40	2.37	2.36	10	1
1946	2.43	2.56	2.78	2.91	0.63	0.40	0.30	0.23	0.22	0.19	0.15	0.17	4	
1947	0.18	0.20	0.22	0.16	0.19	0.31	0.29	0.23	0.19	0.16	0.12	0.13		
1948	0.12	0.20	0.15	0.53	0.54	0.35	0.48	0.36	0.28	0.23	0.18	0.19		
1949	0.18	0.22	0.49	0.47	0.39	0.33	0.26	0.23	0.20	0.18	0.15	0.10		
1950	0.09	0.04	0.61	0.96	1.02	1.12	1.29	1.39	1.44	1.45	1.71	1.83	12	2
1951	2.08	2.11	2.37	2.52	2.64	2.70	2.72	2.75	2.76	2.84	2.83	2.78	12	
1952	2.74	2.91	0.73	0.44	0.30	0.25	0.20	0.21	0.18	0.16	0.14	0.15	2	
1953	0.21	0.53	0.43	0.27	0.26	0.21	0.23	0.30	0.25	0.20	0.18	0.22		
1954	0.37	0.34	0.22	0.36	0.36	0.53	0.41	0.31	0.25	0.20	0.16	0.12		
1955	0.17	0.27	0.33	0.21	0.75	0.58	0.35	0.28	0.23	0.19	0.16	0.16		
1956	0.22	0.20	0.45	0.38	0.33	0.27	0.27	0.24	0.21	0.24	0.21	0.57		
1957	0.96	0.62	0.37	0.71	0.69	0.41	0.32	0.23	0.22	0.18	0.14	0.17		
1958	0.23	0.27	0.48	0.43	0.28	0.18	0.14	0.18	0.16	0.15	0.16	0.16		
1959	0.22	0.22	0.20	0.15	0.36	0.40	0.39	0.31	0.24	0.20	0.17	0.18		
1960	0.18	0.52	0.71	0.55	0.40	0.33	0.32	0.27	0.30	0.25	0.21	0.26		
1961	0.26	0.28	0.20	0.17	0.11	0.21	0.22	0.18	0.15	0.13	0.16	0.12		
1962	0.12	0.43	0.44	0.33	0.27	0.25	0.24	0.19	0.25	0.98	0.63	0.36		
1963	0.29	0.29	0.26	0.44	0.34	0.26	0.34	0.27	0.24	0.20	0.16	0.12		
1964	0.32	0.27	0.25	0.17	0.14	0.10	0.10	0.10	0.12	0.13	0.23	0.19		
1965	0.21	0.22	0.16	0.74	0.68	0.39	0.27	0.22	0.20	0.17	0.16	0.14		
1966	0.11	0.10	0.12	0.22	0.54	0.42	0.38	0.29	0.24	0.22	0.17	0.15		
1967	0.16	0.21	0.14	0.10	0.11	0.21	0.18	0.15	0.14	0.14	0.15	0.14		
1968	0.14	0.13	0.15	0.12	0.13	0.57	0.47	0.35	0.28	0.22	0.17	0.15		
1969	0.30	0.24	0.18	0.11	0.10	0.10	0.08	0.15	0.18	0.18	0.18	0.22	7	2
1970	0.37	0.68	0.75	1.19	1.41	1.53	1.73	2.95	0.52	0.36	0.25	0.21	8	
1971	0.22	0.25	0.38	0.57	1.13	0.74	0.42	0.40	0.33	0.27	0.21	0.16		
1972	0.14	0.17	0.16	0.11	0.23	0.20	0.19	0.17	0.15	0.14	0.25	0.50		
1973	0.37	0.44	0.42	0.54	0.41	0.30	0.25	0.24	0.22	0.19	0.15	0.11		
1974	0.09	0.20	0.24	0.36	0.66	0.50	0.37	0.29	0.24	0.20	0.17	0.28		
1975	0.23	0.24	0.60	0.94	0.71	0.64	0.51	0.39	0.29	0.27	0.22	0.16		
1976	0.24	0.22	0.22	0.38	0.98	0.75	0.47	0.31	0.26	0.21	0.19	0.25		
1977	0.23	0.17	0.21	0.51	0.45	0.40	0.34	0.26	0.23	0.26	0.24	0.20		
1978	0.34	0.36	0.27	0.19	0.15	0.10	0.17	0.18	0.16	0.15	0.15	0.17		
													71 11%	10 2%

☐ 1: Open

▨ 2: Closed Brackish BrackishBrackish

0.31 3: Closed, Potentially Hypersaline

Table 8: Simulated Monthly water level data (m above or below Mean Lake Level) for the Present State (without Mfolozi inflow) and mouth closure occurs at a water level below 0.1 m Mean Lake level.

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Closed	State
1926	0.31	0.24	0.18	0.15	0.19	0.26	0.23	0.19	0.16	0.21	0.16	0.14		
1927	0.21	0.22	0.23	0.37	0.31	0.23	0.23	0.20	0.18	0.16	0.14	0.16		
1928	0.15	0.12	0.11	0.18	0.18	0.58	0.47	0.31	0.29	0.25	0.22	0.27		
1929	0.28	0.24	0.21	0.72	0.56	0.43	0.32	0.24	0.20	0.17	0.16	0.15		
1930	0.12	0.18	0.17	0.15	0.12	0.13	0.13	0.13	0.13	0.13	0.10	0.06		
1931	-0.02	0.09	0.05	-0.09	0.38	0.61	0.88	1.07	1.13	1.11	1.07	1.03	12	4
1932	0.96	1.00	1.22	1.35	1.44	1.47	1.44	1.39	1.35	1.35	1.28	1.23	12	
1933	1.18	1.36	1.68	2.01	2.10	2.14	2.18	2.19	2.20	2.21	2.22	2.16	12	
1934	2.11	2.08	2.19	2.17	2.14	2.10	2.05	2.05	2.04	2.00	1.94	1.85	12	
1935	1.74	1.64	1.53	1.67	1.96	2.16	2.16	2.26	2.27	2.27	2.21	2.16	12	
1936	2.19	2.64	2.67	0.86	0.80	0.54	0.35	0.24	0.19	0.18	0.15	0.14	3	
1937	0.09	0.05	0.46	0.49	0.50	0.51	0.52	0.48	0.55	0.60	0.57	0.49	11	2
1938	0.51	0.43	0.78	0.87	2.07	2.85	2.97	0.60	0.37	0.30	0.23	0.30	7	
1939	0.23	0.52	0.37	0.40	0.27	0.43	0.33	0.33	0.47	0.35	0.30	0.26		
1940	0.20	0.39	0.56	0.40	0.34	0.29	0.26	0.20	0.17	0.15	0.12	0.11		
1941	0.02	-0.04	-0.06	0.16	0.15	0.41	0.45	0.46	0.51	0.51	0.53	0.52	11	2
1942	0.51	0.66	1.12	1.11	1.24	2.11	0.98	0.64	0.40	0.40	0.42	0.31	6	
1943	0.32	0.36	0.40	0.28	0.46	0.34	0.24	0.18	0.30	0.24	0.18	0.22		
1944	0.19	0.17	0.12	0.14	0.26	0.47	0.36	0.28	0.22	0.17	0.12	0.06		
1945	0.01	-0.10	-0.17	0.31	0.53	0.64	0.62	0.57	0.55	0.50	0.43	0.39	12	3
1946	0.37	0.34	0.38	0.37	0.61	0.65	0.64	0.60	0.61	0.58	0.52	0.51	12	
1947	0.50	0.51	0.52	0.44	0.45	0.61	0.64	0.60	0.56	0.51	0.43	0.41	12	
1948	0.36	0.41	0.34	0.83	1.13	1.12	1.44	1.48	1.48	1.46	1.40	1.39	12	
1949	1.37	1.40	1.80	2.01	2.10	2.15	2.14	2.12	2.09	2.06	2.00	1.91	12	
1950	1.86	1.75	2.04	2.19	2.17	2.16	2.19	2.18	2.18	2.14	2.26	2.23	12	
1951	2.28	2.18	2.20	2.16	2.11	2.06	2.01	1.99	1.96	1.96	1.89	1.79	12	
1952	1.71	1.77	2.29	2.34	2.31	2.29	2.25	2.25	2.22	2.18	2.12	2.10	12	
1953	2.12	2.53	2.64	2.57	2.59	2.56	2.59	2.70	2.69	2.65	2.61	2.65	12	
1954	2.87	2.93	2.86	0.83	0.50	0.55	0.40	0.30	0.24	0.19	0.14	0.09	3	
1955	0.13	0.24	0.31	0.18	0.73	0.57	0.34	0.27	0.22	0.18	0.14	0.14		
1956	0.19	0.18	0.42	0.36	0.32	0.25	0.25	0.22	0.19	0.22	0.19	0.56		
1957	0.95	0.61	0.35	0.69	0.68	0.39	0.30	0.22	0.21	0.16	0.12	0.15		
1958	0.21	0.25	0.46	0.42	0.27	0.16	0.12	0.16	0.15	0.13	0.14	0.14		
1959	0.20	0.20	0.18	0.13	0.33	0.38	0.37	0.28	0.23	0.18	0.15	0.16		
1960	0.16	0.49	0.69	0.53	0.39	0.32	0.31	0.26	0.29	0.24	0.19	0.24		
1961	0.25	0.27	0.18	0.14	0.06	0.13	0.16	0.13	0.12	0.10	0.13	0.07		
1962	0.03	0.37	0.56	0.58	0.57	0.58	0.59	0.54	0.60	1.94	2.27	2.22	12	1
1963	2.24	2.30	2.30	2.59	2.61	2.58	2.70	2.69	2.69	2.65	2.59	2.52	12	
1964	2.72	2.71	2.72	2.63	2.57	2.49	2.45	2.40	2.38	2.35	2.41	2.36	12	
1965	2.37	2.37	2.30	0.97	0.72	0.38	0.26	0.21	0.19	0.16	0.15	0.12	3	
1966	0.06	-0.01	-0.03	0.04	0.47	0.57	0.67	0.67	0.65	0.63	0.57	0.52	11	3
1967	0.50	0.53	0.43	0.34	0.31	0.37	0.34	0.28	0.24	0.20	0.18	0.13	12	
1968	0.09	0.05	0.02	-0.04	-0.07	0.42	0.56	0.60	0.59	0.56	0.49	0.45	12	5
1969	0.60	0.56	0.50	0.39	0.31	0.23	0.16	0.15	0.12	0.07	0.01	-0.02	12	3
1970	-0.03	0.01	-0.09	0.03	0.06	0.07	0.11	0.28	0.31	0.33	0.28	0.25	12	6
1971	0.27	0.31	0.51	0.93	2.39	2.88	2.90	0.80	0.44	0.31	0.22	0.15	7	
1972	0.13	0.15	0.13	0.06	0.16	0.15	0.15	0.14	0.12	0.11	0.21	0.46		1
1973	0.33	0.42	0.41	0.53	0.39	0.29	0.23	0.22	0.20	0.17	0.13	0.06		
1974	0.00	0.06	0.10	0.26	0.76	0.93	0.99	0.99	0.98	0.94	0.89	1.01	12	3
1975	0.98	1.00	1.57	2.66	0.91	0.68	0.52	0.39	0.29	0.26	0.21	0.14	4	
1976	0.21	0.19	0.19	0.35	0.94	0.71	0.45	0.30	0.24	0.19	0.17	0.23		
1977	0.21	0.14	0.18	0.48	0.42	0.41	0.34	0.25	0.22	0.25	0.22	0.18		
1978	0.31	0.33	0.24	0.16	0.12	0.04	0.08	0.07	0.04	-0.01	-0.03	-0.04	6	6
													336 53%	38 5.97%

☐ 1: Open ▨ 2: Closed ▨ 0.31 3: Closed, potentially hypersaline

The 2004 Rapid Ecological Water Requirement Study determined the Present Ecological Status of St Lucia using the Estuarine Health Index (DWAF, 2004a). The Health Index consists of a Habitat Health score and a Biological Health score. The scores are 'percentage deviation' from the Reference Condition, *e.g.* if the Present State is still the same as the Reference Condition then the score is 100. The average of these two scores provides the Estuarine Health score (Table 9).

Table 9 Health Status of St Lucia (DWAF, 2004b).

Variable	**Weight**	**Scores for Present state**
Hydrology	25	71
Hydrodynamics and mouth condition	25	40
Water quality	25	57
Physical habitat alteration	25	65
Habitat health score		**58**
Microalgae	20	30
Macrophytes	20	30
Invertebrates	20	30
Fish	20	40
Birds	20	40
Biotic health score		**34**
Estuarine health score		**46**

The health score for the St Lucia Estuary, based on its Present State, was 46, translating into a present ecological status of D indicating that the system was "Largely modified (Table 10).

Table 10. Present Ecological Status based on the Estuary Health Index score.

Estuary Health Index score	**Present Ecological Status**	**General description**
91-100	A- to A+	Unmodified, natural
76-90	B- to B+	Largely natural with few modifications
61-75	C- to C+	Moderately modified
41-60	D- to D+	Largely modified
21-40	E	Highly degraded
0-20	F	Extremely degraded

Lake St Lucia forms part of the Greater St Lucia Wetland Park. The park was granted Word Heritage Site status under the World Heritage Convention Act (November 2000). St Lucia was granted Ramsar status in 1991. Adjacent to the Greater St Lucia Wetland Park is also a Marine Protected Area. The iSimangaliso Wetland Parks Authority and EKZNW administer the park. In terms of socio-economic importance, the Wetland Park forms the focal point that anchors the Lubombo Spatial Development Initiative, which strives to create livelihoods through tourism initiatives (Scott, pers. comm.). From an ecological perspective, estuarine importance is an expression of the value of the system to provide and maintain ecological diversity and function within a local and regional scale. Turpie *et al.* (2004) ranked the St Lucia Estuary nationally as the 6th most important system in South African in terms of conservation importance. The Estuarine Importance Score for Lake St Lucia Estuary was 92, indicating that the estuary was considered as ‘Highly Important’.

The Recommended Ecological Category (REC) represents the level of protection assigned to an estuary. In turn, it is again used to determine the Ecological Water Requirement Flow Scenario. The degree to which an estuary’s health condition needs to be improved depends on the importance of the estuary and any modifying determinants, *i.e.* protected area status and desired protected area status. The proposed rules for the allocation of the recommended Ecological Category are defined in Table 11.

Table 11. Guidelines for allocating a Recommended Ecological Category based on its current or desired protection status and estuarine importance.

Current/desired protection status and estuarine importance	Ecological category	Policy basis
Protected area	A or BAS	Protected and desired protected areas should be restored to, and maintained in the best possible state of health.
Desired Protected Area (based on complementarily)	A or BAS	
Highly important	PES + 1, min B	Highly important estuaries should be in an A or B class.
Important	PES + 1, min C	Important estuaries should be in an A, B or C class.
Of low to average importance	PES, min D	The remaining estuaries can be allowed to remain in a D class.

The St Lucia lakes are a Ramsar site (*i.e.* a protected area in particular for water birds), a World Heritage site and adjacent to a Marine Protected Area. According to the DWAF (2004a) guidelines the recommended Ecological Category should therefore be a Category A; if this is not achievable the Best Attainable State (BAS) is recommended. Due to the very high importance of the St Lucia Estuary, the study recommended that management should strive towards managing the system as a “near pristine” (Category A) estuary because there is insufficient evidence at present to indicate that this is not achievable. This conclusion was further supported by a sensitivity analysis of the effect of mitigation measures such as linking the main St Lucia lake system to the Mfolozi River, reducing the sediment load reaching the estuary and or reducing or eliminating the fishing effort in the system. The analyses indicated that the estuary is remarkably sensitive to the above mentioned mitigation measures and that additional scenarios (not just relating to flow modifications) need to be evaluated in future to establish the viability of elevating the estuary to a near pristine condition (Category A system).

Anthropogenic developments along the banks of the estuary (*i.e.* non-flow related modifications), such as the drainage and canalisation of the Mfolozi Swamp, the construction of weirs on the Nyalazi, Hluhluwe and Mpate rivers and an overall reduction in bird habitat on a national and international scale also contribute to the present degraded status of St Lucia. It is therefore impossible to reverse modifications and to improve the Ecological Category through river flow adjustments alone.

The study strongly recommended that mitigatory actions to reverse impacts caused by non-flow related activities, such as over exploitation of fish and developments in the Mfolozi floodplain, be investigated and if possible be addressed by the responsible authorities. The study also concluded that while the possibility of attaining an Ecological Category A is investigated, the relevant government department should strive towards implementing the recommendations for an Ecological Category B.

NATIONAL BIODIVERSITY ASSESSMENT 2010

International biodiversity obligations require South Africa to report on ecosystem status every five years. A national health assessment was recently undertaken (November 2009) to assess the status of South African estuaries, updating the previous national biodiversity assessment conducted in 2004.

The assessment followed a desktop approach using available data and information, as well as expert knowledge. To allow for spatial interrogation, Google Earth/Spot5 imagery was used to delineate open water areas, estuarine habitat and flood plain areas for all 290 estuaries. Available data on threats, *e.g.* freshwater inflow modification, water quality (*e.g.* effluent discharges, agricultural activities), artificial breaching, habitat modification, living resources exploitation and recreational activities were collated or estimated for every system. Workshops with estuarine experts knowledgeable on systems across different biogeographical regions were convened to estimate ecological health. The Estuarine Health Index was applied to all the systems in South Africa. Health was express as a percentage similarity to a predicted pristine condition.

To reflect the overall ecosystem status of South African estuaries the individual ecological health scores were then translated into health categories (“excellent”, “good”, ‘fair” and “poor”) and aggregated for the various estuarine types. One of the major finding was that while a large number of South African estuaries were still in an “excellent” or “good” condition; these were mainly very small systems. The larger systems which comprise most of the estuarine area in the country, and are the most important nursery grounds, were predominantly in a “fair” or “poor” condition, thus alluding to one of the reasons for the slow stock recovery of linefish species.

The St Lucia lake system was evaluated as part of the National Biodiversity Assessment. This included a revision of the 2004 Rapid Ecological Water Requirement Study and a separate assessment of the Msunduzi and Mfolozi estuaries (Table 12 and 13).

The study found that there was a general decline in the health of St Lucia, particularly over the past six years, and that this could be attributed to its separation from the Mfolozi.

Invertebrates were deemed to be in an especially poor condition as a result of the high salinity in the system. The Msunduzi and Mfolozi estuaries were in a significantly healthier condition, with the Msunduzi given a score of 63% (Category C) and Mfolozi 57 % (Category D), relative to their pristine conditions. This said, aspects such as habitat destruction, poor water quality, loss of riparian vegetation, modification in the abundance and community composition of invertebrates fish and birds were pointing to a worrying decline in health of the overall system. This is of great concern because the larger St Lucia system represents nearly 50% of South Africa's estuarine area.

Table 12. Updated Health Status of Lake St Lucia (DWAF, 2004, CSIR in prep).

Component	**2004**	**2009**
Hydrology	71	35
Hydrodynamics	40	40
Water Quality	57	56
Physical habitat	65	65
Habitat Score	**58**	**49**
Microalgae	30	30
Macrophytes	30	30
Invertebrates	30	10
Fish	40	25*
Birds	40	40
Biological Score	**34**	**27**
Estuary Health Index Score	**46**	**38**
Ecological Category	**D**	**E**

*The 2004 score of 40 was decreased by 15% due to fishing pressures after comments made by Cyrus (pers. comm.)

Table 13. The health status of the Msunduzi and Mfolozi estuaries (CSIR in prep).

Component	**Msunduzi**	**Mfolozi**
Hydrology	80	80
Hydrodynamics	90	70
Water Quality	62	50
Physical habitat	40	60
Habitat Score	**68**	**65**
Microalgae	73	68
Macrophytes	50	30
Invertebrates	40	50
Fish	60	60
Birds	70	40
Biological Score	**59**	**50**
Estuary Health Index Score	**63**	**57**
Ecological Category	**C**	**D**

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were drawn from the above studies:

- The Mfolozi River Estuary should be re-connected to Lake St Lucia in the mouth area.
- The greater St Lucia estuarine system operates in long cycles and there are only data for some of its phases/states. There is therefore an ongoing data collecting requirement (*e.g.* bathymetry, nutrient dynamics and sedimentation).
- There is a need to look at engineering solutions for sediment load – but this should not prevent the linking of the two systems near St Lucia mouth.
- If a common St Lucia mouth closes it will back flood into the Mfolozi/Msunduzi system. Flow velocities will decrease and the river will deposit more of its sediment load in the Mfolozi and Msunduzi causing some localised siltation, but the systems should be able to flush this during floods.
- The St Lucia Estuary should be able to flush coarser sediment accumulated in the Narrows during breaching and fine sediment can be taken out during re-suspension when the mouth is open.

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AN ASSESSMENT OF THE MICROALGAE AND MACROPHYTES OF THE MSUNDUZI ESTUARY

Sibulele Nondoda[1], Janine Adams[1*], Guy Bate[1] & Ricky Taylor[2]

Affiliation: [1]Department of Botany, Nelson Mandela Metropolitan University, Port Elizabeth
[2]Ezemvelo KZN Wildlife, St Lucia Estuary, and School of Biological and Conservation Sciences, University of KwaZulu-Natal, Pietermaritzburg
**Email: janine.adams@nmmu.ac.za*

INTRODUCTION

Historically, the Mfolozi and the Msunduzi systems had a common mouth and an important relationship with the St Lucia Estuary. The Mfolozi used to flow into the Msunduzi channel, but in 1952 the Mfolozi was artificially diverted to flow directly into the sea at Maphelane, 1.5 km south of St Lucia. Presently the Mfolozi and the Msunduzi are separate systems with a common mouth. St Lucia is separated from the Msunduzi and the Mfolozi by dykes and banks up to 3 m high (Begg, 1978; van Vuuren, 2009). The dynamic St Lucia system is controlled by numerous processes including a very variable rainfall, high evaporation rate, freshwater inflow from the eastern dune cordon, variable river inflow and periodic large floods, each operating on different temporal and spatial scales. For the past eight years the St Lucia Estuary has experienced droughts and as a result the mouth closed naturally in July 2002. The only way of alleviating this and other droughts is to permanently re-link the Mfolozi to St Lucia, which historically has been its ‘major freshwater supplier’. However, before any artificial re-linking can be implemented the structure and functioning of the Mfolozi/Msunduzi system must be understood so that no unexpected damage is done to it.

The Msunduzi Estuary is driven by infrequent flood events which alter channel morphology. Begg (1978) described the floods of the Msunduzi catchment as ‘vicious and devastating’, with average flow rates of 2000 $m^3 s^{-1}$. The largest and most devastating floods on record, the ones that completely altered the river courses of both the Mfolozi and the Msunduzi, occurred in 1984 and 1987. In 1984, Cyclone Domoina resulted in discharges that peaked at 16 000 $m^3 s^{-1}$ and caused a change of flow from a northern Mfolozi River course into the southern Msunduzi River course. After Domoina, sugarcane farmers returned the Mfolozi River to its original northern course, to prevent flooding of farms on the Mfolozi swamp (Grenfell *et al*., 2009).

Macrophytes and microalgae are good indicators of the health of an estuary. Macrophytes are anchored and each plant species has a different range of environmental conditions that it can tolerate. There have been a few recent publications on the primary producers of St Lucia Estuary (Taylor, 2006; Taylor *et al*., 2006a; Bate & Smailes, 2008; Gordon *et al*., 2008) but no detailed work has been conducted on either the Mfolozi or Msunduzi estuaries. The purpose of this study was to provide a baseline of information on the botanical characteristics of the Msunduzi Estuary and to gain an impression of the changes in the vegetation that have taken place over the recent past.

Specific objectives of the study were to:

- Record the present vegetation distribution along the length of the Msunduzi Estuary and compare it with earlier photographs.
- Interpret the vegetation changes that have taken place in the recent past and propose possible causes.
- Measure phytoplankton biomass and community composition together with physico-chemical factors within the water column.
- Sample and identify benthic microalgae.

SUMMARY OF FINDINGS

Salinity, Secchi depth and nutrients

The Msunduzi Estuary is shallow and river-dominated with an average depth of 1 m. Hyposaline conditions were dominant throughout the estuary in April 2009. The only site with a marine influence was 0.84 km from the mouth (Figure 1). The estuary was extremely turbid at the time of sampling. Figure 2 illustrates Secchi depths ranging from 0.1 m to 0.25 m. The greatest Secchi depth was 0.25 m in the vicinity of the mouth, followed by 0.22 m at 13.11 km from the mouth. Salinity conditions are important as they determine estuarine biological processes and influence chlorophyll *a* and nutrient concentrations (Bate and Taylor, 2008). The state of the mouth influences salinity, nutrients and chlorophyll *a* biomass. It is therefore important to note that these samples were collected during an open mouth period when large quantities of nutrients were likely flowing in the water towards the sea. River dominated estuaries tend to have low phytoplankton biomass because of high flow rates and a short water retention time. (Snow *et al*., 2000, 2008).

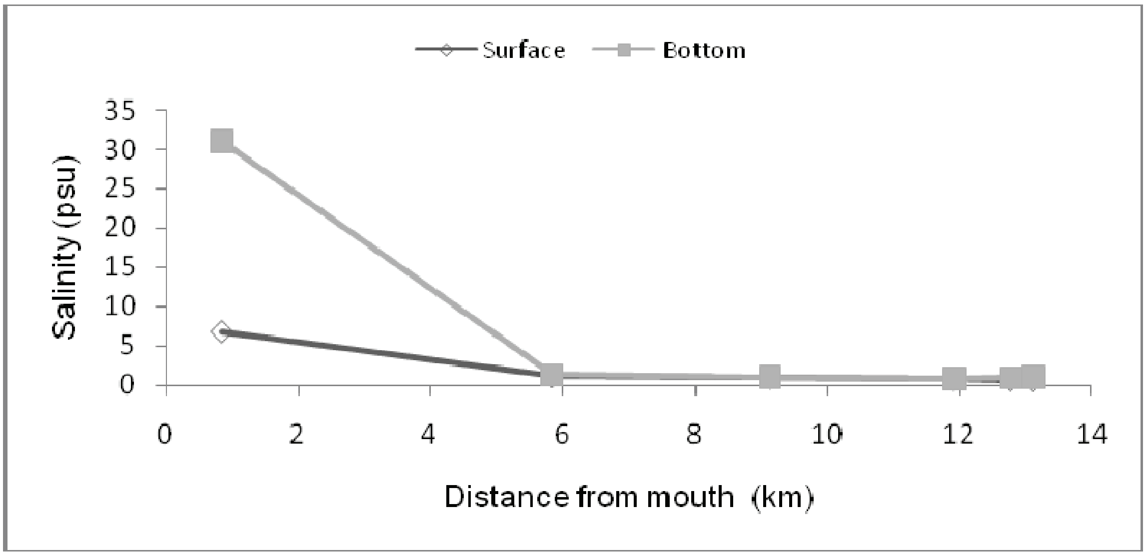

Figure 1. The salinity of the Msunduzi Estuary (April 2009) from the mouth to the upper reaches.

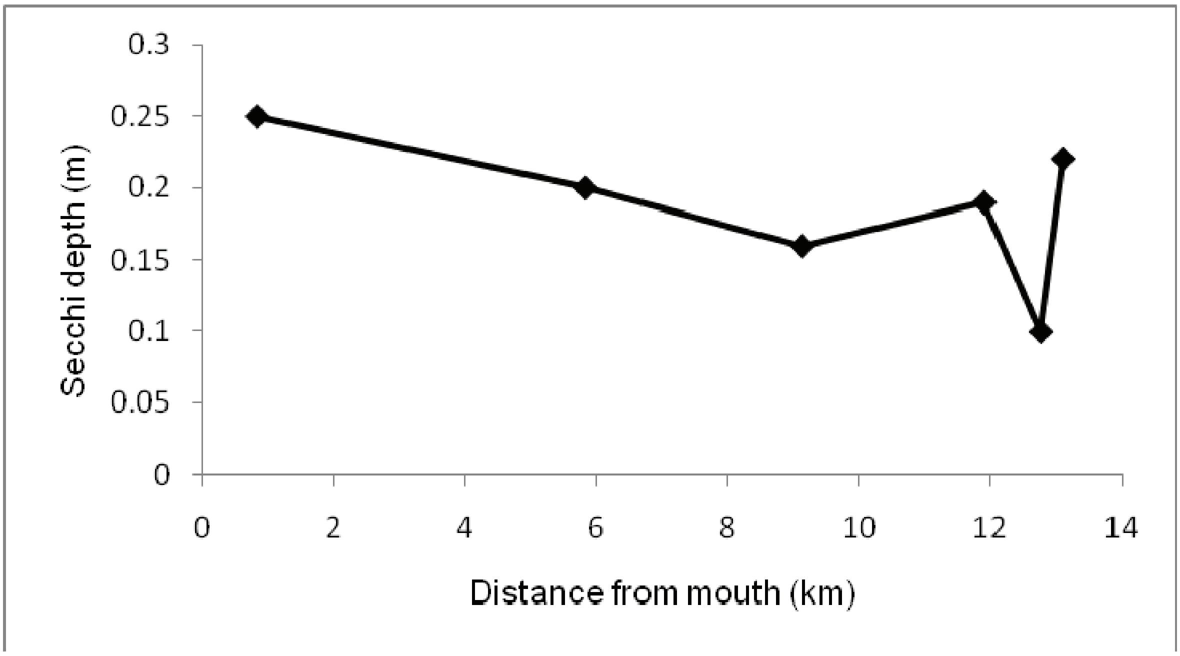

Figure 2. Secchi depth along the length of the Msunduzi Estuary.

Figure 3 shows phosphate concentrations along the length of the estuary. No statistically significant difference could be detected between phosphate concentrations of the surface and bottom water column (t = 1. 22, df = 7, p = 0.263). In addition no statistically significant difference could be detected between nitrate concentrations of the surface and bottom water column (t = 1. 26, df = 7, p = 0.247) (Figure 4).

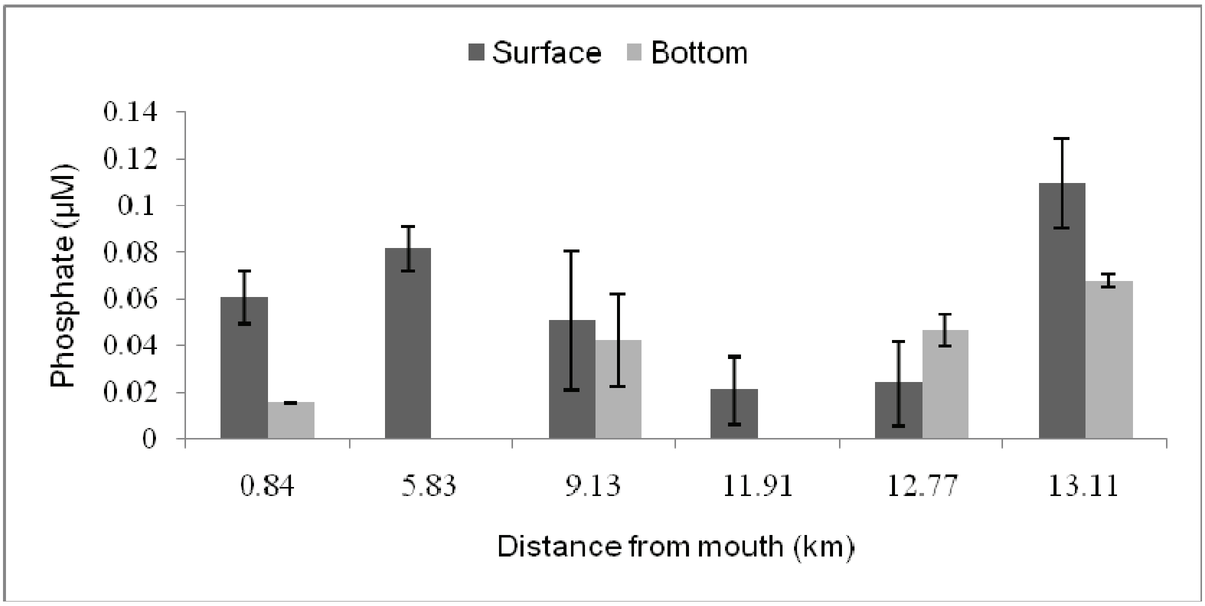

Figure 3. Soluble reactive phosphate concentrations along the length of the estuary (vertical bars represent ± SE).

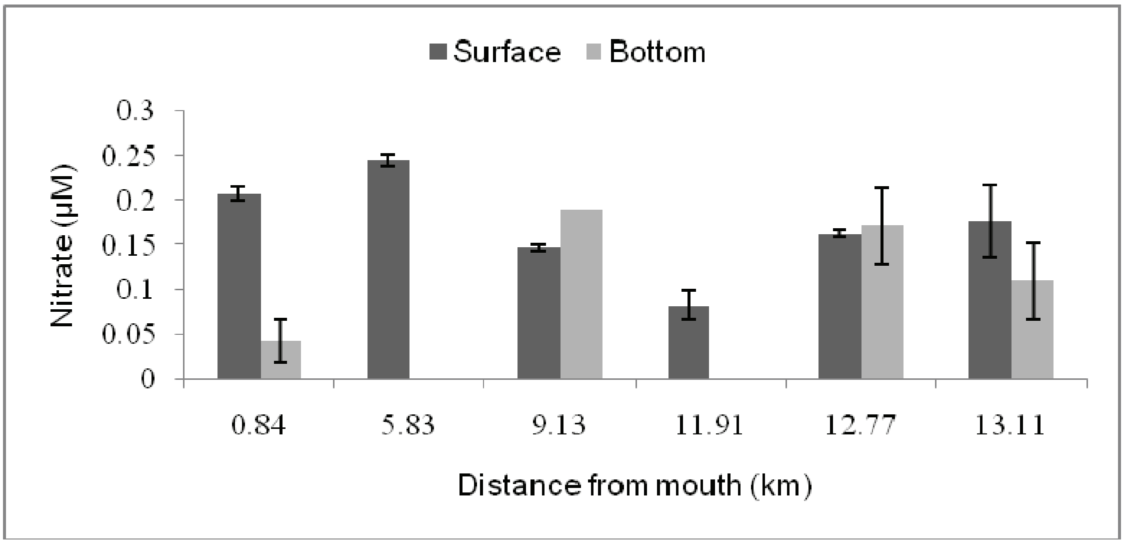

Figure 4. Nitrate concentrations along the length of the estuary. Vertical bars represent ± SE.

Phytoplankton biomass

Figure 5 shows water column chlorophyll *a* concentrations along the length of the estuary. There was no significant difference between the concentrations of the surface and bottom water ($p > 0.05$, $n = 12$, $Z = 1.07$; Wilcoxon paired-sample test). The highest average chlorophyll *a* concentration was 12.6 µg l^{-1} at 0.84 km, at the only site influenced by seawater and the lowest concentration was 1.2 µg l^{-1} at 5.83 km from the mouth.

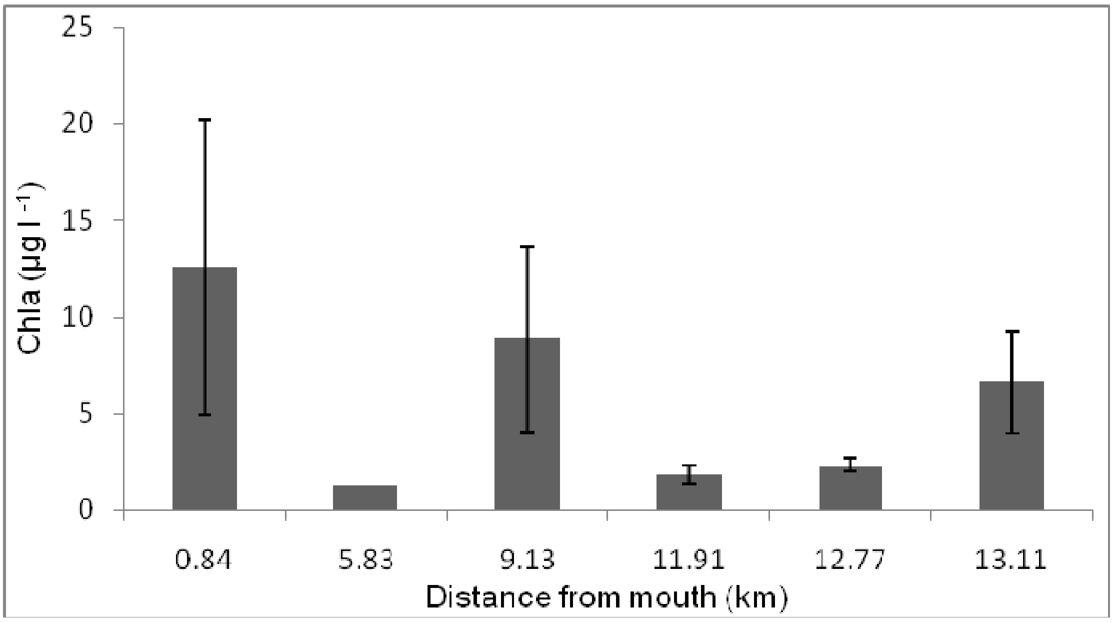

Figure 5. Longitudinal phytoplankton chlorophyll *a* concentrations in the estuary. Vertical bars represent ± SE.

Average chlorophyll *a* concentrations ranged between 1.24 and 12.6 µg l^{-1} but were lower than 7 µg l^{-1} at most of the sites. High nutrient concentrations in the fresher water indicated that river water was the source of nutrients. The maximum chlorophyll *a* concentration of 12.6 µg l^{-1} was found at 0.84 km from the mouth. There was no evidence of a highly productive river estuary interface (REI) zone (Bate *et al.*, 2002) as the average chlorophyll *a* of the six sites sampled along the length of the Msunduzi Estuary was 6.0 ± 2.3 µg l^{-1} and the mean phytoplankton chlorophyll *a* was 1.86 µg l^{-1}. This is in the low biomass class of the classification scheme of phytoplankton chlorophyll *a* (Table 1).

Table 1. Classification scheme of median phytoplankton chlorophyll *a* for estuaries obtained using microalgal biomass data from estuary freshwater requirement studies (Snow, 2008).

Biomass class	**Median chlorophyll *a*** (µg l^{-1})
Very low	Less than 1.0
Low	1 to 3.5
Medium	3.5 to 8.0
High	> 8.0

Phytoplankton community composition

Figure 6 shows the relative abundance of phytoplankton groups and the dominance of diatoms. The highest diatom abundance was 88% found at 11.91 km from the mouth and the lowest was 21% at 13.11 km. The lowest abundance of flagellates was 12% at 11.91 km and the highest was 79% at 13.11 km. The dominant diatom species, *Nitzschia palea* (Kützing) W. Smith was present in high concentrations of up to 13 935 frustules ml $^{-1}$ in the surface water column (Figure 7). It is linear-lanceolate in shape and has capitate endings with fibulae that are evenly spaced. Taylor *et al.* (2006b) described the species as cosmopolitan, frequently found in polluted water, characterized by moderate to high electrolyte content. The species thrives in hyposaline conditions, with salinity ranging from 0 to 3 psu. It has also been found upstream in the Mngazana Estuary and at the Breede Estuary (Bate *et al.*, 2004). The species was dominant throughout the Msunduzi Estuary indicating poor water quality.

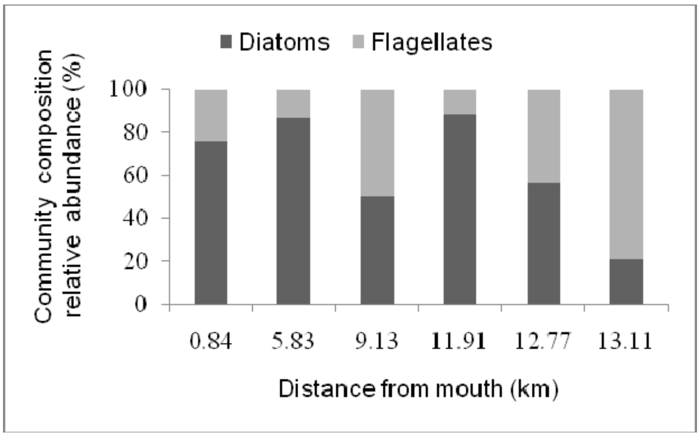

Figure 6. Relative abundance of microalgal groups in the water column along the length of the estuary.

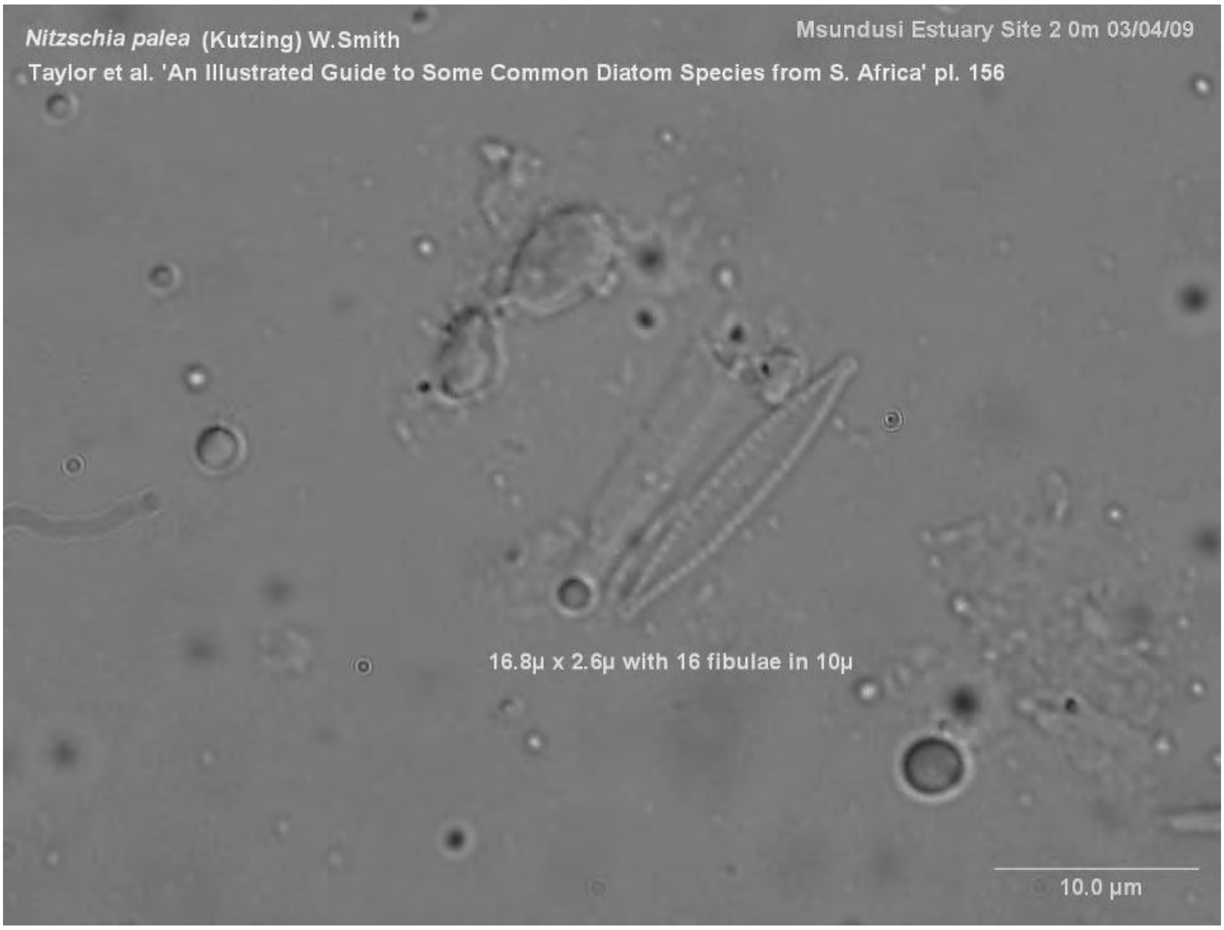

Figure 7. The dominant diatom species, *Nitzschia palea (*Kützing) W. Smith.

Benthic microalgal species

A total of five benthic diatom species was dominant throughout the estuary (Table 2). All of these species have been reported to have a cosmopolitan distribution (Taylor *et al*., 2006b). *Tryblionella calida* occurred at four of the six sites, from the site influenced by seawater (at 0.84 km) to the hyposaline sites. These diatom species were different from those found in the water column but are also indicative of poor water quality. The agricultural drains from the sugarcane areas are a likely source of nutrients. *Nitzschia clausii*, which was dominant in the lower reaches (0.84 km) and in the upper reaches (13.11 km) is a species that thrives under brackish coastal waters and in water rich in electrolytes (>500 µS/cm) and inland waters. The species is indicative of polluted water and is highly tolerant to strongly polluted conditions (Taylor *et al*., 2006b). *Trybliionella calida* commonly occurs in water with high primary productivity, rich in mineral nutrients and with elevated electrolyte content. *Navicula veneta* which was only dominant in the upper reaches (11.91 km) is commonly found in very eutrophic water which is electrolyte rich. It is frequently dominant in water containing industrial discharges. *Nitzschia closterium* is commonly found in the plankton of brackish water and wetlands while *Gyrosigma obtusatum* is commonly found in oligotrophic to mesotrophic water with low alkalinity.

Table 2. Benthic diatom species collected in the Msunduzi Estuary. Relative abundance of dominant species (dominance %) and total number of species at each site are included.

Distance (km) from the sea	**Site**	**Taxon**	**Dominance (%)**	**No. of taxa**
0.84	6	*Nitzschia clausii* Hantzsch	38	19
		Gyrosigma obtusatum (Sullivant and Wormsley) Boyer	19	
		Trybliionella calida (Grunow) DG Mann	16	
5.83	5	*No dominant*		11
9.13	4	*Gyrosigma obtusatum* (Sullivant and Wormsley) Boyer	31	21
		Trybliionella calida (Grunow) DG Mann	18	
11.91	3	*Trybliionella calida* (Grunow) DG Mann	63	15
		Navicula veneta Kutzing	18	
12.77	2	*Trybliionella calida* (Grunow) DG Mann	18	27
		Gyrosigma obtusatum (Sullivant and Wormsley) Boyer	13	
		Nitzschia closterium (Ehrenberg) W.Smith	10	
13.11	1	*Nitzschia clausii* Hantzsch	50	21

Vegetation distribution

The estuarine vegetation was identified from aerial photographs, classified and mapped and the determinants of the different community types described. The area covered by the different vegetation types was measured using image analysis software, Arc GIS 9.2. Figure 8 indicates the dominant mapping units used for vegetation mapping from 2006 aerial images. Due to limited coverage of the 1937 aerial images, it was not possible to compare area cover of habitats between 1937 and 2006 (Table 3). In 2006, 9.1% of the land which was previously wetland vegetation was used for subsistence agriculture. In 1937 vegetation was in a pristine state and there was no disturbed or cultivated land.

On both banks of the Msunduzi and in the Mfolozi swamp there are large stands of reeds. Reeds are important in filtering out sediments and in taking up nutrients from the water column. They also serve as habitat and refuge sites for invertebrates, fish and birds. In some areas, at close proximity to the banks, the reeds have been cleared to provide space for cultivated lands (Habitat D in Figures 9 and 10). This can have adverse ecological effects because the loss of riparian vegetation often results in bank erosion and sedimentation in the main channel. Reeds and sedges, areas with a mosaic of *Cyperus* and *Phragmites* species covered 1118.3 ha in 2006 and made up 34% of the wetland vegetation.

In the lower reaches of the estuary (Habitat E in Figures 9 and 10) two species of *Phragmites* lined the banks. There were also narrow bands (5-10 m inland) of the white mangrove, *Avicennia marina* behind the reeds. *Phragmites* species thrive under hyposaline conditions, where salinity is less than 15 psu and in saline areas adjacent to areas with freshwater seepage (Adams & Bate, 1999).

In 1937 there were patchy and isolated areas of swamp forest shown as G in Figure 9. Now, grass and shrubs are growing on areas that have ‘recently’ been subjected to disturbance, i.e. E in Figure 10. Floods in the Msunduzi River have altered channel morphology and influenced the distribution and cover of wetland vegetation. The first aerial photographs of the catchment taken in 1937 (Figure 8) show swamp forest concentrated around the old river course. The 1960 aerial photographs showed that there had been a southward migration of swamp forest and the forest canopy was denser. In the 1970 aerial photographs there was an increase in the cover of swamp forest which spread along the banks.

In the 1975 aerial photographs the swamp forest had developed into a dense forest; however there was evidence of subsistence agriculture. This is seen as a small area of what appeared to be eight separate gardens. In the 1992 aerial photographs there had been an approximate tenfold increase in the area used for subsistence agriculture. At the same time, however, there were signs that swamp forest was spreading southwards and encroaching onto areas previously occupied by reeds. This is probably an indication that the wetland area was becoming drier. In the 2000 aerial photographs there was a considerable increase in swamp forest cover south of the old river course and there were numerous isolated canopies in the area previously dominated by reeds and sedges. The existence of swamp forest in the area may now be threatened by the rapid increase in subsistence agriculture since 1992 (Figure 11B, C and D).

Table 3. Area cover and contribution to total percentage cover of mapping units (Nd = no data because the 1937 photographs did not show enough detail to record these areas).

Mapping units	**Area (ha)**	**% Cover**	**Area (ha)**	**% Cover**
	2006	**2006**	**1937**	**1937**
Bare sand	163.0	3.8	394.1	14.0
Cultivated	394.3	9.1	Nd	Nd
Development	0.2	0.005	Nd	Nd
Disturbed land	72.5	1.7	Nd	Nd
Dune forest	936.6	21.7	1021.8	36.4
Grass and shrubs	299.9	6.9	315.3	11.2
Mangroves	11.1	0.3	Nd	Nd
Reeds	94.9	2.2	607.3	21.6
Reeds and sedges	1118.3	25.9	Nd	Nd
Swamp forest	1231.8	28.5	468.9	16.7
Total area (ha)	**4322.4**		**2807.5**	

	**Mangroves** – The dominant mangrove species in the Msunduzi Estuary was *Avicennia marina.*
	**Cultivated land** on the banks of the estuary. The most common species observed were bananas, tomatoes, guavas and "amadumbe" (*Colocasia esculenta*).
	**Disturbed Land** – These are areas which have recently been cleared of vegetation. The figure illustrates an area which has undergone slash and burn. The initial growth in these areas is grass, shrubs and pioneer species.
	**Reeds** were dominant on the banks of the estuary. The most dominant species were *Phragmites australis* and *Phragmites mauritianus.*
	**Swamp forest** – the dominant swamp forest species were *Barringtonia racemosa*, *Ficus trichopoda* and *Bridelia micrantha*.

Figure 8. The dominant vegetation and mapping units used in the 2006 vegetation map of the Msunduzi Estuary.

Figure 9. Vegetation distribution along the Msunduzi Estuary in 1937.

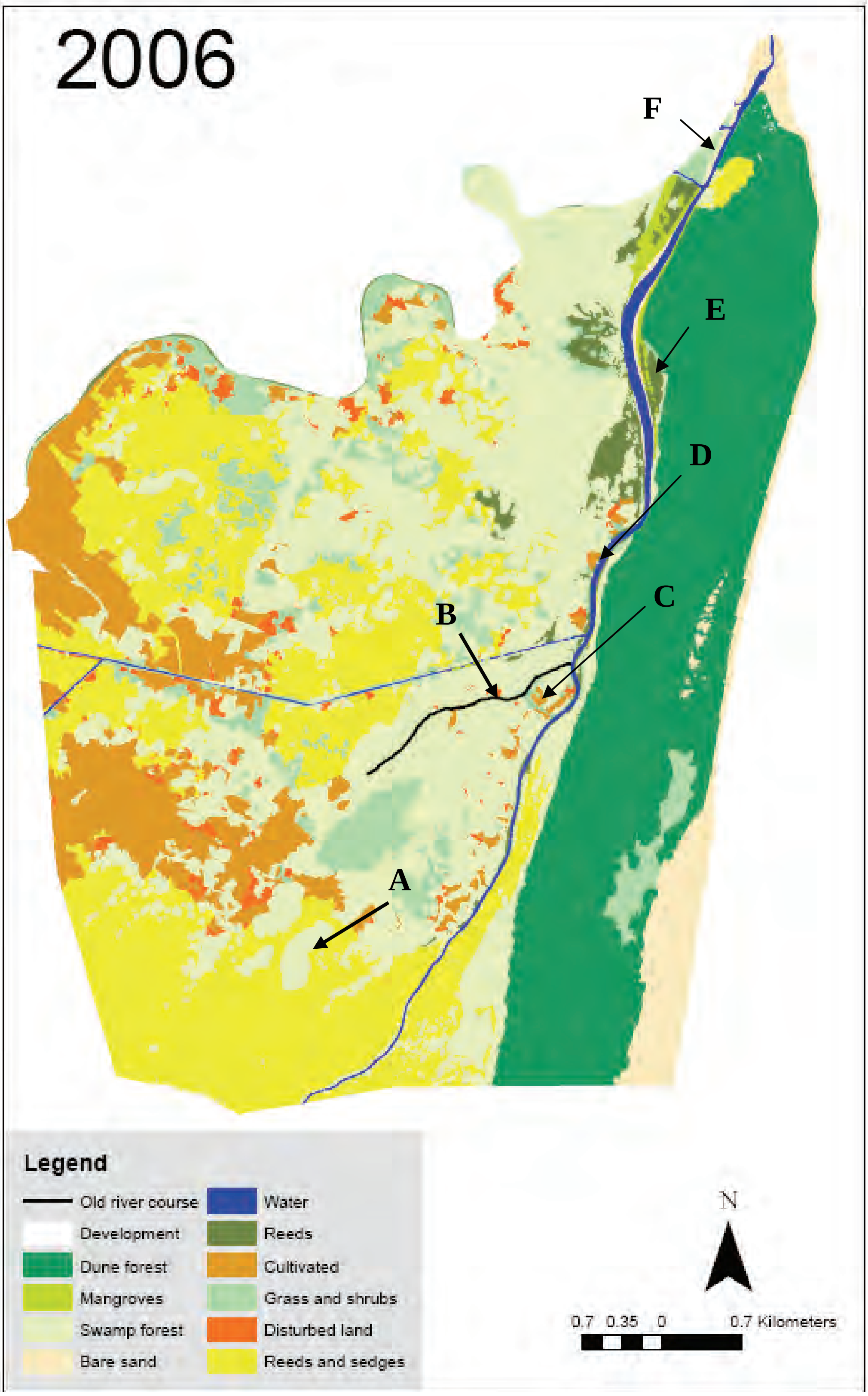

Figure 10. Vegetation distribution along the Msunduzi Estuary and the Mfolozi swamp in 2006. Sites A-F are referred to in the text.

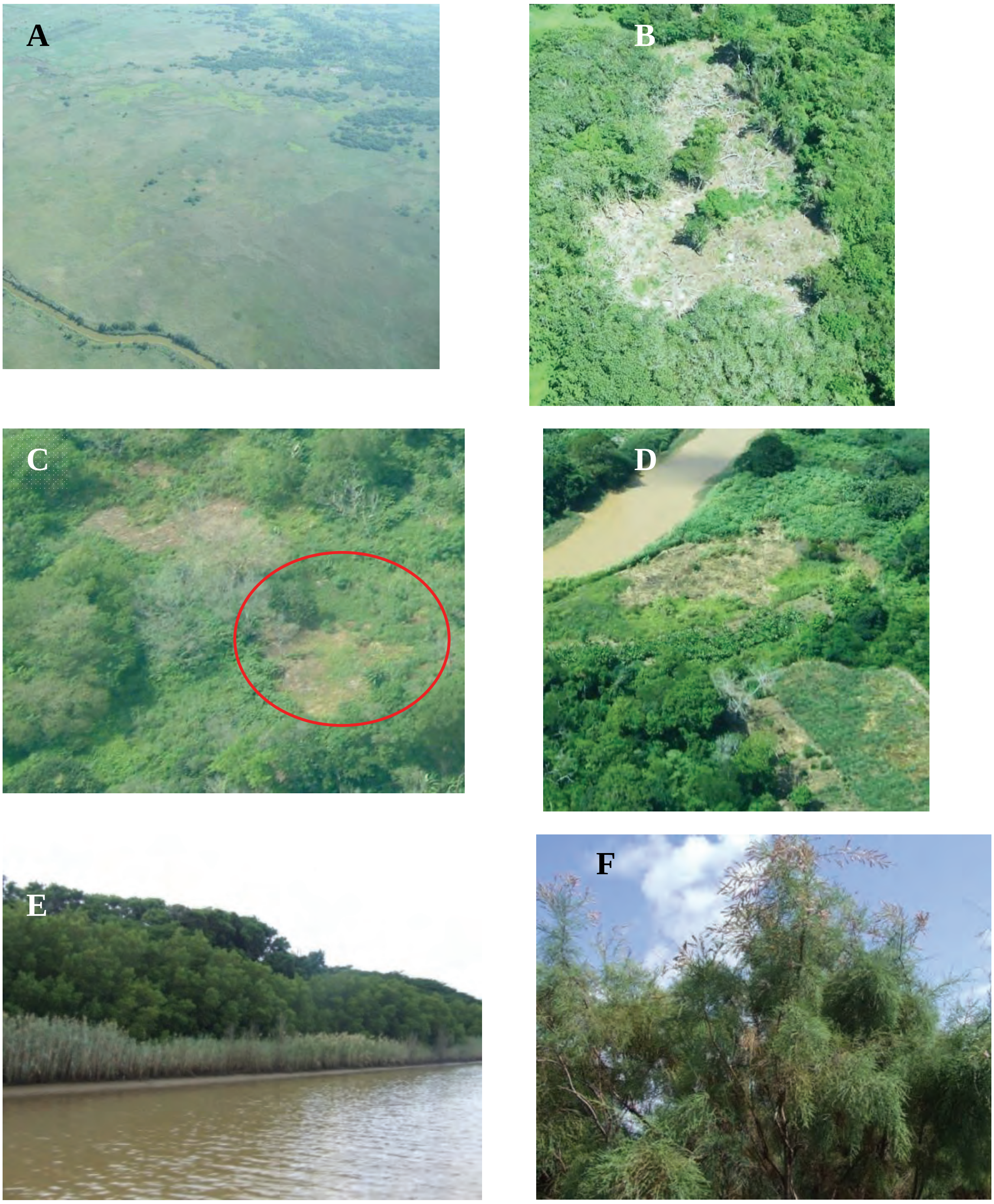

Figure 11. A-F sites with vegetation changes. **A**) areas where reeds were dominant are being replaced by swamp forest, **B**) areas where vegetation has recently been cleared, **C**) grass, shrubs and pioneer species dominate disturbed areas, **D**) areas where *Phragmites* was dominant now converted to cultivated land, **E**) narrow bands of *Avicennia marina* behind *Phragmites* species**,** **F**) *Tamarix ramosissima* now an invasive plant dominant in the present grass and shrub habitat F.

In the 2009 field survey the cleared areas visited within the swamp forest had been slashed and burnt (presumably) to prepare for subsistence agriculture. Plants commonly found on cultivated areas were bananas, tomatoes, guavas and "amadumbe." Amadumbe are tubers of *Colocasia esculenta*, commonly known as the 'potato of the tropics'. Slash and burn has several adverse impacts on wetland structure and function. Tinker *et al*. (1996) reported that areas exposed to slash and burn result in emissions of green house gases, loss of soil carbon dioxide, alteration of runoff and evapotranspiration. Infiltration rates are altered through tillage of the soil, which then results in mineralisation and denitrification of soil carbons. Madong a Birang *et al.* (2003) reported that slash and burn reduces the diversity, activity and abundance of soil fauna such as earthworms. This is unfavorable because earthworms improve soil fertility through their role in nutrient cycling. Combustion of cleared vegetation will also have an impact on soil nutrients through a reduction of humus and soil particle size through cementing clay and silt particles, resulting in a coarser soil texture. The clearing of forest vegetation can also alter local microclimate temperatures and soil temperature (Tacconi & Vayda, 2006). Subsistence agricultural land should be rehabilitated in an effort to conserve the Mfolozi Swamp which was known for its mosaic of land forms and wetland vegetation. Rehabilitation studies e.g. Yuwati *et al*. (2007) and Ismail *et al*. (2003) indicate that swamp forest can be successfully rehabilitated.

Table 4 is a list of species from the Msunduzi Estuary identified from the 2009 field trip. It was interesting to find a specimen of *Thespesia populnea*. This is a tropical species rare in South Africa. It is a mangrove associate which only occurs in the tropics and in South Africa is only found in KwaZulu-Natal. It flourishes in areas with a mean annual rainfall of 500 to 5000 mm and average annual temperatures of 20 to 26^{o}C. *Thespesia populnea* is a coastal species and can tolerate infrequent inundation and saline conditions. It provides important ecosystem services, such as preventing erosion as it grows on the edge of mangrove forests (Friday & Okano, 2006). Species such as *Potamogeton pectinatus* were common in the upper reaches of the Msunduzi Estuary due to dominant hyposaline conditions (< 15 PSU).

Table 5 indicates the alien and invasive plant species identified during the 2009 field trip. *Tamarix ramosissima* (F in Figure 10) is often found as an invasive in wetlands (Brock, 1994). Its growth and distribution are not driven by soil factors, but limited by temperature. It photosynthesises optimally between 23 and 28°C, and temperatures above 32°C decrease the rate of photosynthesis by 20% (Brock, 1994).

Table 4. Plant species list for the Msunduzi Estuary from the 2009 field trip.

Family	**Species**	**Common name**	**GIS mapping unit**
Anacardiaceae	*Rhus kosiensis*		Swamp forest
Apocynaceae	*Rauvolfia natalensis* Sond.	Quinine tree	Swamp forest
Avicenniaceae	*Avicennia marina* (Forssk.) Vierh.	White mangrove	Mangrove
Ceratophyllaceae	*Ceratophyllum demersum* L.	Hornwort	Swamp forest

Conolvulaceae	*Ipomoea obscura* (L.) ker- Gawl.	Obscure morning glory	Swamp forest
Cyperaceae	*Cyperus albostriatus* Schrad.	Umbrella sedge	Reeds and sedges
	Cyperus textilis Thumb.	Mat sedge	Reeds and sedges
	Schoenoplectus scirpoideus (Schrad.) Browning		Reeds and sedges
Euphorbiaceae	*Bridelia micrantha* (Hochst.) Baill.	Coast gold leaf	Swamp forest
Fabaceae	*Acacia kosiensis* P.P. Swartz	Sweet thorn	Grass and shrubs
	Acacia robusta Burch.	Black thorn Acacia	Grass and shrubs
	Schotia brachypetala Sond.	Weeping Boer – bean	Dune forest
Icacinaceae	*Apodyte dimidiata* E. Mey.exArn.	White pear	Swamp forest
Juncaceae	*Juncus kraussii* Hochst. Subsp. *kraussii*	Dune slack rush	Reeds and sedges
Lecythidaceae	*Barringtonia racemosa* (L.) Roxb.	Lagoon mangrove	Swamp forest
Malvaceae	*Hibiscus tiliaceus* L. Subsp.*tiliaceus*	Lagoon hibiscus	Swamp forest
	Thespesia populnea (L.) Soland. Ex Correa	Portia tree	Dune forest
Meliaceae	*Eckebergia pterophylla* (C.D.C) Hofmeyr.	Rock ash	Dune forest
Moraceae	*Ficus natalensis* Hochst. Subsp. *natalensis*	Natal fig	Swamp forest
	Ficus sycomorus L. Subsp. *sycomorus*	Sycamore fig	Swamp forest
	Ficus trichopoda Baker	Swamp fig	Swamp forest
Nymphaeaceae	*Nymphaea lotus* L.	Lily	Water
Poaceae	*Echinochloa colonum* P. Beauv.	Swamp grass	Grass and shrubs
	Leersia hexandra Sw.	Grass	Grass and shrubs
	Phragmites australis (Cav.) Steud.	Common reed	Reeds
	Phragmites mauritianus Kunth.	Reed grass	Reeds
	Potamogeton pectinatus L.	Pond weed	Water
	Stenotaphrum secundatum (H. Walter) Kuntze		Grass and shrubs
Pteridaceae	*Acrostichum aureum* L.	Mangrove fern	Swamp forest
Rhamnaceae	*Scutia myrtina* (Burm. F.) Kurz	Velvet bushwillow	Dune forest
Rhizophoraceae	*Bruguira gymnorrhiza* (L.) Lam.	Black mangrove	Swamp forest

Table 5. Alien and invasive vegetation found in the Mfolozi/Msunduzi system.

Family	**Species**	**Common name**	**Habitats**
Anacardiaceae	*Schinus terebinthifolius*	Brazilian pepper	Grass and shrubs
Asteraceae	*Chromolaena* odorata (L.) King and H. Rob	Triffid weed	Grass and shrubs
	Conyza bonariensis (L.) Cronquist.	Horseweed	Swamp forest
	Xanthium spinosum	Burrweed	Swamp forest
Caesalpiniaceae	*Cassia didymobotrya* Fresen.	Peanut butter cassia	Grass and shrubs
Cannaceae	*Canna indica* L.	Canna	Grass and shrubs
Euphorbiaceae	*Ricinus communis* L.	Castor oil	
Fabaceae	*Sesbania punicea* (Cav.) Benth.	Sesbania	Grass and shrubs
Meliaceae	*Melia azedarach* Linn.	Syringa	Grass and shrubs
Myrtaceae	*Psidium guajava* Linn.	Guava	Swamp forest
Solanaceae	*Solanum chrysotrichum* Schltdl.	Devil’s fig	Grass and shrubs
	Solanum mauritianum Scop.	Bugweed	Grass and shrubs
Tamaricaceae	*Tamarix ramosissima*	Tamarix	Grass and shrubs

CONCLUSIONS AND RECOMMENDATIONS

The hydrology of the Msunduzi Estuary is greatly influenced by flood events that scour the river course, alter channel morphology and influence the distribution and cover of the wetland vegetation. The available aerial photographs, used as a time-series, show the dynamic nature of the area and the vegetation responses. Further ‘ground-truthing’ is needed to improve the accuracy of the preliminary vegetation maps presented for this area. Mouth closure, high water level and back-flooding will influence the mangroves in the Msunduzi / Mfolozi mouth area. Long-term monitoring will be required to track the health of this habitat in response to any future management actions. It is important that strategic adaptive management takes place; management actions are implemented and monitored to see if they are achieving the desired effect. Like most floodplain systems with disturbed catchments there are a large number of different alien and invasive plants that should be removed. The health of the swamp forest also needs to be monitored in light of the slash and burn activities in the area.

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BENTHIC FAUNAL DISTRIBUTION AND ABUNDANCE IN THE MFOLOZI/MSUNDUZI ESTUARY

SG Ngqulana, RK Owen*, L Vivier & DP Cyrus

Affiliation: Coastal Research Unit of Zululand, Department of Zoology, University of Zululand, KwaDlangezwa
**Email:* rowen@pan.uzulu.ac.za

ABSTRACT

The Mfolozi/Msunduzi Estuary historically shared a common mouth with the St Lucia estuarine system. In 1952, a separate mouth was created, 1.5 km south of St Lucia mouth, to prevent silt carried by the Mfolozi River from entering Lake St Lucia. Despite its proximity to the comparatively well-studied St Lucia estuary, there is very little information on the Mfolozi/Msunduzi estuary in general and no information on its benthos. In the present study, seventeen taxa were recorded from biannual quantitative sampling in 2007 and 2008. Results indicated that the system was dominated by the polychaetes *Ceratonereis* sp., *Dendronereis arborifera* and *Capitella capitata*, the crab *Paratylodiplax blephariskios* and the tanaid *Apseudes digitalis*. The main factors influencing the distribution of the benthos were oxygen concentration, temperature, the open or closed state of the mouth and salinity, with particle size and organic content of the substratum also being important in determining community structure. Although the dominant taxa were previously recorded as abundant in St Lucia, numbers present in the Mfolozi/Msunduzi were generally lower than those recorded in St Lucia, suggesting that periodic flooding and the unstable nature of the sediments in the Mfolozi/Msunduzi prevented its benthos from attaining the densities recorded in the adjacent St Lucia estuary. While the Mfolozi/Msunduzi is classified as a river mouth, its benthos was more similar in composition to that of the Mhlathuze and Mlalazi estuaries, which are classified as an estuarine bay and a permanently open estuary, respectively. It is suggested that reclassification of the Mfolozi/Msunduzi system as a permanently open estuary would be more appropriate in terms of its benthos.

INTRODUCTION

The Mfolozi/Msunduzi estuarine system is formed from the combination of the Mfolozi and Msunduzi rivers, which have a common mouth just south of the mouth of the St Lucia estuarine system in northern KwaZulu-Natal (Figure 1).

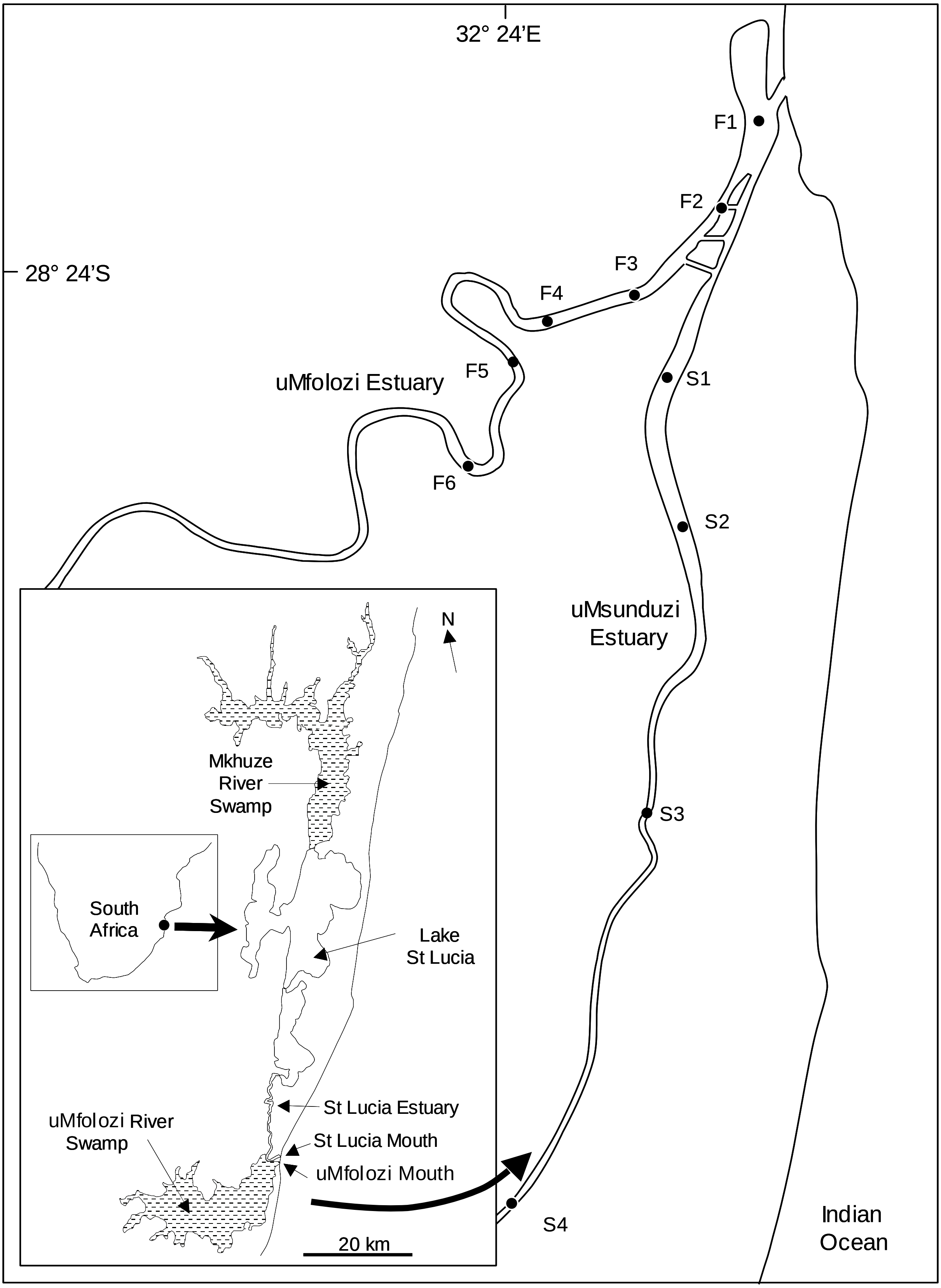


Figure 1. Positions of benthic sampling sites in the Mfolozi/Msunduzi estuarine system.

After the Thukela River, which drains a catchment of approximately 28 000 km^2, the Mfolozi River drains the second largest catchment in KwaZulu-Natal, estimated at between 9918 and 10 700 km^2. The Msunduzi drains a much smaller catchment of 559 km^2 (Begg, 1978). Like the Thukela, the Mfolozi/Msunduzi estuary is classified as a river mouth (Whitfield, 2000). The Mfolozi has a history of severe flooding during which the river has been noted to flow across its floodplain into the Msunduzi, depositing silt on the land between the two rivers (Begg, 1978). From 1927 the planting of sugar cane on the floodplain led to the Mfolozi being canalised in an attempt to contain the floodwater, with levees built to prevent the spread of water onto the adjacent land. The Mfolozi/Msunduzi system originally shared a common mouth with the St Lucia system, but canalisation of the Mfolozi and drainage of the Mfolozi swamps led to increased siltation in the lower part of the St Lucia estuary. Consequently, in 1952 a separate mouth for the Mfolozi/Msunduzi estuary was excavated 1.5 km south of St Lucia to prevent silt carried by the Mfolozi from entering St Lucia (Begg 1978).

There is very little information on the Mfolozi/Msunduzi estuary system, in spite of its proximity to the comparatively well-studied St Lucia Estuary. Although Begg (1978) provides a summary of physico-chemical characteristics of the Mfolozi/Msunduzi system, he conceded that the system was poorly understood and warranted attention in the face of problems arising from sugar cane farming, including swamp destruction, canalisation, levee construction, organic pollution, cane encroachment and siltation. There were no quantitative data available on the biotic components of the system until the start of the current research programme, which also investigated fish (Vivier *et al*., 2010) and zooplankton (Jerling *et al.,* 2010).

Benthic studies in Zululand have focused mainly on the St Lucia Estuary under different salinity regimes in the lake compartments that included hypersaline (Day *et al*., 1954; Boltt, 1975) marine (Millard & Broekhuysen, 1970; Boltt, 1975; Blaber *et al*., 1983; Weerts, 1993) and low salinity conditions (Boltt, 1975; Cyrus, 1988; Weerts, 1993). Boltt (1974) provided the first quantitative description of the benthos in the St Lucia Estuary in the Narrows section, which comprises the tidal part of the St Lucia system (Figure 1). In his study, Boltt (1974) showed that the benthic community was different from that of the lakes and that the benthic biomass was approximately 100 times greater in similar substrata. Owen and Forbes (1997) described the changes in the infaunal macrobenthic community in the Narrows, between 1983 and 1994, which included cyclonic flooding and salinity values ranging from near-zero to 51. More recently, Pillay & Perissinotto (2008) undertook a benthic survey during the 2005 drought year and MacKay *et al*. (2010) described macrobenthic responses over the broader drought period between 2004 and 2008.

Ezemvelo KZN Wildlife (EKZNW) identified the lack of information on the Mfolozi/Msunduzi estuary as a gap in the estuarine information in KwaZulu-Natal and listed it as a priority project with Marine and Coastal Management (MCM). The Coastal Research Unit of Zululand (CRUZ) of the University of Zululand initiated a study of the estuary in March 2007 with the objective of investigating the biotic and physico-chemical aspects of the estuary. This paper describes the subtidal benthic component of the fauna.

METHODS

Sampling

Samples were collected in March and August 2007 and again in 2008. Ten study sites were selected in the Mfolozi/Msunduzi system to represent the lower, middle and upper tidal reaches in each branch of the estuary, with six sites in the Mfolozi and four sites in the Msunduzi (Figure 1). A Zabalocki-type Ekman grab, sampling an area of 0.0236 m^2, was used to collect five replicate benthic samples from each site. Samples were preserved in a 10% formalin solution and stained with the vital dye Phloxine B to aid sorting in the laboratory. Animals were identified to species level where possible. Sediment samples were collected at each site for particle size analysis and organic content. Water quality parameters of the system including, salinity, temperature, oxygen concentration, turbidity and pH were determined using a YSI 6920 Sonde data logger.

Data analysis

Sediment samples were analyzed for grain size, sorting coefficient and percent organic content. The silt-clay fraction was separated from the sand by wet sieving and passing the sand fraction, between 2000 and 63µm, through a settling tube. Cumulative percentages of particle size for each sample were plotted against the corresponding phi value where $\varphi = -\log_2$ particle size in mm. Sorting coefficients were calculated using the Inclusive Graphic Standard Deviation according to Gray (1981). The percent organic content of each sample was determined by oven drying approximately 5g of the sediment at 60°C and incinerating the sample at 600°C for 6 hours (Gray, 1981).

Counts of individuals in each taxon were converted to densities (ind.m^{-2}) and averaged for each site to show the community structure and abundance at each site. Species diversity indices including Shannon-Wiener diversity (H'), Margalef's species richness (D) and Species Evenness (J) were used to determine changes in the community structure between the two estuaries, between sites and between seasons during the study period. Single factor analysis of variance (ANOVA) was used to test for temporal and spatial differences in univariate variables.

Multivariate analysis contained in the PRIMER statistical package was used to detect any differences in community structure and abundance between sites and seasons using hierarchical clustering and ordination (Clarke & Warwick, 2001). Species that contributed most within the group similarity were examined using the SIMPER (Similarity Percentages) routine. Differences in the benthic community structure were tested using one-way analysis of similarity (ANOSIM). Matching biotic to environmental patterns (BIO-ENV) was used to determine which abiotic factors were most responsible for structuring the benthic community. Canonical Correspondence analysis (CANOCO) (Ter Braak & Smilauer, 1998) was used to test for correlation between the benthic community composition and environmental variables.

RESULTS

Estuary mouth and environmental conditions

Salinity recorded during the four biannual sampling dates in the Mfolozi/Msunduzi estuary during 2007 and 2008, as well as the mouth conditions during each sampling time, are given in Figure 2.

The mouth of the system was open during March 2007 and 2008, but closed during August 2007 and 2008. The system was relatively fresh when it was closed, with a mean salinity of 6.7, indicating a river-driven system. In contrast, a typical estuarine salinity gradient was observed when the system was open and tidal, with a mean salinity of 26.7.

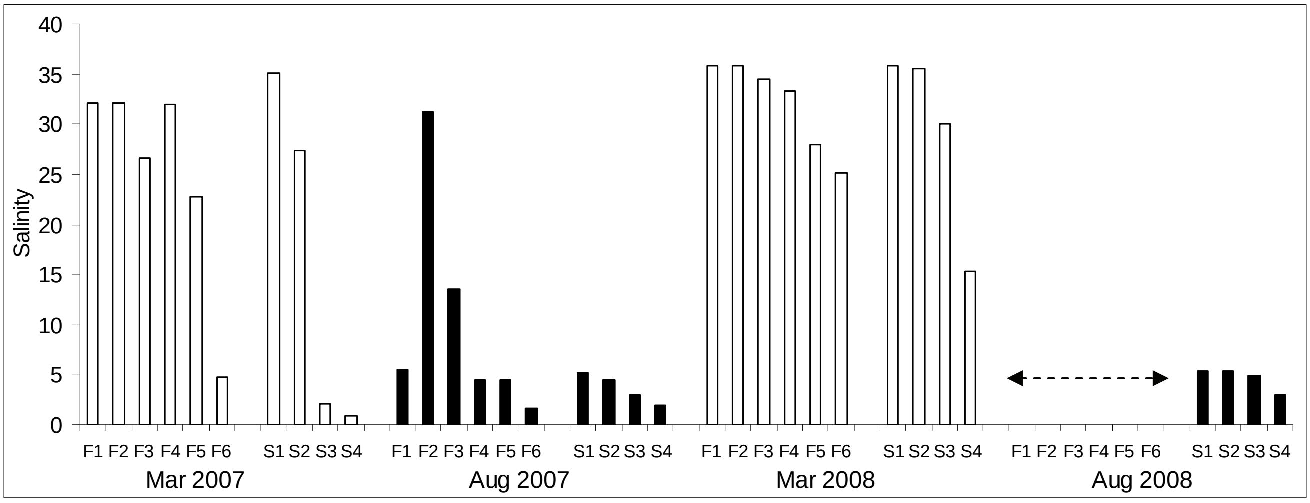


Figure 2. Salinity values recorded during four biannual sampling seasons in the Mfolozi (F1-F6) and Msunduzi (S1-S4) estuaries during 2007 and 2008. Clear bars indicate open mouth and tidal conditions, dark bars indicate closed mouth conditions. Dotted line represents expected salinity values in the Mfolozi Estuary during August 2008.

The salinity gradient ranged from marine salinity values at the mouth, decreasing to 4.8 in the Mfolozi River and 0.9 in the Msunduzi River. Salinity data from the Mfolozi in August 2008 were unfortunately lost but, based on the values from the Msunduzi, it would be expected that similar salinity conditions would have prevailed in the Mfolozi. Temperatures during summer ranged between 25-31ºC and in winter between 18-23ºC. The system remained well oxygenated throughout the study period (6.2-9.9 mg l^{-1}), with slightly higher dissolved oxygen levels during the colder winter periods.

Turbidity was higher during the open mouth, tidal conditions during March (9-476 NTU), as compared with low flow conditions during August (10-82 NTU). Higher turbidity values were recorded in the Msunduzi, compared with the Mfolozi, during both high flow (Msunduzi: 10-476 NTU, Mfolozi 9-44 NTU) and low flow conditions (Msunduzi: 15-82 NTU, Mfolozi 10-26 NTU).

Substrata

Mean particle sizes (median phi), sorting coefficients and organic contents are given in Figure 3.

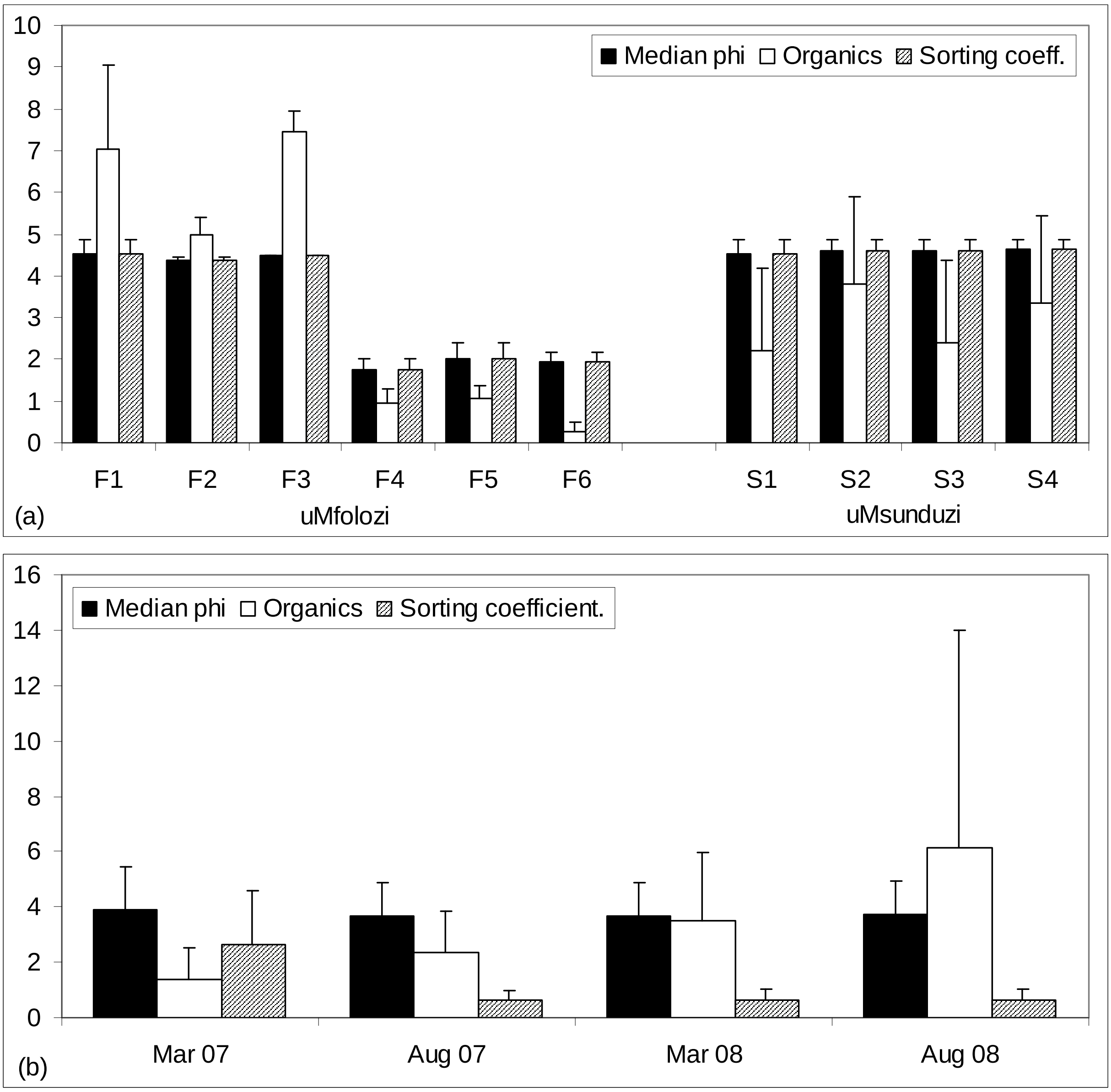


Figure 3. Mean (+1 STD) particle size (median phi value), organic content (%) and sorting coefficient of the sediment (a) at sampling sites in the Mfolozi (F1-F6) and Msunduzi (S1-S4) estuaries, and (b) during four biannual sampling seasons over the period 2007-2008.

Sediments in the Mfolozi ranged from medium-fine sand to mud. The mouth and lower reaches (Sites F1-F3) were characterised by mud (median phi >4) and the upper reaches were dominated by medium to fine sands. The sediment in the Msunduzi was relatively uniform and consisted predominantly of mud, with median phi values ranging between 4.5 and 5.

There were highly significant differences in sediment particle size between sampling sites in Mfolozi (F= 124.6; $p<0.001$), but not in the Msunduzi. There were no significant differences in particle size between seasons in the Mfolozi, but sediments in the Msunduzi were significantly finer in March 2007 compared with the other sampling seasons (F= 40.7; $p<0.001$).

Mean sorting coefficients from the Mfolozi showed that the substratum ranged from poorly sorted in the lower reaches to well sorted in the upper reaches, while sediments in the Msunduzi were very poorly sorted throughout. There were significant differences in the sorting coefficient between sampling seasons, with the sediment being very poorly sorted in March 2007, while from August 2007 to August 2008 the sediment was moderately well sorted (F= 8.9; $p<0.001$).

Mean organic contents differed significantly between sites in the Mfolozi, ranging from very high in the lower reaches (Sites F1-F3) to very low at Site F6 in the upper reaches (F= 3.6; $p<0.003$). In the Msunduzi Estuary, the organic content was medium-high at all four sampling sites. There was a gradual increase in the mean organic content of the sediment during the study period. The organic content of the sediment was significantly higher (14.8-20.4%) in the lower reaches of the Mfolozi Estuary in August 2008, while from March 2007 to March 2008, the mean organic content ranged between 1.3-3.5% (F= 23.5; $p<0.03$).

Benthic distribution and abundance

A total of 17 taxa were recorded in the Mfolozi/Msunduzi system during the study period, with 16 and 13 taxa recorded in the Mfolozi and Msunduzi branches of the estuary respectively (Table 1). Mean densities per site were 415 m^{-2} in the Mfolozi and 441 m^{-2} in the Msunduzi. The highest benthic density per site was recorded in the lower reaches at Site F1 in the Mfolozi and at Site S2 in the Msunduzi. The number of taxa per site ranged from seven to 14 in the Mfolozi Estuary and from eight to 10 in the Msunduzi, with highest values recorded in the lower reaches. The benthic community was dominated by the polychaetes *Ceratonereis* sp., *Dendronereis arborifera* and *Capitella capitata*, the crab *Paratylodiplax blephariskios* and the tanaid *Apseudes digitalis* (Table 1).

Although there were no significant differences between sampling sites with regard to species number, benthic density ($ind.m^{-2}$), richness (D) and species diversity (H'), highest values in all these indices were recorded at the mouth and Site F2 in the Mfolozi Estuary, gradually decreasing towards the upper reaches (Figure 4). Species number, benthic density, species richness and species diversity were higher in the lower reaches of the Mfolozi (Site F1-F3) compared with the Msunduzi (Site S1-S4), while lower values were recorded in the upper reaches of the Mfolozi (Site F4-F6). There were, however, significant differences between sampling seasons in regard to species richness (F= 3.46 and $p=0.03$) and species diversity (F= 3.53 and $p= 0.03$), with the highest values being recorded in March 2008 and the lowest values recorded in August 2008. There were no significant differences between sampling seasons with regard to species number and benthic density (Figure 4).

The dominant benthic taxa differed between the four sampling seasons (Figure 5.) During 2007, the benthos was dominated by *Ceratonereis* sp., whereas in March 2008 it was dominated by *P. blephariskios* and in August 2008 by naidid oligochaetes. The tanaid *A.*

digitalis was abundant during August 2007 and 2008, but not during the March sampling. The polychaete *Prionospio sexoculata* was abundant during 2007, but not during 2008. There were also significant differences in the composition of the dominant benthic taxa between the Mfolozi and Msunduzi estuaries (Figure 6). The Mfolozi was dominated by *Ceratonereis* sp. and *D. arborifera*, which were also abundant in the Msunduzi. However, the Msunduzi was dominated by *A. digitalis* and *P. blephariskios.* The tanaid accounted for 19% of the benthos in the Msunduzi, but formed <0.5% of the benthos in the Mfolozi.

Changes in benthic community structure

Analysis of similarity revealed that there were significant temporal and spatial changes in the benthic assemblage of the Mfolozi/Msunduzi system during the study period. There were significant differences between the four sampling seasons ($R = 0.17$, $p = 0.001$), between sampling sites ($R = 0.2$, $p = 0.005$) and between the Mfolozi and Msunduzi communities ($R = 0.11$, $p = 0.02$). Within the Msunduzi there were significant differences between sites ($R = 0.27$, $p = 0.02$), but not between sampling seasons, or between the upper and lower reaches. Within the Mfolozi assemblage, there were significant differences between sampling seasons ($R = 0.18$, $p = 0.018$) and between the upper and lower reaches ($R = 0.32$, $p = 0.001$), but not between sampling sites.

Analysis of similarity also showed that both temporal and spatial changes in the system were responsible for forging the benthic assemblage during the study period. This resulted in a cluster and MDS ordination plot in which no distinct community groups could be distinguished (Figure. 7).

In the cluster analysis, which shows the benthic samples per sampling season, there was only one distinct group of samples from a particular season, reach or site, namely the August 2007 samples. Within this group, benthic samples from both estuaries and from the upper and lower reaches were all grouped together. In the MDS plot, which shows the benthic samples from each estuary, there was no separation between samples from the two systems or from particular sites.

In order better to understand the spatial trends in the benthic assemblage, the benthic data were averaged across the four sampling seasons. Classification and ordination revealed a distinct spatial gradient in the benthic assemblage of both estuaries from the lower to the upper reaches (Figure 8). There was a clear spatial separation between the benthic assemblage of the lower (F1-F3) and the upper (F4-F6) reaches of the Mfolozi (Figure 8), while in the Msunduzi, the Site S1-S3 assemblage was separated from the Site S4 assemblage. Furthermore, the benthic community of the lower end of the Msunduzi (Site S1) more resembled that of the lower reaches of the Mfolozi (F1-F3) than that of the upper reaches of the Msunduzi.

Table 1. Mean density (No.m^{-2}) per site of the benthic taxa recorded in the Mfolozi (F1-F6) and Msunduzi (S1-S4) estuaries as well as the total densities recorded during the four biannual sampling seasons. The five dominant taxa (contribution shown in bold) made up 81.3% of the total benthic fauna F = Mfolozi, S = Msunduzi

	uMfolozi Estuary						uMsunduzi Estuary				Sampling Season				Total	%
Taxa	F1	F2	F3	F4	F5	F6	S1	S2	S3	S4	Mar 07	Aug 07	Mar 08	Aug 08		Contrib
ANNELIDA																
Oligochaeta																
Naididae sp.	27.5	44.5	4.2	2.1	2.1	214.0	2.1	4.2	4.2	298.7	1127.1	372.9	8.5	906.8	2415	**14.33**
Polychaeta																
Capitella capitata		2.1			6.4		2.1				33.9		8.5		42	0.25
Ceratonereis sp.	491.5	152.5	65.7	108.1	10.6	42.4	271.2	42.4	29.7	27.5	1559.3	2610.2	627.1	169.5	4966	**29.47**
Dendronereis arborifera	182.2	21.2		129.2	150.4	10.6	27.5	2.1	6.4	8.5	1347.5	339.0	347.5	118.6	2153	**12.77**
Dendronereis zululandica	21.2	33.9		2.1	27.5				4.2		118.6	237.3			356	2.11
Orbinidae sp		2.1									8.5				8	0.05
Prionospio sexoculata.	84.7	127.1	14.8	2.1		10.6	57.2	2.1	2.1	4.2	110.2	1016.9	76.3	16.9	1220	**7.24**
Polychaete sp.								8.5				33.9			34	0.20
MOLLUSCA																
Eumarcia paupercula		2.1												8.5	8	0.05
ARTHROPODA																
Amphipoda																
Corophium triaenonyx	2.1										8.5				8	0.05
Grandidierella bonnieroides	1.7	20.3				0.4	8.9	17.8	0.4	0.4		11.9	186.4	1.7	200	1.19
Melita sp.	6.8	81.4				1.7	35.6	71.2	1.7	1.7		47.5	745.8	6.8	1000	**5.93**
Amphipod sp.1	14.8	10.6	4.2				21.2	4.2	2.1		25.4	169.5	33.9		229	1.36
Tanaidacea																
Apseudes digitalis				2.1		2.1	4.2	108.1	80.5	209.7	16.9	898.3	42.4	669.5	1627	**9.66**
Mysidacea																
Mesopodopsis africanus		2.1		4.2							16.9	8.5			25	0.15
Brachyura																
Paratylodiplax blephariskios	4.2	146.2	76.3	21.2			33.9	345.3	8.5		76.3	728.8	1169.5	567.8	2542	**15.09**
Portunus pelagicus		2.1								2.1	16.9				17	0.10
Total	837	648	165	271	197	282	464	606	140	553	4466	6475	3246	2466	16853	
Number of taxa	10	14	5	8	5	7	10	10	10	8	13	12	10	9	17	

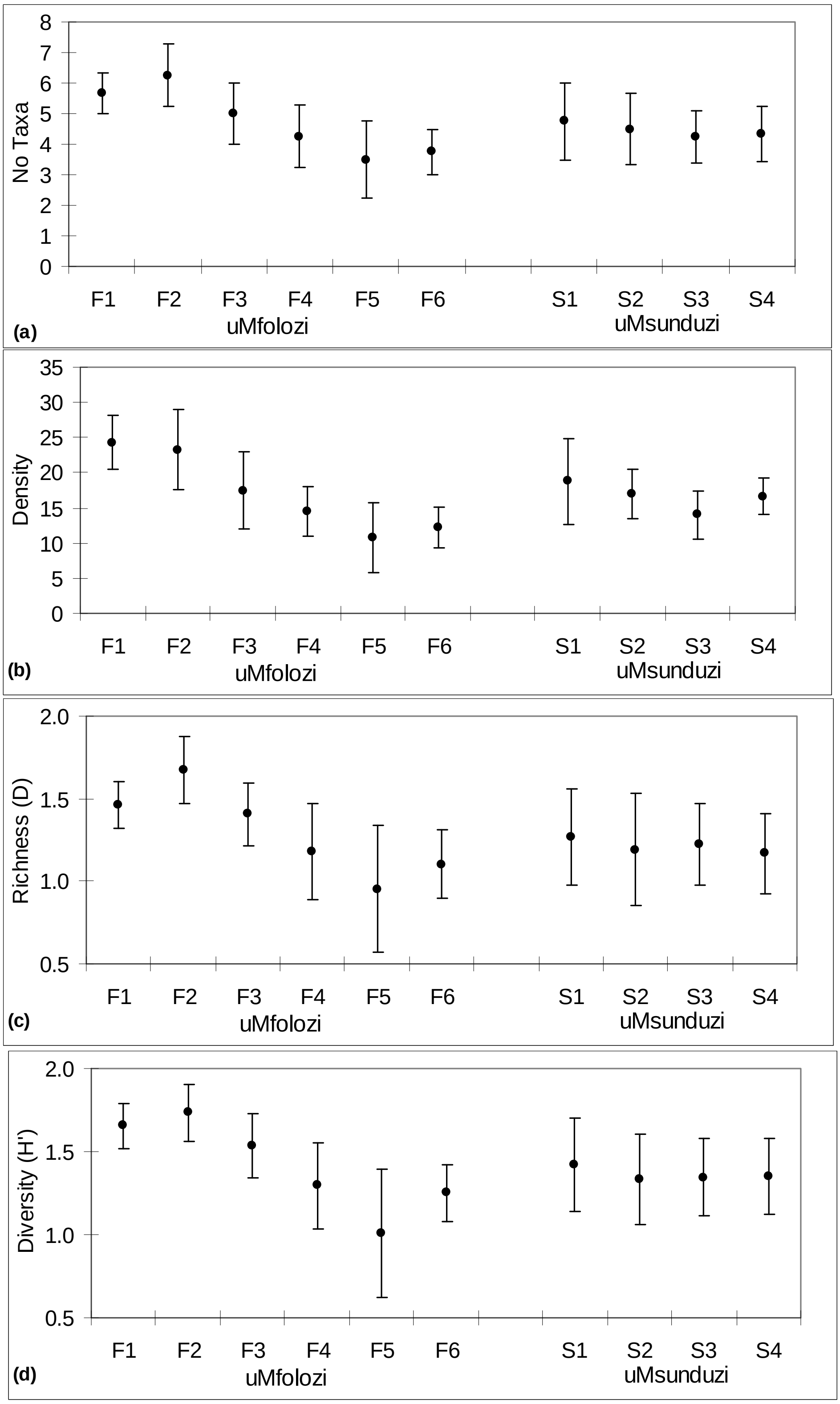


Figure 4. Mean (+1 STD) number of taxa, density, species richness (D) and species diversity (H’) recorded in the Mfolozi (F1-F6) and Msunduzi (S1-S4) estuaries over the period 2007-2008.

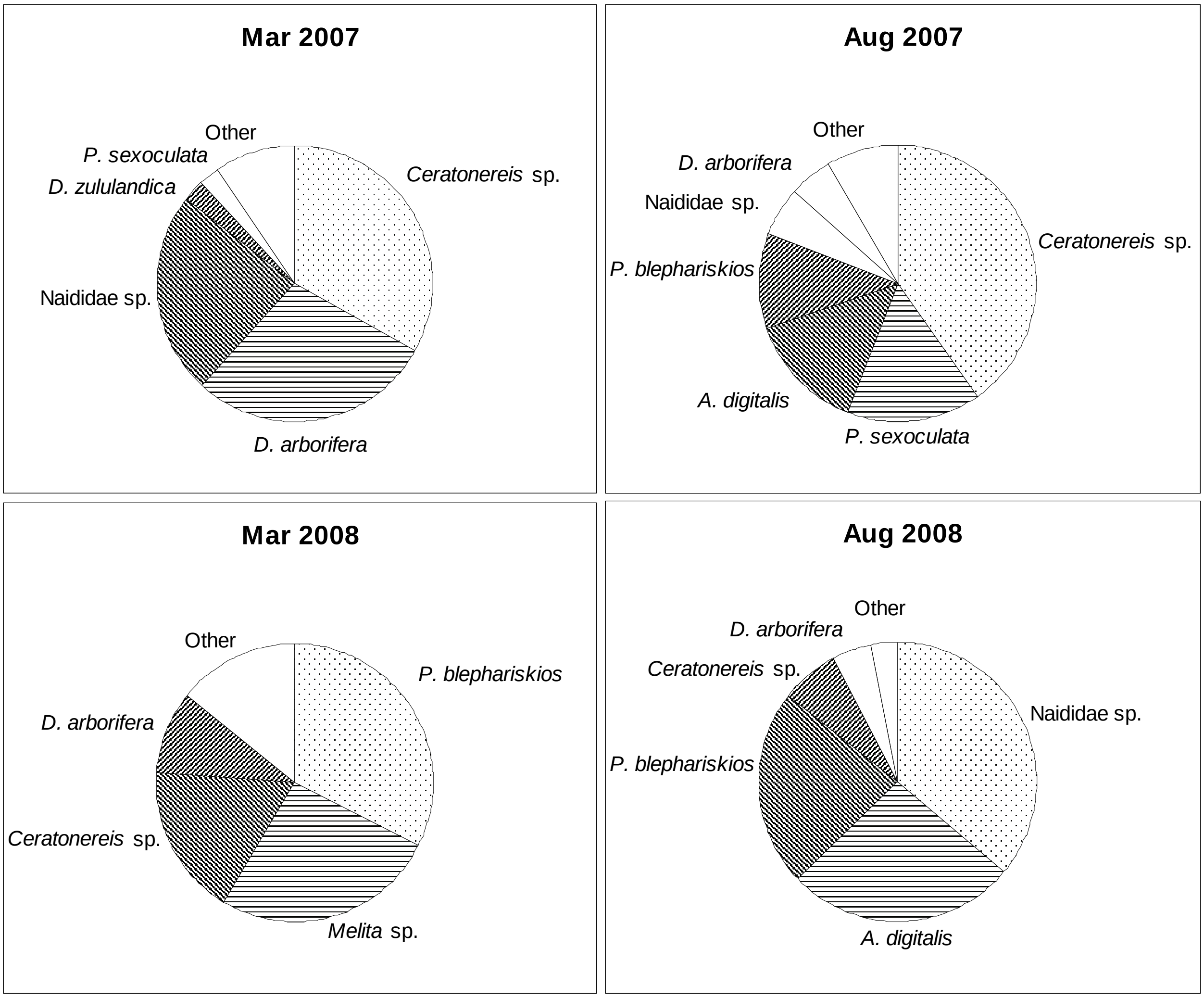


Figure 5. The dominant benthic taxa recorded in the Mfolozi/Msunduzi system during each of the four biannual sampling seasons over the period 2007-2008.

The taxa most responsible for structuring the benthic community within the Mfolozi and Msunduzi branches, based on their mean similarities within each group, are presented in Table 2. The mean similarity within the benthic assemblage of the Mfolozi and Msunduzi was only 36.4% and 30% respectively, indicating relatively unstable benthic communities in both estuaries. The SIMPER results indicated that *Ceratonereis* sp., *D. arborifera, P. blephariskios* and Naididae were the taxa most responsible for structuring the benthic community in both branches. In the Mfolozi *Ceratonereis* sp., *D. arborifera* and *P. sexoculata* accounted for 76% of the mean similarity within the benthic assemblage of the estuary, while in the Msunduzi *D. arborifera* was replaced by *A. digitalis* as the second most important species in the estuary. *Ceratonereis* sp. was particularly important in structuring the Mfolozi benthic community, as it contributed 45.3% of the mean similarity within the community of the estuary. *Paratylodiplax blephariskios,* usually an important species in structuring the benthic assemblage of muddy systems, contributed 14% to the similarity in the Msunduzi Estuary while in the Mfolozi Estuary, these crabs contributed only 3.1% to the mean similarity.

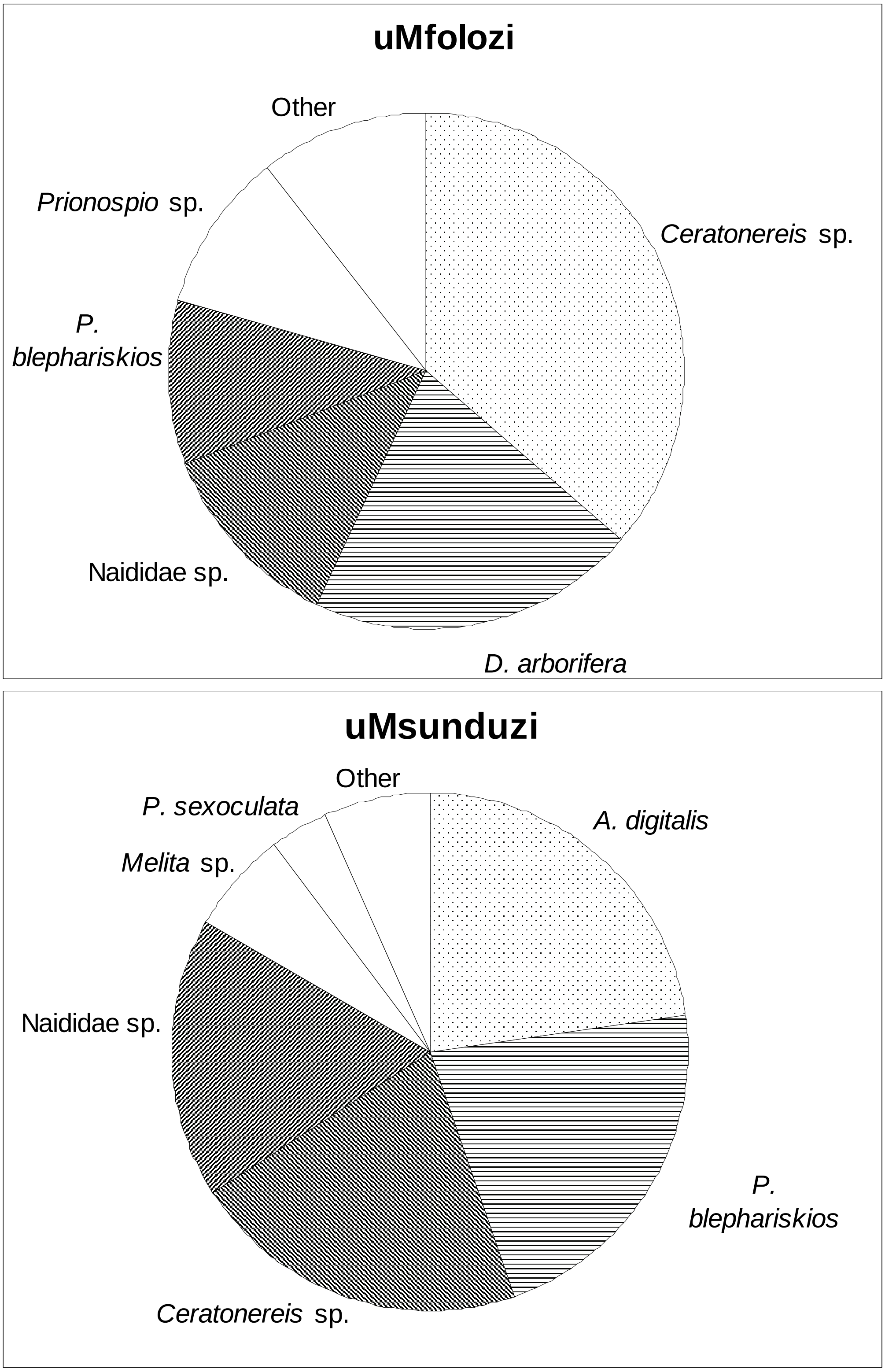


Figure 6. The dominant benthic taxa recorded in the Mfolozi and Msunduzi estuaries during the period 2007-2008.

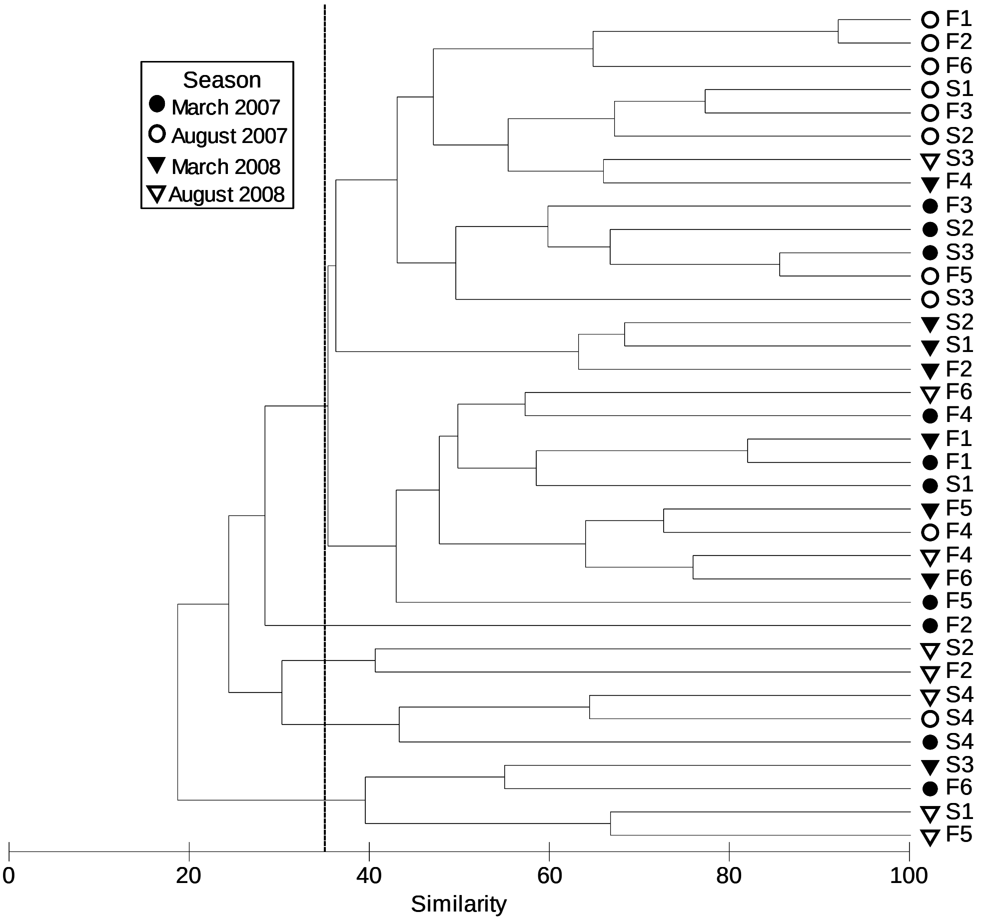
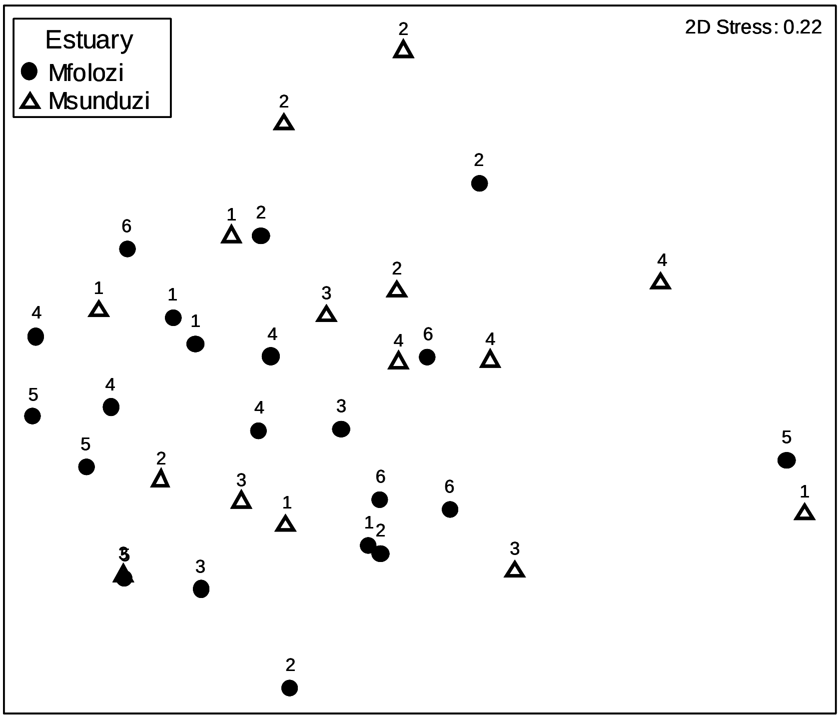


Figure 7. Classification and MDS ordination constructed from Bray-Curtis similarities showing differences in the community structure and abundance between sites and seasons. Numbers on MDS plot indicated site numbers. F = Mfolozi, S = Msunduzi



Relationship between species assemblage and environmental factors

The weighted Spearman correlation coefficients for the correlation between the benthic assemblage and abiotic factors are presented in Table 3. The single variable responsible for structuring the benthic assemblage of the Mfolozi/Msunduzi system during 2007 and 2008 was temperature, indicating that inherent seasonal variation in estuarine conditions was the most important determinant of benthic community structure, followed by salinity and sediment particle size.

Table 2: The species, mean similarity and percentage contribution (>2%) of the dominant benthic taxa recorded in the Mfolozi and Msunduzi estuaries in 2007-2008.

Species	Mean similarity	Contribution %
uMfolozi Estuary: Mean similarity within group: 36.4%		
Ceratonereis sp.	16.5	45.3
Dendronereis arborifera	6.1	16.9
Prionospio sexoculata.	3.1	8.4
Naididae sp.	3.1	8.4
Paratylodiplax blephariskios	1.1	3.1
uMsunduzi Estuary: Mean similarity within group: 30.0%		
Ceratonereis sp.	7.4	24.8
Apseudes digitalis	5.9	19.8
Paratylodiplax blephariskios	4.2	14.0
Naididae sp.	3.6	11.9
Dendronereis arborifera	1.4	4.6
Amphipod sp.1	1.1	3.7
Melita sp.	0.8	2.6
Mean dissimilarity between groups= 68.8%		

The best combination of environmental variables which played an important role in the distribution and abundance of benthos consisted of two abiotic factors, temperature and salinity (Table 3). The second and third best combination of abiotic factors included percent organic content and particle size of the sediment. These results indicate that a combination of natural factors (temperature), mouth condition (salinity) and sediment characteristics (particle size and organic content) were responsible for structuring the benthic community.

Canonical Correspondence Analysis provided further insight into the relationship between the benthic assemblage and abiotic variables (Figure 9). Dissolved oxygen concentration was an important variable in structuring the benthic community, followed by salinity, temperature, percent organic content in the sediment and particle size. Turbidity, pH, water depth or sediment sorting coefficient were the variables least important in structuring the community.

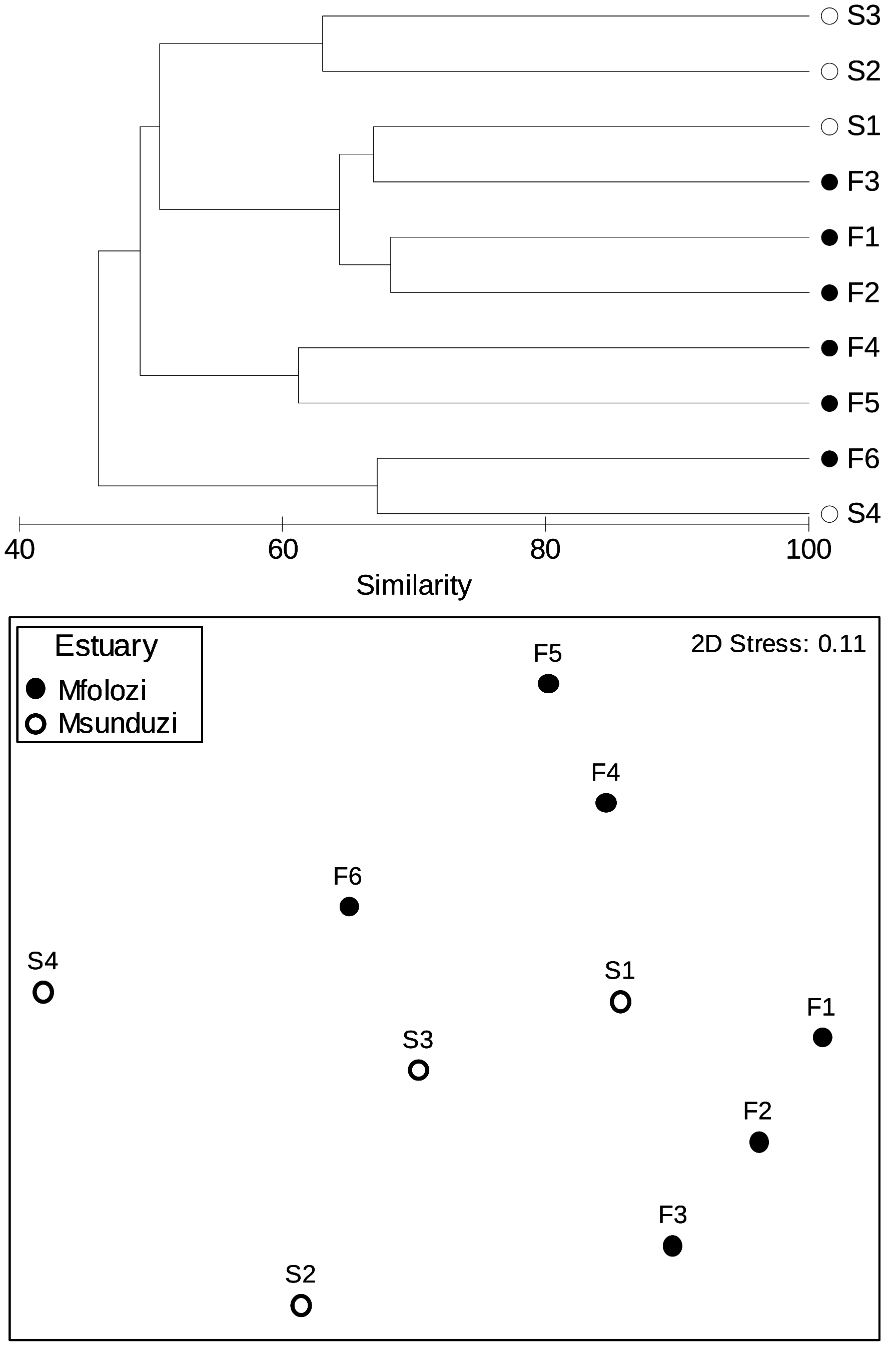


Figure 8. Classification and MDS ordination of benthic data averaged over four sampling seasons during 2007-2008 in the Mfolozi/Msunduzi estuarine system. F = Mfolozi, S = Msunduzi.

There was a positive correlation between temperature and salinity, which is understandable, given that the estuary mouth was open during late summer and closed during late winter. There was a negative correlation between salinity and dissolved oxygen, with higher oxygen levels being recorded during the colder winter sampling period. There was also no correlation between the influence of salinity and sediment characteristics, i.e. particle size and organic content, indicating that mouth condition and the associated increase in river and tidal flow did not influence sediment properties. There was, however, an inverse correlation between salinity and turbidity, which seems to indicate that the highest turbidity was recorded when salinity was low and the mouth was closed.

Table 3. The weighted Spearman Correlation Coefficient values (ρ_w) between the benthic assemblage and physical parameters in the Mfolozi and Msunduzi estuaries during 2007 and 2008.

No. variables	ρ_w	Variables
Single variable:		
1	0.19	Temperature
1	0.11	Salinity
1	0.07	Sediment particle size
Best combination of variables:		
2	0.22	Temperature, Salinity
3	0.20	Temperature, Salinity, Organic Content
3	0.20	Temperature, Salinity, Sediment particle size
4	0.19	Temperature, Salinity, Sediment particle size, Sorting Coefficient

Turbidity, pH, water depth or sediment sorting coefficient were the variables least important in structuring the benthic community. There was a positive correlation between temperature and salinity, which is understandable, given that the estuary mouth was open during late summer and closed during late winter. There was a negative correlation between salinity and dissolved oxygen, with higher oxygen levels being recorded during the colder winter sampling period. There was also no correlation between the influence of salinity and sediment characteristics, i.e. particle size and organic content, indicating that mouth condition and the associated increase in river and tidal flow did not influence sediment properties. There was, however, an inverse correlation between salinity and turbidity, which seems to indicate that the highest turbidities were recorded when salinities were low and the mouth was closed.

In Figure 9, which shows the influence of abiotic variables on the distribution of the benthos during the four sampling seasons, a temporal gradient and a spatial gradient are evident. The temporal gradient, which is associated with changes in salinity and temperature and run from top to bottom on the canonical correspondence plot, separates summer (March 2007 and 2008) and winter (August 2007 and 2008) samples. The spatial gradient, running from left to right across the plot, is associated with sediment particle size and organic content. During March 2007 and 2008 the benthic communities were clearly associated with higher salinity and temperature, as these were the seasons during late summer when the mouth was open and a strong tidal effect was observed. The August 2007 and 2008 communities were associated with low salinity (resulting from mouth closure) and low temperatures. These winter communities were also associated with more muddy environments.

DISCUSSION

The dominance of polychaetes and other opportunistic taxa such as *A. digitalis* and Naididae in the Mfolozi/Msunduzi system reflects a euryhaline r-selected fauna capable of colonising and inhabiting fluvial sediments characteristic of a river-dominated estuary. While inherent seasonal changes in temperature, combined with the state of the mouth and salinity were the primary sources of variability in the benthos, particle size and organic content of the substratum were also important factors in determining community structure. This agrees with a recent study of the subtidal macrozoobenthos of the river-dominated Great Berg Estuary on the west coast of South Africa, which was dominated by polychaetes and amphipods (Wooldridge & Deyzel, 2009). Salinity was found to be the most important variable driving community structure in the Great Berg River in the dry summer season, with water temperature and chlorophyll-*a* best explaining the correlation between benthic structure and composition in the wet winter season.

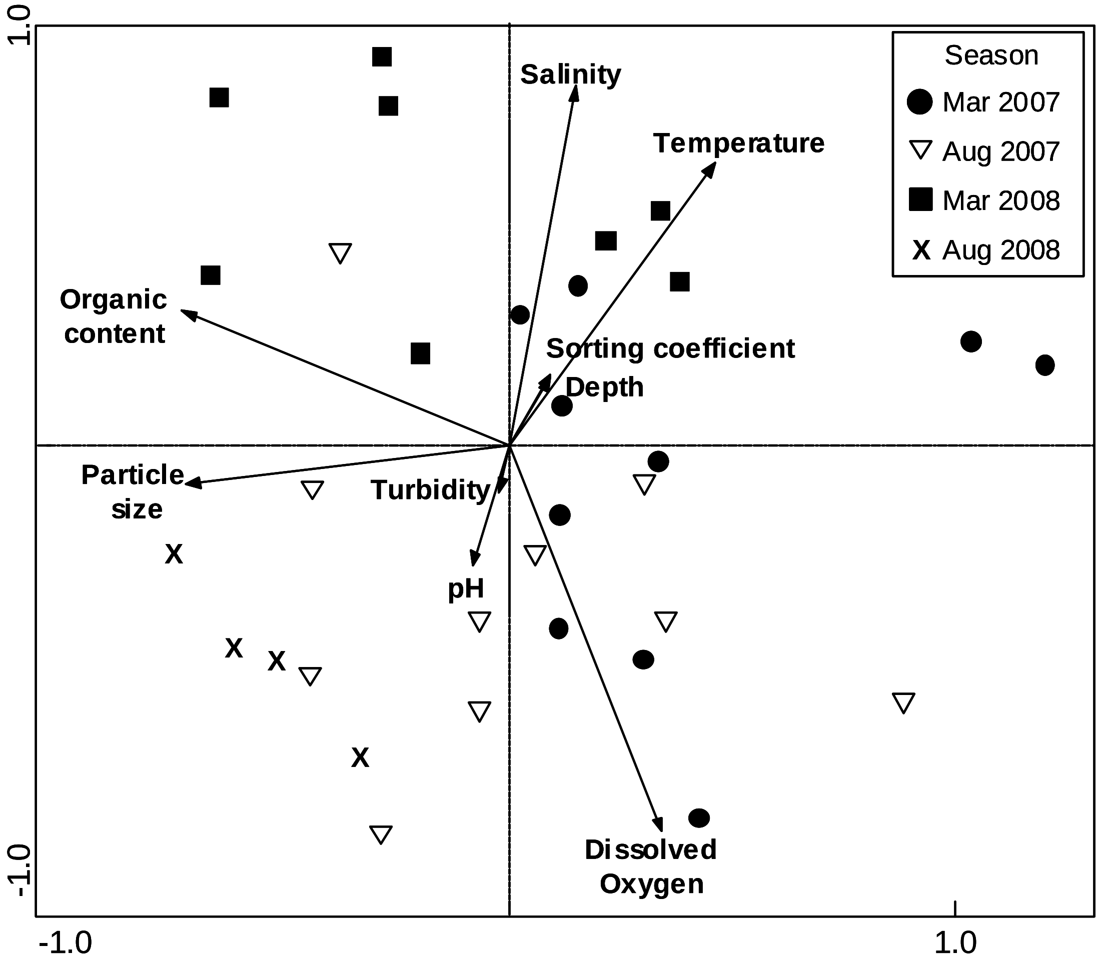


Figure 9. Canonical Correspondence Analysis (CCA) showing the relationship between physical parameters and the benthic assemblage during the four biannual sampling seasons in the Mfolozi/Msunduzi system during 2007 and 2008.

All taxa recorded in the Mfolozi/Msunduzi have been recorded in the adjacent St Lucia system, although the total of 17 taxa recorded in this study falls short of the 22 taxa recorded in the St Lucia Narrows between 1983 and 1984 (Owen & Forbes, 1997), the 23 recorded in 2005 (Pillay & Perissinotto,2008) and the 30 recorded between 2004 and 2008 by MacKay *et al*. (2010). This indicates that species richness in the Mfolozi/Msunduzi system was substantially lower than that in the tidal part of the St Lucia Estuary. In addition, the abundance of dominant taxa recorded in the Mfolosi/Msunduzi was also markedly lower than in St Lucia. Densities of *A. digitalis* in the St Lucia Narrows ranged from the 100s to over 10,000 m^{-2}, the crab *P. blephariskios* was typically recorded at densities of between 1000 and 1500 m^{-2} and the polychaete *D. arborifera* reached densities of up to 1000 m^{-2} (Owen & Forbes, 1997). This suggests that the Mfolozi/Msunduzi system is relatively impoverished, compared with St Lucia, in terms of both species abundance and richness.

The absence of bivalves such as *Solen cylindraceus*, *Macoma* sp. and *Dosinia hepatica* in the Mfolosi/Msunduzi is notable, especially as they have all been recorded in the St Lucia Narrows at some stage (Owen & Forbes, 1997; MacKay *et al*., 2010). *Eumarcia paupercula* was the only bivalve recorded in the Mfolosi/Msunduzi, as a single record from only one site (F2) in August 2008. Bivalves in St Lucia have generally been associated with marine and hypersaline conditions (Blaber *et al*., 1983; Weerts, 1993), with *S. cylindraceus* only recorded as juveniles in the Narrows after being flushed from the lakes following flooding (Owen & Forbes, 1997). *Solen cylindraceus* does not appear to tolerate tidal fluctuations in salinity, whereas *E. paupercula* and *D. hepatica* have persisted in the Narrows and appear to be more tolerant of salinity changes (Owen & Forbes, 1997). *Dosinia hepatica* has been shown to survive flooding by closing the valves of its shell to isolate itself from low salinity water (McLachlan & Erasmus, 1974; Hanekom, 1989) so its absence from the Mfolosi/Msunduzi must be due either to unstable sediments or unfavourable conditions for filter feeding, such as the high turbidity that would be associated with flooding.

The ability of opportunistic benthic organisms, especially polychaetes, to repopulate disturbed substrata rapidly has been well documented (Santos & Simon, 1980; Gray, 1981; Diaz, 1984). While benthic abundance declined after episodic flooding in the Narrows (Owen & Forbes, 1997), the generally low numbers of individuals in the Mfolozi/Msunduzi system may be ascribed to a river-dominated estuary susceptible to more frequent deposition and disturbance of fluvial sediments by flooding. Canalisation of the Mfolosi would have increased sand and silt deposition into the estuary, while run-off from cane fields would increase silt deposition in the Msunduzi, especially as floodwaters from the Mfolozi have historically been noted to spill over into the Msunduzi (Begg, 1978). Unstable sediment conditions, whether through smothering or scouring, would prevent benthic numbers reaching the densities recorded at St Lucia, which has no major rivers entering it. Floods in the Narrows, such as those following cyclones Domoina and Imboa in 1984 and 1987, have been episodic rather than seasonal, with benthic abundance at St Lucia affected more recently by salinity and the state of the mouth rather than by scouring or silt deposition (Owen & Forbes, 1997).

Although errant polychaetes were found at most sites in the Mfolozi/Msunduzi irrespective of the nature of the substratum, burrowing or tube-building species such as *P. blephariskios, A. digitalis* and *Grandidierella bonnieroides* were generally absent from the sandier sites in the upper Mfolozi. Muddy substrata in the St Lucia Narrows were numerically and gravimetrically dominated by *P. blephariskios* (Owen & Forbes, 1997) and this crab forms an important part of the benthos wherever it occurs. It was shown that the distribution of *P. blephariskios* was determined by a combination of the nature of the substratum and the distance from the mouth (Owen *et al.*, 2000). In the Narrows, crab distribution was determined by the combination of median particle size and degree of sorting of the sediment, as well as by distance from the mouth. In the Mhlathuze Estuary (approximately 50 km south of St Lucia) crabs were recorded only in substrata with a median phi value above 4, whereas in the Narrows they were recorded in substrata with median phi values above 2.3. This difference was ascribed to the sandier sites in the Mhlathuze being moderately well to well sorted, whereas the sandier sites in the Narrows were poorly sorted, showing that *P. blephariskios* can inhabit poorly-sorted fine sand with a higher mud content than the better-sorted sands of the Mhlathuze. This concurs with the absence of the crab from the upper sites sampled in the Mfolozi, which were well-sorted fine sands. Although the sites sampled in the Msunduzi were uniformly muddy, salinity at the upper two sites was generally below 5, reflecting the river-dominated nature of the system and suggesting that the extent of tidal penetration and transport of crab (and other) post larvae would be limited. Crab densities in St Lucia also declined from the lower to the upper Narrows over a distance of approximately 20 kilometres, even though the substratum in the upper Narrows was suitable for the crab. This decline was explained by the crab having an obligate marine phase whereby eggs released in the estuary are carried to the sea on ebb currents to re-enter the estuary as post larvae (Papadopoulos *et al*., 2002), and would also explain the higher densities of the crab closer to the mouth in the Mfolozi/Msunduzi system.

The Mfolozi/Msunduzi system is classified as a river mouth, but its benthos was notably different from that of the Thukela estuary, which is also classified as a river mouth (Begg, 1978; Whitfield, 2000). In a survey conducted in 1997/8 by MacKay *et al*. (2004), benthos in the Thukela was dominated by oligochaetes and freshwater taxa such as insects. None of these taxa were recorded in the Mfolozi/Msunduzi. However, a follow-up survey of the Thukela in 2001 showed that the benthic community had changed to a polychaete-dominated community under low flow conditions. In the Thukela estuary saltwater intrusion is noted to extend only some 2 km above the mouth (MacKay *et al*. 2004). With the Thukela draining a catchment approximately three times larger than that of the Mfolozi, it carries a much larger volume of water and thus the freshwater nature of its benthos would be expected. It would be more appropriate to compare the benthos of the Mfolozi/Msunduzi with that of the Mhlathuze estuary, which is classified as an estuarine bay, and the Mlalazi estuary, which is classified as a permanently open estuary (Whitfield, 2000). The benthos in both the Mhlathuze (MacKay & Cyrus, 1999) and the Mlalazi estuaries (Mabaso, 2003) was dominated by polychaetes, especially *Prionspio* sp., *D. arborifera* and capitellidae, together with *A. digitalis*, and *P. blephariskios,* all being taxa recorded in the Mfolozi/Msunduzi system and indicating that, at least in terms of its benthic community, the Mfolozi/Msunduzi would be better classified as a permanently open estuary rather than as a river mouth.

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FRESHWATER PRAWNS AND THE ECOLOGICAL IMPORTANCE OF SUSTAINABLE LINKS BETWEEN THE MFOLOZI/MSUNDUZI AND ST LUCIA WETLANDS

Iain Bickerton*

Affiliation: Consulting Aquatic Ecologist, Morningside, Durban
**Email: ibickert@saol.com*

INTRODUCTION

The genus *Macrobrachium* comprises a group of river or freshwater prawns represented in southern Africa by about seven species (Kensley, 1981). All species of the genus *Macrobrachium* in southern Africa exhibit catadromous lifestyles where adults migrate downstream to breed with juveniles returning upstream to grow to maturity (Bickerton, 1989, Hart *et al*., 2001). Of particular note is that *Macrobrachium* species require access to brackish water usually associated with an estuary, for larval development in order to complete their life cycles (Bickerton, 1989; Hart *et al*., 2001). In order to enable this, breeding adults either migrate or are washed downstream during floods and breed in the lower reaches of rivers usually where there is some estuarine or marine influence.

After the high rainfall period of early 1976, large numbers of *Macrobrachium* prawns began to appear in the then Natal Parks Board (NPB) bait fishery catches. The fishery normally relied on catches of penaeid prawns from the Narrows. Although *Macrobrachium* spp. had been recorded in St Lucia before 1976 (Day *et al.*, 1954; Crass, 1956; Millard, and Broekhuysen, 1970; Champion *in litt*.), such large numbers of these carids had not been seen in previous bait fishery catches. Between April and June 1976 *Macrobrachium* prawns apparently comprised more than 30% of the total bait catch and by January-March 1977 some samples taken from the Narrows contained only *Macrobrachium* prawns (Bickerton, 1989).

Figure 1 shows a generalized life-cycle of a typical river prawn of the genus *Macrobrachium*. Adults mostly live in fresh or brackish water. During breeding periods, adults usually either migrate downstream or are washed downstream by floods. The downstream movement, whether caused by floods or swimming by adult prawns, enhances the possibility of larvae hatching in brackish or salt water. This is a requirement for successful larval development in many species. Females carry the eggs on the pleopods. Larvae hatch and are released usually in the brackish water of estuaries and lagoons. There are up to thirteen stages in the larval development (Williamson, 1972), after which juvenile or post-larval stages migrate upstream where they grow to maturity in rivers, streams and swamplands.

Breeding migrations similar to those described above have also been recorded for entirely freshwater *Macrobrachium* spp. Instead of hatching in estuaries or lagoons the larvae of freshwater species hatch in the lower reaches of river systems where the water is still fresh (Lee & Fielder, 1979, 1984). The upstream migration has been suggested to be a phylogenetic mechanism for preventing the larval and post-larval stages in particular, from being washed into the sea (Lee & Fielder, 1979).

In some *Macrobrachium* spp. (e.g. *M. nobilii*; *M. malcolmsonii*), the brackish water environment necessary for the completion of larval development is reached, not by migration of the adult, but by passive migration of the stage I larva (zoea). This larval stage is known not to feed, but relies on the yolk energy from the egg. The duration of the first larval stage appears to be related to the life history of *Macrobrachium* spp. (Balasundaram & Pandian, 1982). It is longest (> 8 days) in those species having a larval migration history, moderate (about 5 days) in species having adult migration and shortest (2 days) in those species which are not characterized by larval and/or adult migration life history.

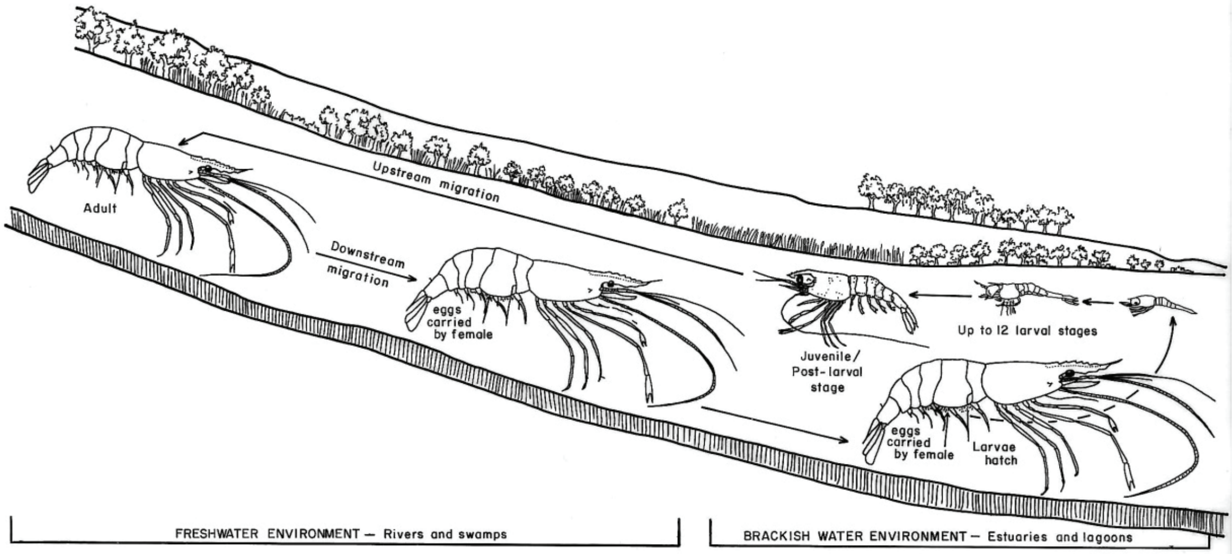


Figure 1. The life-cycle of a typical *Macrobrachium* prawn (from Bickerton, 1989).

Details of the taxonomy, biology and ecology of some south-east African *Macrobrachium* species in the St Lucia system were investigated by Bickerton (1989) after a series of floods during a wet phase in the hydrological cycle. Outcomes of the study included attempts to determine factors controlling invasions of the St Lucia system by *Macrobrachium* spp. so as to enable prediction of the conditions under which such invasions might occur in the future. This contribution is a summary of those aspects of the study that focus on the ecological importance of sustainable links between the Mfolozi/Msunduzi and St Lucia wetlands.

IMPORTANT FINDINGS FROM BICKERTON (1989)

Conditions for successful reproduction of *Macrobrachium* species

In order to understand the ecology of a species, it is important to have a thorough knowledge of the most vulnerable stages of its life history. In the case of benthic invertebrates these are the breeding and larval stages. In a changing environment, it is advantageous to postpone or minimize reproduction until a favourable period is anticipated and then to expend a large effort in maximizing reproduction when suitable conditions materialise (Wilbur *et al*., 1974). Such a life history strategy might be expected to be of particular benefit to *Macrobrachium* spp. populations that are dependent on both estuarine and freshwater habitats for completion of their life cycles. Indeed, in a dynamic ecosystem such as St Lucia, subject to severe changes associated with extreme floods and extended periods of drought, continued survival may depend on such opportunism.

Of prime importance to the successful reproduction of populations of *Macrobrachium* spp. is the location of suitable habitats for larval and juvenile development (Raman, 1967; Rajyalakshmi and Ranadhir, 1969; Rajalakshmi, 1980; Read, 1985a and b). Adults of species requiring brackish water for larval development are often located in freshwater areas in rivers and swamps (Raman, 1967; Read, 1985b). For this reason successful breeding frequently requires, not only elevated temperatures (Dudgeon, 1985), but must also be synchronized with the period of peak seasonal rainfall (Rajyalakshmi, 1980; Read, 1985b) thereby enhancing the chances of larvae and juveniles finding quiet brackish backwater areas.

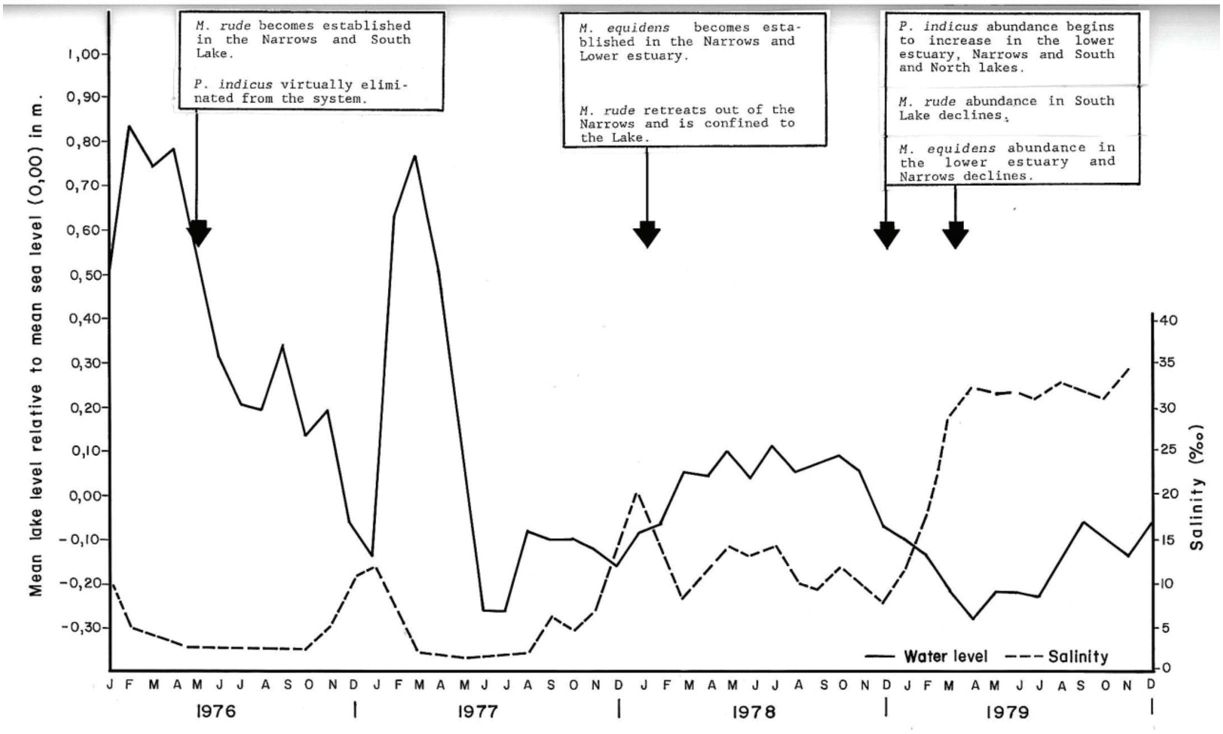
Hypothesis for *Macrobrachium* population fluctuations

The general trends following the influx of *Macrobrachium* prawns into the St Lucia system in 1976 as outlined in Figure 2 were:

- Initially *M. rude* occurred throughout the Narrows and in South Lake during the course of 1976 and 1977.
- By the summer of 1977/78, *M. rude* had retreated up the Narrows and appeared to be confined to the Lake with only a few specimens of this species being sampled in the Narrows. At this time *M. equidens* became established in the lower estuary and Narrows. There appeared to be minor migrations of *M. rude* into the upper reaches of the Narrows during the winter months of 1978, but otherwise the estuary and Narrows were dominated by *M. equidens*.
- *M. scabriculum* was found in the lake only and persisted there from 1977 to 1979, although its abundance declined during the course of the study period as salinity rose.
- Half-way through the study period, penaeid prawns (largely *Fenneropenaeus indicus*) became re-established in the lower estuary and Narrows and moved into South Lake from the summer of 1978/79 onwards, as salinity rose in those parts of the system.

The question arises as to why there was an influx of *Macrobrachium* species into St Lucia in large numbers after the 1976 floods, when this phenomenon had not been observed by the Natal Parks Board (NPB) after previous floods. Based on the results of this study, an hypothesis is presented that attempts to explain how *Macrobrachium* spp. entered St Lucia after the 1976 floods and why they became established there during the three-year low-salinity phase that followed.

The 1976 floods were unusual in that there was near-continuous flooding of the lower reaches of the Mfolozi/Msunduzi Floodplain from January to May (McGill, 1980), giving rise to floodwater connections and sheet flow from the Mfolozi/Msunduzi wetlands into St Lucia Estuary (Taylor & Collings, 1988). Annual summer flooding did not normally last later than February or March (McGill, 1980, Pitman *et al.*, 1981; Looser, 1985). The protracted summer 1976 flood period was critical to the entry of *M. rude* into St Lucia Estuary. Evidence supporting this was obtained by sampling in the Mfolozi/Msunduzi Floodplain in April 1980 by which time *M. rude* had been all but eliminated from St Lucia Estuary and the Narrows. A total of 212 adult *M. rude* were caught in freshwater, immediately downstream of the Monzi/Uloa Bridge using 20 traps set in one overnight period. The catch comprised 68 males and 144 females, 58% of which were ovigerous. Assuming that *M. rude* occurred in similar abundance in the Mfolozi/Msunduzi rivers and Floodplain during the autumn 1976 breeding period, floodwater connections with St Lucia Estuary at the time would have provided a means of entry. The major *M. rude* breeding period is in the autumn (March to May). Breeding adults entering St Lucia Estuary and the southern parts of the lake during the floods were able, therefore, to exploit the favourable salinity conditions there (Figure 2). The *M. rude* collected by the NPB Bait Fishery in 1976 were mostly large adults in the 2 year and over size classes suggesting that they originated from outside the Narrows. Flow data for the Mfolozi (McGill, 1980; Looser, 1985) as well as rainfall figures for St Lucia Village suggest that further *M. rude* influxes could have occurred during 1977.


M. rude becomes established in the Narrows and South Lake.

P. indicus virtually eliminated from the system.

M. equidens becomes established in the Narrows and Lower estuary.

M. rude retreats out of the Narrows and is confined to the Lake.

P. indicus abundance begins to increase in the lower estuary, Narrows and South and North lakes.

M. rude abundance in South Lake declines.

M. equidens abundance in the lower estuary and Narrows declines.

Figure 2. Changes in the distribution and abundance of *Macrobrachium rude* and *M. equidens* in relation to Lake level and salinity (as measured at Charter’s Creek).

The argument that *M. rude* adults possibly entered the St Lucia system not from the Mfolozi/Msunduzi, but via the Mkuze Swamps in the north, has two counter considerations. Firstly the distribution and abundance of *M. rude* in the system during 1977 suggested a southern rather than northern origin for these prawns *i.e*. abundance was generally greatest in the Narrows and in the southern parts of South Lake. Secondly, an extensive fish survey of the Mkuze Swamps in March 1988 (Skelton *et al*., 1988) did not reveal the presence of any *Macrobrachium* spp., although a number of *Caridina* specimens were collected (Skelton *pers*. *comm*.).

The establishment of *M. equidens* in St Lucia Estuary coincided with the retreat of *M. rude* from the Narrows and into the lake. These two species appear to be mutually exclusive in that *M. equidens* was never found in the lake and *M. rude*, if collected in the same samples as *M. equidens* in the upper Narrows, comprised only a small proportion of the total catch. This was similar to the *M. equidens* invasion of the Bonny River, Nigeria, described by Powell (1986). How *M. equidens* entered St Lucia in 1978 is not clear, but this species was later recorded in salinity above 15 PSU in the Mfolozi and Mlalazi estuaries further south.

Macrobrachium equidens had not been caught in the St Lucia system prior to February 1978. In view of the probable misidentification of *M. rude* as *M. equidens* in southern Africa (Johnson, 1973), previous records of *M. equidens* at St Lucia are doubtful. The origin of the *M. equidens* populations at St Lucia is therefore problematic. Denne (1968) found that although *M. equidens* is capable of both hyper- and hypo-osmoregulation, it has not yet developed the capacity to osmoregulate in water of low salinity (<5 PSU). Read (1982) interpreted this as indicating that, from an evolutionary viewpoint, *M. equidens* is a recent invader of the estuarine environment from the sea. Colonisation of the Narrows by *M. equidens* could have been from the sea, although there are no local records of *Macrobrachium* species from either near- or offshore areas, with the possible exception of the SA Museum *M. equidens* specimen which was collected in Delagoa Bay before 1950 (Bickerton, 1989). De Freitas (1980), however, in an extensive study of penaeid prawns in Delagoa Bay from 1968 to 1973, makes no mention of *Macrobrachium* spp. in any of the catches, although fauna other than penaeids is listed.

Macrobrachium scabriculum occurred in the lake only, and usually was localized around the mouths of peripheral streams, and never in very large numbers. Being the most freshwater orientated of the three species, it appeared to have originated from the streams and wetlands peripheral to the lake.

The persistence of *M. rude* and *M. equidens* in large numbers in St Lucia occurred at a time when penaeid prawns and particularly *Fenneropenaeus indicus* abundance in the system had declined with flooding and lowered salinity (Forbes & Benfield, 1985). Environmental conditions during the low-salinity phase following the 1976 floods were therefore likely to have favoured *M. rude* and later *M. equidens*, in the lower estuary and Narrows at the expense of *F. indicus* (Da Silva, 1986). Since comparison of gut-content analyses of *M. rude* (Bickerton, 1989) and *F. indicus* (Joubert & Davies, 1966) suggested possible competition for food resources between these two species, the absence of *F. indicus* could have influenced the persistence of *M. rude*. As penaeid prawns and *Macrobrachium* species are components of the macrobenthos, competition for space may have been a significant factor. The former enter St Lucia from the sea as late larval and early post-larval stages and the latter as breeding adults mainly from freshwater swamps and rivers. The common use of lagoons, estuaries and deltas by both penaeid prawns and *Macrobrachium* species has been described by several authors (Gamba, 1982; Frusher, 1983; Gamba & Rodriguez, 1987; Robertson & Duke, 1987). In all cases these ecosystems serve as nursery areas for penaeids and as both spawning and nursery habitats for *Macrobrachium* species.

Since the Mfolozi/Msunduzi river used to have a common mouth with St Lucia before 1952 (Figure 3), *Macrobrachium* influxes into St Lucia during low-salinity phases would have been facilitated by open channel connections between the Mfolozi/Msunduzi floodplain and St Lucia Estuary. Natal Parks Board (NPB) bait fishery operations began in 1952, the year that the Mfolozi/Msunduzi River was artificially separated from St Lucia. This probably explains the lack of records of large-scale influxes of *Macrobrachium* prawns into the estuary and Narrows except following extreme floods.

Construction of the Mfolozi/St Lucia Link Canal (Figure 3) during the early 1980s has probably facilitated *Macrobrachium* influxes into the lower reaches of the St Lucia System when salinity conditions in the estuary and Narrows are suitably low. This was borne out by the *M. rude* influx that occurred after Cyclone Domoina which struck the area in January/February 1984, although the magnitude of the floods at the time would have allowed this even if the canal had not been constructed. A more recent influx into the Narrows occurred during the much smaller floods early in 1985 and the existence of the Mfolozi/St Lucia Link Canal almost certainly facilitated this.

Population ecology of *Macrobrachium rude* in the Mfolozi/Msunduzi floodplain

Failure of seasonal floods has a deleterious effect on the annual recruitment of juvenile *M. rosenbergii* (Raman, 1967) and *M. malcolmsonii* in India (Rajyalakshmi and Ranadhir, 1969; Rajyalakshmi, 1980). Furthermore, fluctuations of localised adult populations in response to both seasonal and annual variations in rainfall and river run-off were also described by these authors. Elsewhere, similar movements of *Macrobrachium* spp. adults and juveniles have been indicated by several authors (Hughes & Richard, 1973; Lee and Fielder, 1979, 1984; Frusher, 1983; Gamba & Rodriguez, 1987). More locally, Read (1985b) associated downstream and upstream migrations of *M. petersii* in the Keiskamma River and estuary with high (wet year) and low (dry year) run-off respectively.

The local inhabitants of the Mfolozi/Msunduzi Floodplain trap *Macrobrachium* prawns in the water courses (personal observations), using techniques similar to those employed by the inhabitants of deltas in India (Rajyalakshmi & Ranadhir, 1969; Kurian & Sebastian, 1986). Discussions with these local people confirmed that large numbers of adult *Macrobrachium* prawns are present in the drainage canals on the Floodplain, particularly after flooding in the summer months. The lack of abundance of other *Macrobrachium* spp. in the area indicates that these are *M. rude*. The large prawns apparently disappear towards the end of autumn and only juveniles are present in winter and spring. This was verified by sampling backwaters containing submerged vegetation with a hand net and traps in the winter of 1987 (Bickerton, 1989). The local Floodplain inhabitants were of the opinion that adult prawns moved into the main river courses at the end of autumn.

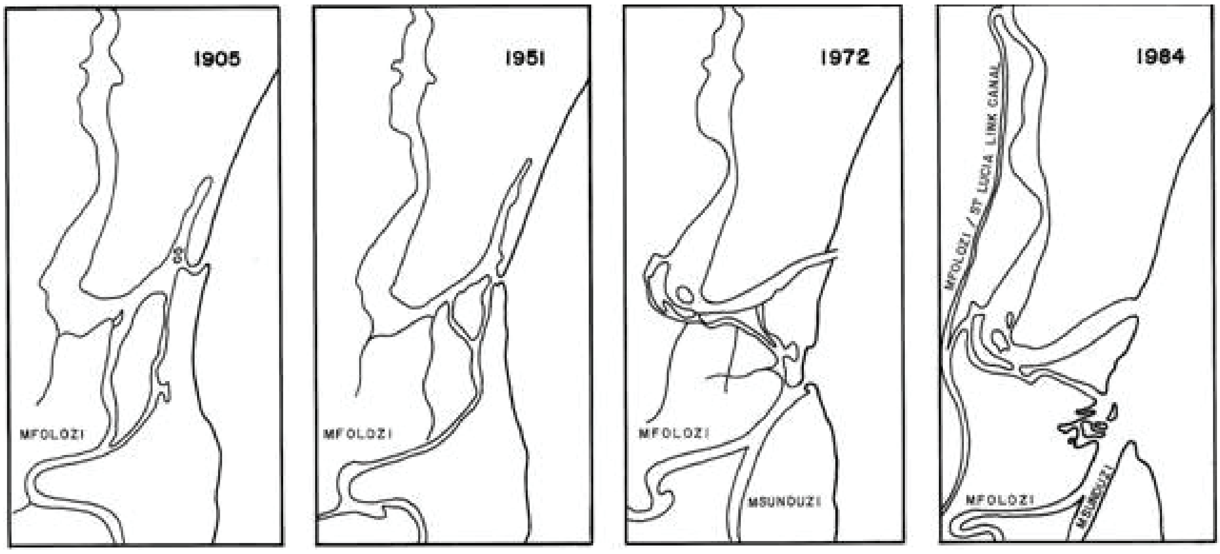


Figure 3. Natural and man-made changes in St Lucia and Mfolozi/Msunduzi estuaries showing different open channel connections before 1952, which would have facilitated influxes of *Macrobrachium* prawns into St Lucia from the Mfolozi/Msunduzi Floodplain.

Based on what is known for *M. rosenbergii* and *M. malcolmsonii* in India (Ibrahim, 1962; Raman, 1964; Rao, 1967; Raman, 1967; Rajyalakshmi & Ranadhir, 1969; Rajyalakshmi, 1980) it appears that the annual cycle of *M. rude* movements and breeding activity in the Mfolozi/Msunduzi rivers and floodplain, is similar to those of the Indian species. During the 4-year period prior to the 1976 influx of *M. rude* into St Lucia, good rains fell in the Mfolozi catchment (Looser, 1985), particularly in 1972 and 1975 (McGill, 1980; Pitman *et al.*, 1981). Conversely the 4-year period preceding Cyclone Domoina was characterized by drought (Looser, 1985). During this dry period the Mfolozi in the lower reaches of the floodplain ceased flowing at times, leaving isolated pools of stagnant water. This was observed in August 1980 (personal observations). An extended period of drought such as occurred from 1980 to 1983 is likely to severely reduce the *M. rude* population on the Mfolozi/Msunduzi floodplain. Conversely an increase in the population might be expected after a series of average to above-average rainfall years. Cursory inspection of the NPB Bait Fishery data suggested that the *Macrobrachium* influx into the Narrows following Cyclone Domoina was minor compared to that of 1976. Although based only on speculation, this difference could have been related to the dry and wet phases respectively, preceding the floods.

A schematic diagram, based on the findings of this study, depicting the possible interactions of factors likely to affect the dynamics of *M. rude* populations in the Mfolozi/Msunduzi floodplain and St Lucia system, is shown in Figure 4, which is interpreted as follows:

- Water temperatures in the St Lucia system generally exceed 20^{o}C from spring (September) to autumn (May). During this time the onset of reproductive development in *M. rude* populations in the Mfolozi/Msunduzi rivers is induced by the temperature-photoperiod regime.
- Annual flooding of the Mfolozi/Msunduzi usually occurs in the late summer (February) or early autumn (March). Breeding adult *M. rude* are washed downstream into the

floodplain during such floods. Although seasonal flooding normally occurs in late summer, aseasonal floods at any time between early spring (September) and late autumn (May) would also result in a downstream movement of breeding *M. rude*. The numbers of ovigerous females would, however, probably be lower in the spring months as favourable conditions for breeding would only have just begun. In this way temperature and day length give the cue for the initiation of the reproductive cycle and floods provide the vehicle for transport to the habitat suitable for breeding and larval development.

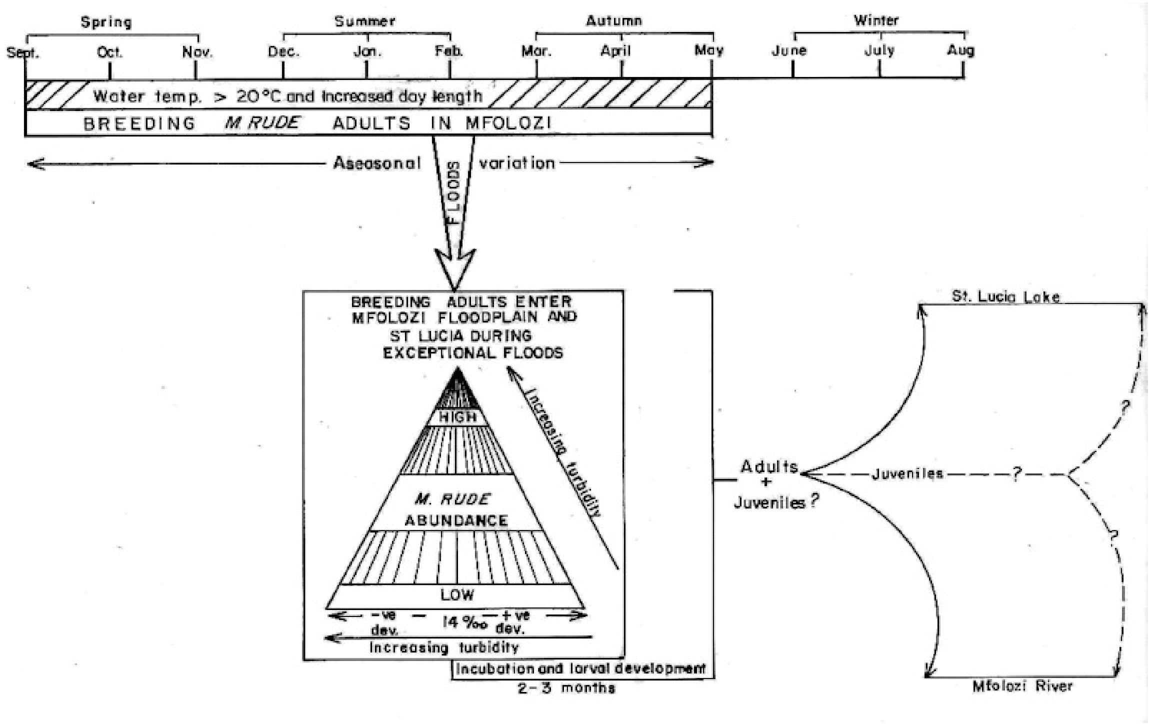


Figure 4. Proposed *Macrobrachium rude* population model (from Bickerton, 1989).

- During exceptional floods when sheet flow or open water connections between the Mfolozi/Msunduzi floodplain and St Lucia Estuary are made, breeding *M. rude* are introduced into the Narrows where conditions are also suitable for breeding and larval development.
- With the subsidence of floodwaters, adult *M. rude* in the lower Mfolozi/Msunduzi floodplain and St Lucia tend to be most abundant in turbid water in the salinity range 8-20 PSU. This range represents the larval rather than adult requirements with the optimum salinity for *M. rude* larval development being approximately 14 PSU.
- Incubation and larval development takes, at most, three months and under optimum conditions of salinity (14 PSU) and temperature (possibly 25-28^{o}C) the duration is probably closer to two months.
- The low rainfall (and consequent run-off) winter period (June to August) following the usual autumn breeding peak, allows retention of larval stages and juveniles in the quiet tidal backwaters of channels and canals in the lower Mfolozi/Msunduzi floodplain and the southern parts of St Lucia. If the early larval stages of *M. rude* are associated with salt

front regions (as demonstrated for *M. petersii* by Read, 1985a) such conditions could be found in the channels and drainage canals. Salt fronts could also prevail in the Narrows, particularly after floods when a high lake level causes low-salinity water to drain towards the sea.

- At the end of the autumn breeding period, adult *M. rude* in the Mfolozi/Msunduzi floodplain move into the deeper river courses and probably migrate upstream with juveniles either following at the end of winter, or remaining in the vegetation-lined backwaters of the Floodplain until they have attained adult size. If the latter occurs, then the first upriver migration of this age group would be at the end of the following year's autumn breeding period. This being the case, it is probable that first breeding occurs at an age of one year (Bickerton, 1989) followed by the upstream migration.
- An "upstream" migration of *M. rude* similar to that described for the Mfolozi and Msunduzi rivers, probably also takes place in Lake St Lucia and the Narrows, although population structure data (Bickerton, 1989) suggest that it is possibly not as well defined.
- The essence of the population model is that the Mfolozi/Msunduzi Floodplain and lower reaches of the St Lucia system (after exceptional floods) serve as breeding and nursery habitats for *M. rude* populations in the Mfolozi/Msunduzi (and possibly also the rivers which enter the lake) when environmental conditions favour these river prawns.

***Macrobrachium* species as a food resource**

Macrobrachium species support fisheries in the Indo-Pacific, West Africa and North and South America (Bickerton, 1989). In many cases, *Macrobrachium* fisheries capitalize on increased densities of the prawns due to breeding migrations, particularly in estuaries and the lower reaches of rivers. Some of these fisheries are therefore seasonal.

Of the three *Macrobrachium* species dealt with in this study, only *M. rude* appears to be of any significance in fishery catches. In India, *M. rude* supports regular fisheries in the Bombay region, Kerala and the northern half of the coast of the Bay of Bengal (Holthuis, 1980). It supports seasonal (autumn months) fisheries in Bengal and Orissa State, in particular in Chilka Lake (Holthuis, 1980; Kurian & Sebastian, 1986). *Macrobrachium rude* is also fished in small numbers in estuaries on the east African coast of Tanzania and Kenya (Bailey & Crichton, 1971; Fischer & Bianchi, 1984). *Macrobrachium scabriculum* is used as food when caught, but because of its relatively small size it is of minor commercial value (Bailey & Crichton, 1971; Holthuis, 1980; Kurian & Sebastian, 1986). *Macrobrachium equidens* is listed as being of commercial importance in India, but is only found in Kerala and then in small numbers (Holthuis, 1980; Kurian & Sebastian, 1986). In Indonesia, *M. equidens* is caught, but is usually incidental to fishery catches for other species (Holthuis, 1980).

On the Mfolozi/Msunduzi floodplain, *M. rude* and other *Macrobrachium* spp. (e.g. *M. petersii* and *M. lepidactylus* – Bickerton, 1989) are trapped for food by the local inhabitants, using various primitive techniques (*e.g.* a hessian sack containing maize meal and suspended on a pole in the water current – personal observations). These river prawns are important as a protein food source to the subsistence dwellers of the floodplain, particularly during the summer and early autumn months when prawn abundance is high (personal communication with local inhabitants). *Macrobrachium* prawns have been reported to be of similar value to subsistence fishermen of the lower regions of the Purari Delta, Papua New Guinea (Frusher, 1983) as well as deltaic regions of India (Kurian and Sebastian, 1986).

***Macrobrachium* species movements and habitat requirements**

Of vital importance in the life-cycle of south-east African *Macrobrachium* species is that the movement of adults and juveniles between freshwater lakes, rivers and swamps and estuarine and deltaic brackish water habitats, be unhindered (even the most freshwater-orientated *M. lepidactylus* requires brackish water of at least 8 PSU for larval development – Cort 1983). The maintenance of populations of these prawns depends on recruitment of juveniles from saline breeding and nursery areas. Permanent exclusion of the critical stages of the reproductive cycle from such areas by natural or man-made obstructions will result in localized extinction of the *Macrobrachium* species population concerned.

The work of Balasundaram & Pandian (1982) has shown that the duration of the stage I larva in *Macrobrachium* can be related to the life history of the species. The time span between hatching of the stage I larva, which in local species does not appear to feed (Read 1982, Cort 1983, personal observations), but relies on yolk energy from the egg for survival, and its metamorphosis to stage II can be critical for successful larval development (Balasundaram and Pandian 1982). This is particularly so if adults live in freshwater and successful larval development is dependent on passive migration of the stage I larva to the necessary saline waters of estuaries and deltas (Bickerton 1989). The duration of stage I larvae appears to be longest (> 8 days) in those *Macrobrachium* spp. having a larval migration history, moderate (about 5 days) in species having adult migration and shortest (2 days) in those species that are not characterized by larval and/or adult migration life histories (Balasundaram & Pandian 1982). There is thus a need to establish the larval and post larval characteristics and environmental requirements of southern African *Macrobrachium* species from a conservation viewpoint. In this context the work of Cort (1983) has shown that the stage I larva of *M. lepidactylus* can survive unfed in freshwater for seven days. This could be an important characteristic which allows adults of this species to penetrate more than 150 km inland from the coast.

With regard to the salinity requirements of local species, it is notable that no *Macrobrachium* species were ever recorded from Lake Sibaya (Hart, 1979) during a very extensive limnological study (Allanson, 1979) of this freshwater coastal lake which is situated about 50 km north of Lake St Lucia. As for other north-eastern KwaZulu-Natal coastal lakes, both St Lucia and Sibaya evolved as drowned valleys associated with river systems (Hill, 1975; Allanson, 1981). Although Sibaya was previously open to the sea (Hill, 1969), it is now closed off by a Holocene dune barrier and despite being permanently fresh, contains a relict fauna with marine affinities (Allanson *et al*., 1966). It is possible that *Macrobrachium* prawns were present in Sibaya, but became locally extinct there when the lake turned permanently fresh. This proposal is strengthened by the fact that *Macrobrachium* spp. have been recorded in the Kosi Lakes system (Bickerton, 1989) lying to the north of Sibaya which, although otherwise similar to Sibaya, has a tidal basin in its lower reaches. The ingress of seawater in the Kosi system allows the establishment of brackish water conditions suitable for *Macrobrachium* spp. larval development, a characteristic that Sibaya lacks. Further south at Richards Bay, the freshwater Lake Cubhu supports five species of *Macrobrachium*

(Schoonbee *et al*., 1989). Significantly, the lake is connected to the saline Mhlatuze Lagoon by a stream.

***Macrobrachium* habitat destruction and rehabilitation**

In India, deltaic brackish backwater areas have been encroached upon by infilling for urban expansion and "bund" or levee construction for paddy cultivation (Kurian & Sebastian, 1986). According to the prevailing law in many coastal states of India, saline water ingress is not permitted and "bunds" or levees are constructed to make the land usable for agriculture. Such activities have had a major impact on the prawn resources and in places, *e.g*. the Cochin backwater, have virtually eliminated *Macrobrachium* fisheries which previously flourished (Sakthivel, 1985). Ironically, areas "reclaimed" from the intertidal zone for agriculture have proved to be unprofitable due to low yield. This has prompted amendments to the prevailing law of the State Governments in order to promote the propagation of prawns and fish in such areas (Sakthivel, 1985) because of their importance as exploitable resources.

Begg (1988), in a report on the distribution extent and status of the wetlands in the Mfolozi catchment, found that, in the face of expanding human populations and economic pressures for urban expansion, agricultural production and other economic uses, 58% of the original total catchment wetland area no longer exists. Since they comprise an important component of the catchment, Begg's report included an assessment of the Mfolozi/Msunduzi wetlands and floodplain. The details in the following paragraph on historical changes that have taken place were partially extracted from that report.

Prior to any man-induced modification or alteration, the Mfolozi/Msunduzi swampland extended over approximately 21 322 ha, thus making it the largest fluvial coastal plain in South Africa. Of the original area, approximately 9 000 ha have not been "reclaimed" for sugarcane or timber production. However, the undeveloped areas have nevertheless been altered by the construction and maintenance of canals which drain sugarcane fields and levees which prevent floodwaters in the main Mfolozi and Msunduzi watercourses, from spilling into the adjacent swamps. Consequently the natural flood attenuating function of the swamps has been removed (to the satisfaction of the sugar farmers whose fields upstream on the floodplain are less prone to inundation through backing up of floodwaters). Furthermore, the artificial separation of the Mfolozi/Msunduzi mouth from St Lucia Estuary (Figure 3) now tends to channel floodwaters directly into the sea instead of into the lower reaches of St Lucia.

These man-made changes are likely to have had the following detrimental consequences for *Macrobrachium* spp. (in particular *M. rude*) populations in the Mfolozi:

- Levees which prevent floodwaters from spilling into wetlands adjacent to the main river course also prevent river prawns from being deposited in peripheral areas where flow velocity is retarded. Under undisturbed natural conditions, such peripheral areas are important for retaining breeding adults in the floodplain, thereby preventing their loss to the sea and ultimately from the local population. This interpretation is supported by the indications that *M. rude* influxes into the lower St Lucia estuary occur only when

Mfolozi/Msunduzi floodwaters are sufficiently strong to overtop the levees in its lower reaches and spill into St Lucia via the intervening wetland.

- The artificial removal of the Mfolozi/Msunduzi from St Lucia Estuary and the creation of a separate mouth opening directly into the sea, means that those prawns, which are retained in the main river courses during flood flows, are deposited directly into the sea where they are almost certainly lost from the local population. When the Mfolozi/Msunduzi had a common mouth with St Lucia, *Macrobrachium* prawns washed downstream during floods, would have been deposited in the lower St Lucia estuary, from where they could have dispersed into the Narrows and South Lake.
- Periodic maintenance of levees on the banks of canals and the main river courses on the Mfolozi/Msunduzi floodplain removes the fringe vegetation, particularly submerged macrophytes, in which the juvenile river prawns find refuge during the low-flow late autumn and winter period (personal observations).
- The increased incidence and severity of river flow cessation and reduced winter flow due to the general reduction in wetland area throughout the catchment (Begg, 1988) have probably restricted the upstream dispersal of adult and juvenile *Macrobrachium* spp., particularly during prolonged droughts *e.g.* 1980-1983.

The key to the conservation of *Macrobrachium* spp. in the Mfolozi/Msunduzi and St Lucia wetlands from both an ecological viewpoint and also as an exploitable resource, is sound management of the Mfolozi/Msunduzi floodplain. In this respect, the finding of Begg (1988) that although only 43% of the floodplain remained in a semi-natural condition at that time, while agricultural encroachment was continuing, gives cause for serious concern.

Amongst other proposals relating to management of the Mfolozi and St Lucia estuaries from a sedimentary viewpoint, van Heerden & Swart (1986) recommended that no diversion works or canalization be allowed in the lower reaches of the Mfolozi or Msunduzi downstream of the sugar cane fields. In addition these authors proposed that natural swamp and marshland in the lower reaches of the floodplain should be given conservation status. The implementation of both of these recommendations would undoubtedly be of benefit to *Macrobrachium* spp. by way of the re-establishment of natural swamp habitat and the flood attenuating function of the lower portion of the floodplain. Such a step would, however, be in conflict with the interests of the sugar farmers upstream, for reasons already outlined. As a compromise to such divergent interests, serious consideration should be extended to the proposal of Begg (1988) when he concluded that: "If management and conservation of the Mfolozi swamp is to be effective (*i.e.* to ensure long term stability and sustained resource availability) it is essential that an integrated land use plan be prepared. This plan must incorporate the entire swamp system and be adhered to by all parties concerned."

The ecological requirements of *Macrobrachium* prawns and their importance as a resource, particularly to the local inhabitants of the Mfolozi/Msunduzi floodplain, must not be overlooked in the implementation of such a proposal. As was historically (pre-1952) the case, sustainability of links between the Mfolozi/Msunduzi and St Lucia wetlands is implicit in this.

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CHARACTERISATION OF THE MESOZOOPLANKTON COMMUNITY OF THE MFOLOZI/MSUNDUZI ESTUARINE SYSTEM DURING A LOW FLOW PERIOD

HL Jerling*, L Vivier, DP Cyrus & RK Owen

Affiliation: Coastal Research Unit of Zululand, Department of Zoology, University of Zululand, KwaDlangezwa
**Email: hjerling@pan.uzulu.ac.za*

ABSTRACT

The mesozooplankton of the Mfolozi and Msunduzi estuaries, which share a combined mouth, was sampled twice per year during a two-year period of relatively low river flow. Samples were collected during March, after the rainy season when the estuary mouth was open, and during August, after the low-rainfall winter months when the mouth was closed. The estuarine calanoid copepods *Pseudodiaptomus stuhlmanni* and *Acartia natalensis* were numerically dominant, making up 75% of the total number of mesozooplankton recorded. Relatively high abundances were recorded for these copepods, with *P. stuhlmanni* reaching peak densities of 79000 m^{-3}. In the low salinity regions of the estuaries, especially the upper regions of the Msunduzi, the cladoceran *Moina* sp. also attained high densities, reaching 50000 m^{-3}. During sampling sessions when the mouths of the estuaries were closed the systems became relatively fresh, in contrast to open mouth conditions when seawater dominated the lower reaches. Peak densities of estuarine copepods occurred during times of mouth closure. When the mouth was open these copepods generally declined in number and an influx of coastal marine species such as paracalanids, Corycaeidae and chaetognaths were evident. Although higher zooplankton densities were mostly recorded in the Msunduzi estuary, the species composition in the two systems was relatively similar, with no significant differences between them. The Mfolozi Estuary is normally classified as a river mouth type, but during the present study this estuary effectively functioned as a temporarily open/closed type estuary. The low flow conditions did not adversely affect the estuarine mesozooplankton, largely because the mouth never remained closed for any extended period.

INTRODUCTION

The Mfolozi estuarine system was classified by Whitfield (1992) as an example of a river mouth type estuary, where the river usually dominates physical processes within the estuary.

Historically the Mfolozi River entered the St Lucia system through St Lucia Bay, a large basin from which there was a single mouth for both systems to the sea. After substantial sedimentation due to the canalisation and draining of the Mfolozi floodplain to create sugar cane farms, a separate mouth was dredged for the Mfolozi in 1950, effectively stopping any further freshwater inputs to the St Lucia system (Taylor, 2006). The lower section of the Mfolozi is in close contact with the adjacent Msunduzi estuary, where a few canals link the two estuaries, and both open into a communal mouth area, channelling all outflows from the two rivers straight into the Indian Ocean without it influencing St Lucia. Given the current state of the St Lucia system, where droughts cause extended periods of mouth closure, it is likely that the Mfolozi and Msunduzi rivers also hold the key to the future health of St Lucia since, without the input of low salinity water from them, St Lucia is probably destined to degrade further in the near future.

The zooplankton communities of a number of South African estuaries have been documented over the last few decades (Grindley, 1981; Wooldridge, 1999) and more recently by Kibiridge & Perissinotto (2003), Froneman (2004) and Jerling (2005, 2008) amongst others. Nevertheless, for some systems such as the Mfolozi no information is available. Studies on zooplankton in the adjacent St Lucia system cover a period of more than 60 years from 1948 onwards (Grindley, 1982). However, besides a synthesis published in conference proceedings (Grindley, 1982), that author never published his work on St Lucia in any peer-reviewed journal.

The Mfolozi Estuary was ranked 13th out of approximately 250 South African estuarine systems in terms of conservation importance (Turpie *et al*., 2002). Despite this, biological information on the Mfolozi and Msunduzi estuaries remains scarce (Whitfield, 2000). Sedimentation had been studied, *e.g*. Lindsay *et al*. (1996a, 1996b), van Heerden (1993) and Wright (1995), but no other published studies are available. There is a paucity of data on the biota of the two estuaries and no zooplankton studies had been done on either of them. The aim of the present study was, therefore, to provide initial data on the zooplankton communities of these estuaries. The study forms part of a larger project including other aquatic biota as well as linking with an existing programme on the St Lucia system, investigating the effects of the current prolonged drought.

METHODS

Zooplankton samples were collected in the Mfolozi and Msunduzi estuaries during autumn (March) and spring (August) in 2007 and 2008. Since the estuaries are turbid, shallow (depth < 1.5 m) and contain crocodiles and hippopotami, all sampling took place in mid-water depth during daytime. This was done to tie in with the zooplankton sampling programme in the St Lucia system, where all samples were collected during daytime because of logistical problems, the hazardous nature of the system and the presence of large numbers of crocodiles and hippopotami. It is well established that zooplankton samples should ideally be collected after dark and that daytime sampling may lead to an underestimation of some species, especially when turbidity is low, because of the vertical migration of some estuarine zooplankters (Grindley, 1972).

Sampling took place at six sites in the two estuaries (Figure 1). Zooplankton were collected using a 200 µm mesh double plankton net, each 2 m long with a mouth diameter of 300 mm, one being fitted with a flow meter to quantify the samples. The nets were towed in mid-water depth using a small, motorised boat at slow speed for about 3 minutes. To avoid interference from the boat, the nets were attached to a boom and towed in front of the bow. Samples were preserved in the field in estuarine water with about 4% formalin. A sub-sampling method (Jerling & Wooldridge, 1995) was used to analyse zooplankton samples in the laboratory.

At all sites temperature, salinity, pH, dissolved oxygen and turbidity were measured near the surface and bottom using a YSI instrument. Data recorded during August 2008 for the mouth area and the Mfolozi Estuary were however lost.

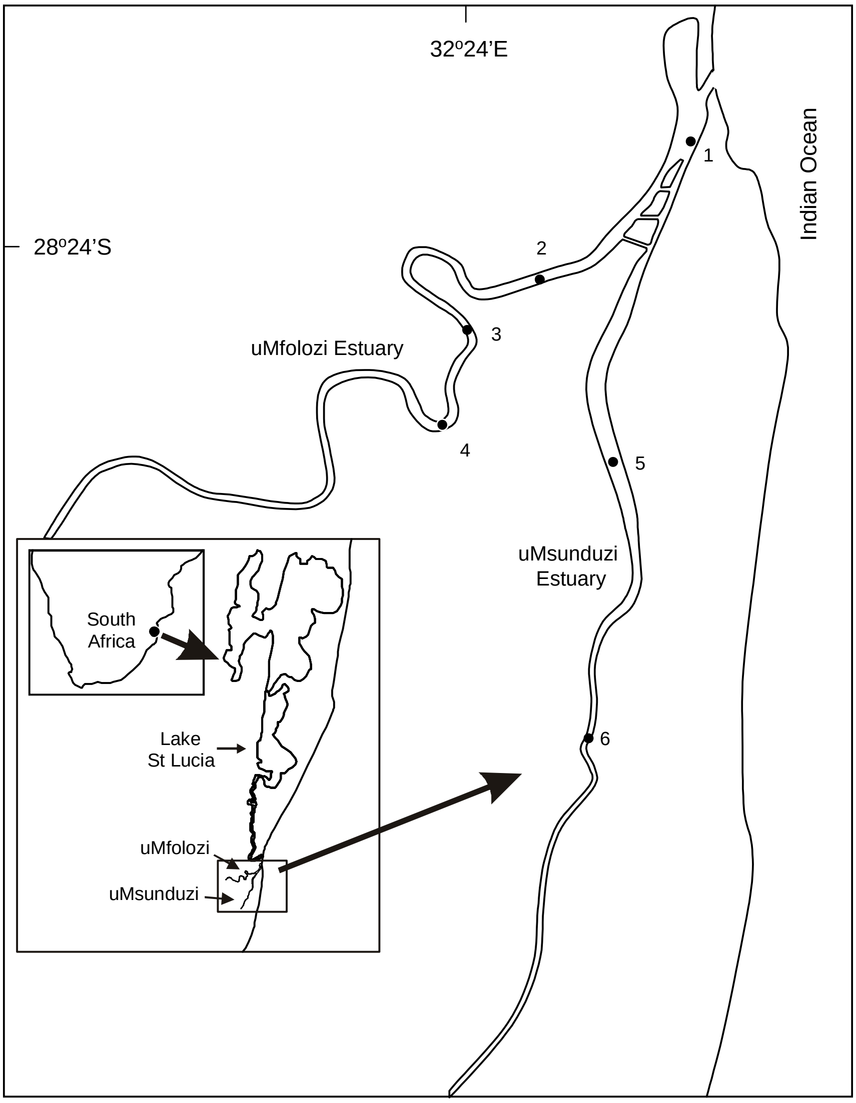

Figure 1. Map of the study area, indicating positions of the zooplankton sampling sites in the Mfolozi and Msunduzi estuaries.

RESULTS

Temperature variations between 20°C during March and 30°C in August (Figure 2) are normal for these subtropical estuaries. Turbidity levels were generally below 20 NTU. No clear spatial patterns were evident, apart from the high turbidity levels recorded during the March sampling sessions in the Msunduzi when measurements were higher than 150 NTU (Figure 2).

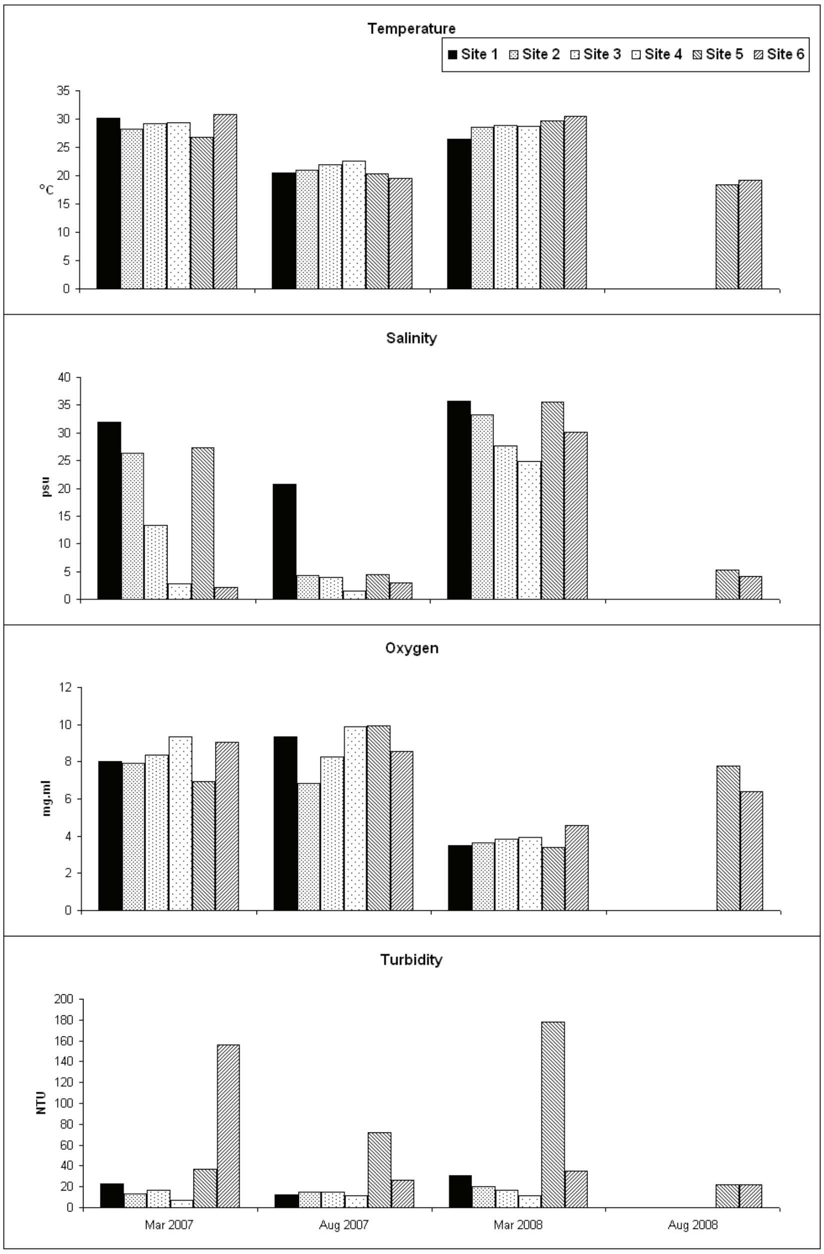

Figure 2. Environmental variables recorded in the Mfolozi and Msunduzi estuaries during 2007 and 2008 at the mesozooplankton sampling sites. No data are available for the mouth and Mfolozi Estuary during August 2008.

The estuary mouth was open during the March 2007 and March 2008 sampling sessions. An axial salinity gradient was evident along both the Mfolozi and Msunduzi on these occasions, being most pronounced in the Mfolozi Estuary during March 2007 when salinity ranged between 3 PSU at the upper station and 32 PSU near the mouth (Figure 2). The March 2007 sampling took place during an outgoing tide, whereas the March 2008 samples were collected during high tide, to make navigation in the Msunduzi easier. The estuary mouth was closed during August 2007 and 2008. Salinity values recorded at the Mfolozi and Msunduzi sites were very low (<6 PSU during these sampling sessions (Figure 2).

A total of 37 taxa were recorded in the estuaries (Table 1). Copepods dominated all samples, with the estuarine calanoids *Pseudodiaptomus stuhlmanni* and *Acartia natalensis* being the most abundant, making up 75% of the total mesozooplankton numbers recorded. Daytime sampling, however, most likely resulted in an underestimation especially of adult instars of *P. stuhlmanni*, which tend to remain in the bottom waters during the day, migrating into near-surface waters at night (Grindley, 1972). Mean mesozooplankton densities recorded when the mouth was open (7 100 m^{-3}, SD = 22 000, range = 13-76 900 m^{-3}) were much lower than when the mouth was closed (24 500 m^{-3}, SD = 31 000, range = 557-79 800 m^{-3}). This difference was, however, not significant at a 95% confidence level ($p = 0.06$), mainly because of one incidence of high densities of *P. stuhlmanni* (59 000 m^{-3}) and cladocerans (17 000 m^{-3}) at the upper sampling site in the Msunduzi while the mouth was open during March 2007.

Maximum mesozooplankton densities occurred more often in the Msunduzi than in the Mfolozi. Mean densities recorded in the Msunduzi were also higher (27 400 m^{-3}, SD = 35700, range = 293-76 900 m^{-3}) than in the Mfolozi (7 600 m^{-3}, SD = 22 700, range = 117-79 800 m^{-3}) but the difference was not significant ($p = 0.10$) as reflected by the high standard deviations. Coastal marine species, including paracalanids, Corycaeidae and chaetognaths, were present in both estuaries during March in 2007 and 2008 when the mouth was open and seawater was entering the system (Figure 3). Abundances were, however, relatively low (range = 0-117 m^{-3}). They were not recorded during spring sampling sessions when the mouth was closed.

Densities of the estuarine calanoids were low (< 400 m^{-3}) during the first sampling session when the mouth was open and salinity high, except for the upper site in the Msunduzi, as explained above (Figure 3). After mouth closure, the numbers of these copepods increased and the maximum density for *Pseudodiaptomus stuhlmanni* of 79000 m^{-3} was recorded at Site 2 during August 2007. Numbers declined again in March 2008 when the mouth opened and seawater entered the estuaries. During August 2008 numbers were still substantially below that recorded in August 2007 (Figure 3). The other dominant estuarine calanoid, *Acartia natalensis*, showed a general increase in densities from the very low abundances (< 10 m^{-3}) recorded during March 2007, when the lower and middle reaches were largely marine-dominated in terms of salinity (Figure 3).

The mysid *Mesopodopsis africana* was recorded in March 2008 at Sites 2, 4 and 6 and during August 2008 at Site 1. Numbers were very low, with a maximum of 17 m^{-3} (range = < 1-17 m^{-3}) during August 2008.

Table 1. Mean densities (numbers m^{-3}) and (SD) of taxa recorded in mesozooplankton samples from the Mfolozi and Msunduzi Estuaries during March and August in 2007 and 2008. ‘Mouth’ represents samples collected near the combined mouth of the two estuaries.

Taxa	***Mouth***	**SD**	***Mfolozi***	**SD**	***Msunduzi***	**SD**
Foraminifera	0	0.00)	0.13	0.46	0	0
Cnidaria	0.24	0.42	0.04	0.1	0.41	0.8
Polychaete larvae	0.3	0.41	0.48	1.68	3.22	9.1
Cladocera						
Moina sp.	2.45	4.9	119	283.81	11041.3	18315.4
Ostracoda	0	0	0	0	0.23	0.46
Calanoida						
Pseudodiaptomus stuhlmanni	15069	18942	7057.5	22935.3	15452.31	24957.4
Acartia natalensis	1619.1	2997.7	388.86	505.93	678.45	1613.38
Calanus *sp.*	0	0	0	0	0.01	0.04
Subeucalanus *sp.*	0	0	0.01	0.02	0.01	0.04
Undinula *sp.*	0	0	0	0	0.04	0.11
Pontellidae	0.14	0.29	0	0	0.12	0.33
Paracalanidae	29.82	58.36	0.53	1.85	8.84	23.77
Temora turbinata	0.05	0.11	0	0	0.01	0.04
Canthocalanus pauper	0	0	0	0	0.07	0.13
Tropodiaptomus *sp.*	0.61	1.23	0	0	0	0
Poecilostomatoida						
Oncaea *sp.*	3.51	6.87	0.27	0.92	3.98	8.17
Corycaeidae	10.57	20.57	0.56	1.84	8.2	19.72
Cyclopoida						
Oithona spp.	5.23	10.32	0.43	1.49	14.11	39.83
Unid. FW and brackish water	0.61	1.23	3.09	9.03	32.14	70.66
Siphonostomatoida						
Caligidae	0.14	0.29	0	0.02	0	0
Harpacticoida	0.91	1.36	2.39	3.93	1.97	5.53
Mysidacea						
Mesopodopsis africana	4.27	8.54	0.28	0.92	0.02	0.05
Cypris larvae	0.05	0.11	0.02	0.04	0	0
Amphipoda	0.14	0.29	0	0	0.78	2.21
Isopoda	0.03	0.05	0	0	0	0
Decapoda						
Lucifer sp.	0.03	0.05	0	0	0.01	0.04
Prawn zoeae	1.05	1.05	10.78	24.59	2.56	4.67
Crab zoeae	10.28	12.16	51.88	69.33	79.2	203.35
Crab megalopa	0.29	0.58	0	0	0.08	0.22
Mollusca						
Mollusc larvae	134.86	142.43	28.82	60.03	69.62	129.72
Cyphonautes larvae	0.53	0.99	0	0	0.11	0.22
Chaetognaths	0.77	1.41	0.02	0.05	0.55	1.45
Appendicularia	0.81	1.23	0.01	0.02	0.77	2.19
Doliolidae	0	0	0	0	0.13	0.36
Fish eggs	2.41	4.17	1.15	3.7	1.1	2.89
Fish larvae	60.02	113.27	6.22	8.74	16.33	17.18
Insect larvae	0	0	0.01	0.04	0	0

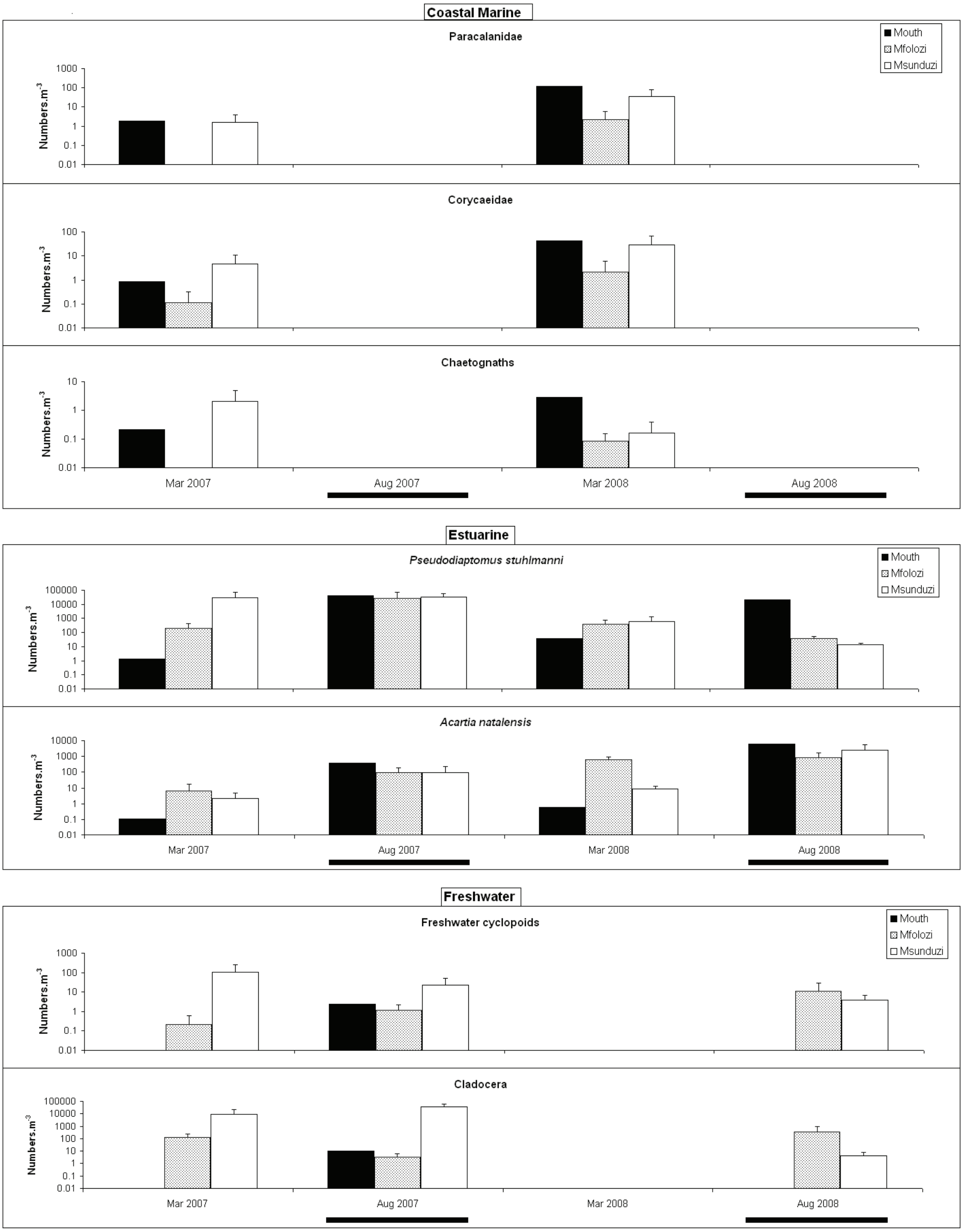

Figure 3. Mean abundance and SD of dominant coastal marine and estuarine copepods and freshwater mesozooplankton recorded in the Mfolozi and Msunduzi Estuaries during 2007 and 2008. No replicate samples were collected for the mouth area. Horizontal bars indicate sessions when the mouth was closed.

Freshwater cyclopoids and cladocera were mostly recorded during times of mouth closure (Figure 3), but also in March 2007 at the upper sampling sites which had very low salinities relative to the mouth and middle reaches. The freshwater Cladocera, predominantly *Moina* sp., reached densities exceeding 50 000 m^{-3} at the upper station in the Msunduzi in August 2007.

Meroplankton, including crab zoeae, fish larvae and mollusc larvae, was recorded during all sampling sessions. Numbers were, however, very low (range = < 1-790 m^{-3}) during March 2007. The dominant meroplankton taxa, crab zoeae and mollusc veliger larvae, reached maximum densities during autumn 2008, when the mouth was open.

DISCUSSION

Copepods are in general the dominant component of mesozooplankton communities in estuarine systems (Grindley, 1981). In the present study two calanoids, *Pseudodiaptomus stuhlmanni* and *Acartia natalensis* numerically dominated the mesozooplankton. The maximum densities recorded for these two copepods compare favourably with those reported for congeneric species in the Sundays River (Jerling & Wooldridge, 1995) and Kromme Estuaries (Wooldridge & Callahan, 2000). However, this result must also be viewed in light of the fact that sampling took place during daytime, which normally would lead to an underestimation of some of the plankters (Grindley, 1972; Kibiridge & Perissinotto, 2003), as well as the inefficient sampling of small taxa due to the 200 µm mesh used.

Three congeneric *Pseudodiaptomus* species are recorded in estuaries along the Zululand coast. *Pseudodiaptomus hessei* was recorded in Nhlabane estuary (Jerling, 2005) and the Thukela (MacKay *et al*., 2003), and *P. stuhlmanni* in the Mhlathuze Estuary and Richards Bay harbour (Jerling, 2008), Kosi Bay lakes and St Lucia (unpublished data). Very low densities of a third species, *P. nudus*, were intermittently recorded in the Mhlathuze (Jerling, 2008) and St Lucia systems (unpublished data). The latter species is of coastal marine origin and usually only occurs near the estuary mouth. *P. hessei* occurs along the entire coastline of South Africa, while *P. stuhlmanni* is restricted to east coast estuaries (Wooldridge, 1999).The other dominant calanoid genus, *Acartia*, is represented in Zululand estuaries by one estuarine species, *A. natalensis*. This species is also recorded in high numbers in estuaries along the south coast of South Africa, where it coexists with *A. longipatella* and *A. africana* (Wooldridge, 1999).

Mysids were not well represented in the Mfolozi or Msunduzi samples. The only mysid recorded was *Mesopodopsis africana* which was present in both estuaries during March 2008 and at the mouth site during August 2008. It's very low numbers are in contrast to those in many other estuaries, where mysids may contribute significantly to the mesozooplankton biomass (Wooldridge, 1999).

Somewhat surprising are the high densities of freshwater cladocera, which made up 23 % of the total mesozooplankton numbers recorded. No other South African estuary has shown cladoceran densities of this nature. The presence of these cladocerans is directly linked to the freshwater input from the rivers and their elevated densities are probably due to nutrient inputs from sugarcane irrigation runoff.

The only other estuary in Zululand of the river mouth type (Whitfield, 1992) in which the zooplankton community has been investigated is the Thukela (MacKay *et al.*, 2003). The Thukela is a fast-flowing river and the mixing zone of fresh- and seawater often extends beyond the estuary out into the sea. Due to its high flow levels this estuary understandably supports an impoverished zooplankton community, with low densities of the usually dominant estuarine copepods and some marine species entering on the flood tide (MacKay *et al.*, 2003). River flow in the Mfolozi and Msunduzi is in general not as strong as in the Thukela. The present study also occurred during a relatively low flow period for the Mfolozi River. Begg (1978) reported a mean annual flow of 33 $m^3 s^{-1}$ for this river, which is much higher than the mean annual flow of 7 $m^3 s^{-1}$ recorded during 2007 and 2008 at river flow gauging station W2H032 (Department of Water Affairs and Forestry data). Although Whitfield (1992) classified the Mfolozi as a river mouth type of estuary, it functioned more like a temporarily open/closed estuary during the low flow conditions of the present study. This low freshwater flow allowed seawater to penetrate to the upper sampling sites during high tide at times when the mouth was open. A more stable hydrological environment for zooplankton was also created by the lower flow, supporting suggestions that estuarine zooplankton survive and reproduce better under more stable conditions (Grindley, 1977, Grindley & Wooldridge, 1974). Persistence of high zooplankton densities related to stability of the water column was also reported for a seasonally closed temperate estuary in Australia (Gaughan & Potter, 1995).

On average, lower total numbers of zooplankton were recorded in the Mfolozi and Msunduzi when the mouth was open. One exception was the high densities of *Pseudodiaptomus stuhlmanni* and cladocerans at the upper Msunduzi sampling site when the mouth was open during March 2007. Salinities at that site were very low, indicating dominance of freshwater from the river. In contrast, during March 2008 relatively high salinities, indicating influx of seawater at all sampling sites, were likely responsible for the lower mesozooplankton densities at that time. Lower zooplankton densities have also been reported for temporarily open/closed estuaries during periods when the mouth was open (Perissinotto *et al.*, 2000, Froneman, 2004). This may be attributed to the outflow of nutrient-rich estuarine water into the sea and to flooding with relatively nutrient-poor seawater. This flushing of estuaries is, however, only temporary and it is known that periodic flooding and a regular freshwater base flow play an important role in the ecological functioning of these systems (Wooldridge & Callahan, 2000).

Just as long-term freshwater deprivation has a negative influence on the biota of estuaries (e.g. Whitfield & Bruton, 1989; Jerling, 2005), continuous strong flows will also prevent the establishment of a healthy zooplankton community (e.g. MacKay *et al.*, 2003). Secondary production in the water column of estuaries is largely influenced by the abundance of the estuarine copepods (e.g. Jerling & Wooldridge, 1991).

During the present study, rather than having an adverse effect, low flow conditions in the Mfolozi – Msunduzi system supported a relatively healthy estuarine copepod biomass, and therefore also secondary production in the system. This is because the flow was still strong enough to prevent long-term mouth closure, simultaneously maintaining an axial salinity gradient which is known to support higher estuarine copepod biomass (Schlacher & Wooldridge, 1996).

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FISH ASSEMBLAGES IN THE MFOLOZI/MSUNDUZI ESTUARINE SYSTEM WHEN NOT LINKED TO THE ST LUCIA MOUTH

L Vivier*, DP Cyrus, R K Owen & HL Jerling

Affiliation: Coastal Research Unit of Zululand, Department of Zoology, University of Zululand, KwaDlangezwa
**Email: lvivier@pan.uzulu.ac.za*

ABSTRACT

The fish community of the Mfolozi/Msunduzi Estuary was investigated with particular emphasis on its role as a nursery area for marine fish when the adjacent St Lucia mouth is closed. The mouth was open during March 2007 and 2008 with high-turbidity river water flowing into the sea, and was closed during August 2007 and 2008. Fish were sampled biannually during March and August in 2007 and 2008 with seine nets at five sites throughout the system. A total of 5886 fish from 59 species were recorded, with a higher number of species and CPUE in the Mfolozi than in the Msunduzi Estuary. Seine net catches were dominated by *Ambassis gymcocephalus*, *Ambassis natalensis*, *Leiognathus equula* and *Valamugil cunnesius*. Juveniles of marine spawning species were present throughout the study period, even when the mouth was closed. The sampled fish assemblage structure was influenced by significant temporal differences between the four biannual sampling seasons, with relatively small spatial differences between the sampling areas. Temperature, salinity and sediment characteristics were most responsible for the structure of the fish assemblage as sampled by seine nets. The results emphasise the importance of the Mfolozi/Msunduzi Estuary as an alternate nursery area.

INTRODUCTION

The Mfolozi/Msunduzi estuarine system (28°24' S; 32°25' E) is located on South Africa's subtropical, predominantly microtidal east coast, south of Lake St Lucia (Figure 1). As discussed in Vivier & Cyrus (2009), the Mfolozi system, with a catchment area of approximately 11 068 km^2 and a mean annual runoff estimated at 887106 m^3 (Orme, 1974), was historically one of the two primary feeder river systems for Lake St Lucia. Lake St Lucia, the largest estuarine system in African and a World Heritage Site (Begg, 1978; Whitfield *et al*., 2006), comprises a shallow basin with an average depth of 0.9 m and a surface area of approximately 350 km^2. The system is highly susceptible to drought conditions, during which the water level decreases and increased salinity leads to hypersaline conditions.

Historically, St Lucia received about 30% of its input from the adjacent Mfolozi River system (Whitfield *et al.*, 2006.), which drained through the extensive Mfolozi swamps towards the sea. The Mfolozi swamps acted as a sediment filter, allowing only relatively sediment-free water to pass through. Sugar cane farming in the Mfolozi floodplain since the 1930s has resulted in large areas of the floodplain being drained with canals being excavated and levees built along the banks for flood protection.

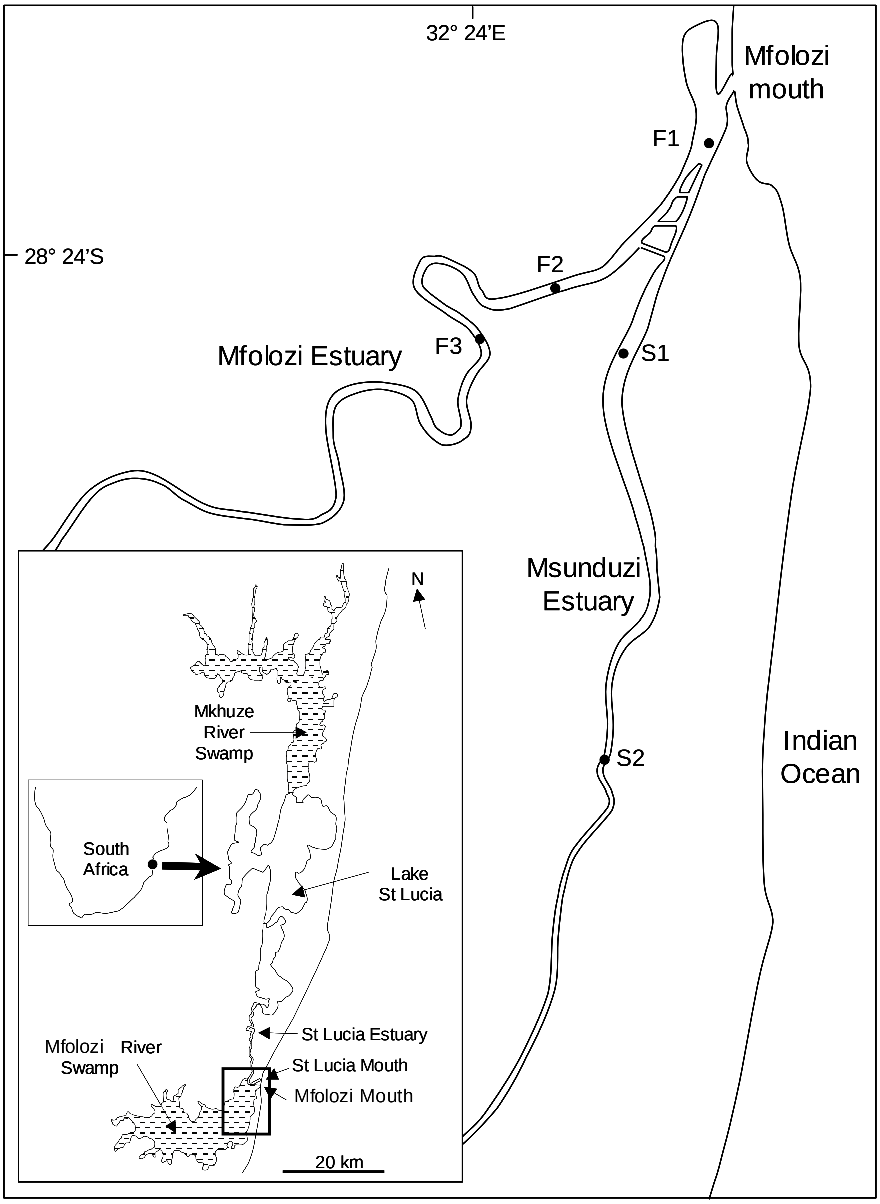

Figure 1. Locality of the Mfolozi/Msunduzi and St Lucia estuarine systems on the KwaZulu-Natal coastline, South Africa, indicating the fish sampling sites in the Mfolozi and Msunduzi estuaries.

Prior to the onset of sugar cane farming, the Mfolozi/Msunduzi and St Lucia estuarine systems had a common mouth, referred to as the St Lucia Bay. At the onset of a drought the joint St Lucia-Mfolozi mouth would close and Mfolozi water would then be diverted naturally into Lake St Lucia, replacing much of the water lost by evaporation from the large surface area of St Lucia and alleviating drought stress in the St Lucia system, including the development of extreme hypersaline conditions. Increased sedimentation of the Mfolozi Estuary due to canalization of the Mfolozi swamps, concurrent with improper catchment management practices, eventually resulted in the combined St Lucia-Mfolozi mouth becoming completely silted up in 1950 (Lindsay *et al*., 1996). To alleviate this problem the two systems were separated in 1958 and a new mouth was created for the Mfolozi Estuary 1.5 km to the south of the St. Lucia mouth.

The Mfolozi Estuary is classified as an open, medium-large subtropical system (Whitfield, 1994) and, together with its tributary the Msunduzi, is the only almost permanently open estuary along a 70km stretch of coastline when the St Lucia Estuary is closed. Regional drought conditions since 2001 resulted in a gradually decreasing water level in Lake St Lucia and in June 2002, the mouth of the St Lucia Estuary closed (Cyrus & Vivier, 2006). The prolonged closure of the St Lucia system since 2002 has led to a large decline in fish, benthos and prawn communities, with deleterious consequences for regional marine populations (Cyrus & Vivier, 2006; Whitfield *et al*., 2006; Mann & Pradervand, 2007).

The current degraded state of the St Lucia system, which comprises 80% of the estuarine area in KwaZulu-Natal, has renewed interest in restoring the St Lucia – Mfolozi link. It has been suggested that the Mfolozi Estuary is a regional refuge and alternative nursery area for fish species that fail to recruit into the closed St Lucia system (Vivier & Cyrus, 2009). However, despite its proximity to the relatively well-studied St Lucia system, there is a paucity of data on the ecological functioning of the Mfolozi/Msunduzi system, and information on its fish community is limited to data from once-off sampling conducted in February 1999 (Harrison *et al*., 2000).

The aim of the present study was to investigate the temporal and spatial changes in seine net catches of fish species in the Mfolozi/Msunduzi Estuary, with particular reference to its function as a nursery for estuary-associated marine fish during closure of the St Lucia mouth.

STUDY AREA

The Mfolozi/Msunduzi Estuary is located in a predominantly summer rainfall region, which is reflected in the seasonal nature of freshwater inputs. Originally, the estuary comprised an extensive wetland system of 19 000 hectares. Agriculture subsequently converted 61% of the system into highly productive sugar cane estates (Orme, 1974). The system is 26km in length and is bounded by low hills to the west and the Indian Ocean to the east. The wetland system consists of two main channels, the Mfolozi and Msunduzi rivers. Upstream of the floodplain, the Mfolozi River follows a meandering course in an incised and confined valley. Upon passing through the western hills, the valley widens considerably from 915 m to over 6 km in just 1.15 km. This rapid change from confinement to a broad floodplain setting results in a reduction in the carrying capacity of the Mfolozi River, creating a node of large-scale deposition at the floodplain head in the form of an alluvial fan (Lindsay *et al*., 1996). The

Mfolozi River forms the floodplain's northern boundary. The smaller Msunduzi River arises in the southwest of the floodplain and flows along its southern end, remaining close to the dune cordon before combining with the Mfolozi River about 0.5 km from the mouth of the system.

MATERIALS AND METHODS

Sampling

The fish of the Mfolozi/Msunduzi Estuary were sampled during March and August 2007 and 2008 at five stations, three in the Mfolozi (F1-F3; Figure 1) and two in the Msunduzi Estuary (S1 and S2; Figure 1). During March 2007 only the Mfolozi Estuary could be sampled, due to an extremely low water level in the Msunduzi Estuary at the time. Fish were sampled using small (10 m x 1.5 m x 6 mm bar mesh) and large seine nets (70 m x 1.5 m x 10 mm bar mesh, with a 6 mm bar mesh bag). All fish collected were identified to species, measured (Standard Length) and returned alive to the system. The Catch per Unit Effort (CPUE) was calculated as the number of individuals caught per metre of net per haul. Water quality parameters (salinity, dissolved oxygen, turbidity and temperature) were measured at each site using a YSI 6920 Sonde (YSI Incorporated).

Statistical analysis

Multivariate data analysis (PRIMER Statistical Package) (Clarke, 1993), incorporating hierarchical and agglomerative community classification methods, was used to analyse for temporal and spatial changes in the fish assemblage. The log (x+1) transformed averaged data were used to produce a Bray Curtis similarity matrix, followed by hierarchical clustering, with group average linking and ordination of data through non-metric multidimensional scaling (nMDS). The ANOSIM procedure was used to test for significant differences in species assemblages between sampling seasons and estuaries, while the SIMPER procedure was used to test for the influence of individual species on the similarity within assemblage groups and the dissimilarity between assemblage groups. Canonical correspondence analysis (CCA), using CANOCO (Ter Braak & Smilauer, 1998) was used to further investigate the relationships between assemblage composition and environmental variables.

Estuarine association

The fish recorded in the Mfolozi and Msunduzi estuaries were classified according to their estuarine dependence, based on a modified version of the system proposed by Whitfield (2005) for sub-Saharan species. All species which breed in the marine environment and which show varying degrees of dependence on estuaries were grouped as marine spawners; species that breed in estuaries were grouped as estuarine spawners; species that occur in estuaries that usually breed in freshwater, were grouped as freshwater spawners.

RESULTS

Estuary mouth and environmental conditions

The salinities recorded during the four biannual sampling seasons in the Mfolozi/Msunduzi Estuary during 2007 and 2008, as well as the mouth conditions during each season, are indicated in Figure 2. The mouth of the Mfolozi/Msunduzi system was open during March 2007 and 2008, and closed during August 2007 and 2008. The system was relatively fresh when closed, with a maximum salinity of 5.5 PSU, indicating a river-flow driven system. In contrast, a typically estuarine salinity gradient was observed when the system was open and tidal, with marine salinity occurring at the mouth, decreasing to 22.7 PSU at Site F3 in the Mfolozi Estuary and to 1 PSU at Site S2 in the Msunduzi Estuary. No salinity measurements were made in the Mfolozi Estuary during August 2008 but, based on the values recorded in the Msunduzi Estuary and the fact that their joint mouth was closed, it is expected that similar salinity conditions would have prevailed in the Mfolozi.

Water temperatures during March (late summer) typically ranged between 25-31ºC, and in August (late winter) between 18-23 ºC. The system remained well oxygenated throughout the study period (6.2-9.9 mg l^{-1}), with slightly higher dissolved oxygen levels recorded during the colder winter periods. Turbidities were higher (9-476 NTU) during the high flow, tidal conditions in March 2007 and 2008, compared to 10-82 NTU under low flow conditions in August. Higher turbidities were recorded in the Msunduzi Estuary than the Mfolozi Estuary both during high flow conditions in March (Msunduzi: 10-476 NTU, Mfolozi: 9-44 NTU) and low flow conditions in August (Msunduzi: 15-82 NTU, Mfolozi: 10-26 NTU).

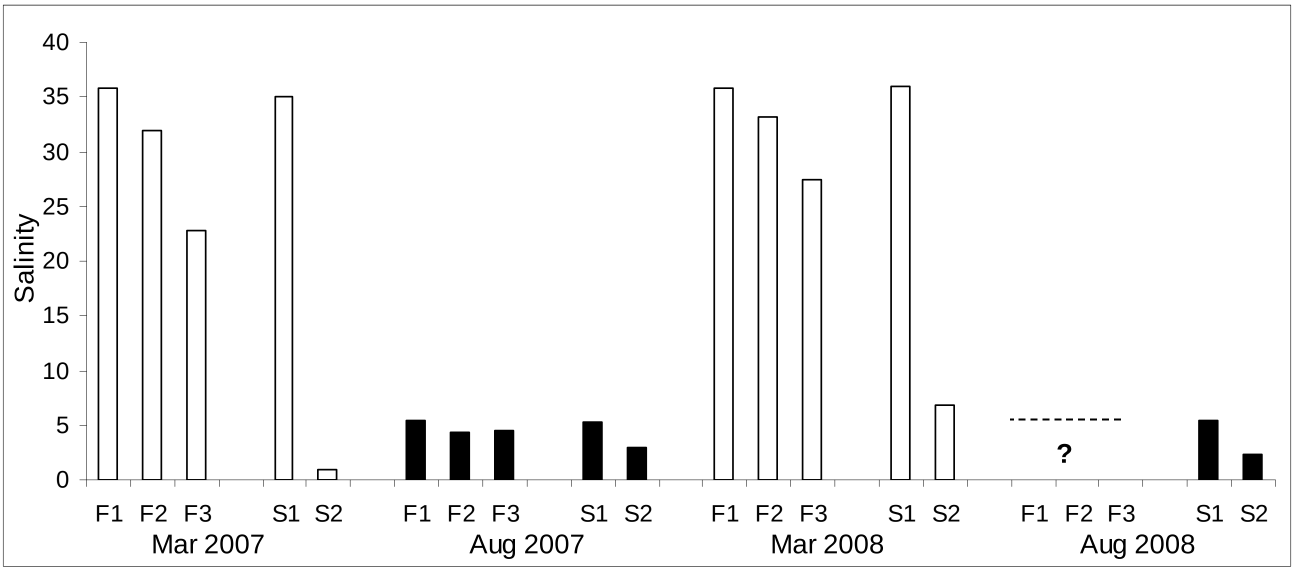

Figure 2. Salinity recorded during four biannual sampling seasons in the Mfolozi (F1, F2 and F3) and Msunduzi (S1 and S2) estuaries during 2007 and 2008. Clear bars indicate open-mouth and tidal conditions, dark bars indicate closed-mouth conditions. Dotted line represents expected salinitiy in the Mfolozi Estuary during August 2008.

Species composition

A total of 5886 fish, representing 59 species, were recorded in the Mfolozi/Msunduzi system using seine netting during 2007 and 2008 (Table 1). Of these, 57 were documented in the Mfolozi Estuary, while only 28 species were recorded in the Msunduzi Estuary. The two species caught in the Msunduzi but not in the Mfolozi Estuary were the estuarine breeders, *Awaous aeneofuscus* and *Periopthalmus africanus,* while a total of 31 species were caught in Mfolozi but not in the Msunduzi Estuary. The total number of species recorded in the Mfolozi/Msunduzi system during each sampling period ranged from 27 in August 2007 to 38 in August 2008, suggesting that species composition varied considerably between the four sampling periods, given that a total of 59 species were recorded. The total number of species recorded under open mouth conditions during the March sampling periods was, however, very similar to that recorded during closed mouth conditions in August, being 47 and 46 species, respectively (Table 1).

The number of species recorded per sampling period in the Mfolozi Estuary was consistently higher when compared to the Msunduzi Estuary (Table 1). The Mfolozi Estuary was, however, sampled on four occasions, while the Msunduzi Estuary was only sampled three times. The mean number of fish species per site in the Mfolozi Estuary during sampling periods when both estuaries were sampled (August 2007, March 2008 and August 2008), was more than double that found in the Msunduzi Estuary, being 18.3 and 7.8, respectively.

The highest number of species was recorded in the lower reaches of the Mfolozi Estuary (F1), with a mean of 24 species per sampling period, compared to a mean of 16 species per sampling period in the upper reaches (F3) of the estuary. In the Msunduzi Estuary the highest number of species was recorded at Site S2, with a mean of 12 per sampling period.

The higher number of species recorded in the Mfolozi Estuary was also reflected in the higher catch and CPUE recorded in this part of the system. During the three sampling periods when both estuaries were sampled (August 2007, March 2008 and August 2008), a total of 4598 fish were recorded, of which 89% were caught in the Mfolozi Estuary. Similarly, in terms of CPUE, 83.9% of the fish were caught in the Mfolozi Estuary. The mean CPUE per site in the Mfolozi Estuary over this period was more than three times that recorded in the Msunduzi Estuary, being 9.6 and 2.8, respectively. The highest CPUE was recorded in the Mfolozi Estuary at Site F1, with a mean CPUE of 15.9 per sampling period, compared to a mean CPUE of 8.2 and 3.9 per sampling period at Site F3 in the Mfolozi Estuary and at Site S2 in the Msunduzi Estuary, respectively.

The fish assemblage of the Mfolozi/Msunduzi system was dominated by two ambassid species, *Ambassis gymnocephalus* and *A. natalensis*, the slimy *Leiognathus equula* and the mullet *Valamugil cunnesius*. These four species together accounted for 65% of the fish recorded in the seine net catches (Figure 3). *Leiognathus equula* was the most abundant species recorded during March 2007 and August 2008, and was 2nd and 4th most abundant during August 2007 and March 2008, respectively. *Valamugil cunnesius* was also consistently abundant during the four sampling seasons, although it was 4th most abundant during March 2007. Although *A. gymnocephalus* was overall the most abundant species, this was mainly due to one very large catch of it (n=623) at Site F1 during March 2008.

Table 1. Numerical CPUE of fish species recorded at various sites in the Mfolozi and Msunduzi estuaries during four sampling periods in 2007-2008. F = Mfolozi sites, S = Msunduzi sites

	Mar-07			Aug 2007					Mar 2008					Aug 2008						
	Mfolozi			Mfolozi			Msunduzi		Mfolozi			Msunduzi		Mfolozi			Msunduzi			%
	F1	F2	F3	F1	F2	F3	S1	S2	F1	F2	F3	S1	S2	F1	F2	F3	S1	S3	Total	Cont.
Acanthopagrus berda	0.01	0.05		0.10	0.07		0.10	0.10	0.06				0.06	0.13	0.13	0.33		0.03	1.17	0.9
Ambassis ambassis		0.07		0.15	0.03	0.27	0.10	0.46						0.20					1.27	1.0
Ambassis gymnocephalus	5.07	0.03							23.85		0.08	1.10	3.64	0.38	0.70				34.85	26.8
Ambassis natalensis	2.44	1.67		0.13					9.75		0.07	0.60	1.50	0.22	0.25	1.30		0.29	18.20	14.0
Argyrosomus japonicus			0.14	0.01	0.03								0.01	0.00		0.01		0.01	0.21	0.2
Atherinomorus sp.	0.47																		0.47	0.4
Awaous aeneofuscus													0.10						0.10	0.1
Caranx ignobilis		0.01	0.01						0.55	0.90	0.09		0.37	0.01					1.96	0.1
Caranx sem			0.04								0.01								0.06	0.1
Caranx sexfaciatus	0.24	0.16	0.11	0.01	0.03				0.27		0.08								0.90	0.1
Carcharhinus leucas									0.01										0.01	0.0
Congridae sp.									0.05										0.05	0.0
Drepane longimana	0.01																	0.01	0.03	0.0
Elops machnata	0.01							0.01											0.03	0.0
Gerres acinaces			0.07						2.46	0.07	0.67				0.03				3.30	2.5
Gerres filamentosus									0.30					0.20		0.01			0.51	0.4
Gerres methueni				0.03	0.40	0.05												0.11	0.60	0.5
Gilchristella aestuaria		0.10	0.20							0.17					0.03				0.50	0.4
Glossogobius callidus									0.07			0.50				0.01			0.58	0.4
Glossogobius giurus					0.01					0.03	0.03			0.02	0.05	0.18			0.32	0.2
Glossogobius tenuiformis				0.40	0.25	0.17		0.11	0.38	0.23	0.03		1.00	0.16	0.30	1.27			4.31	3.3
Goby sp.				0.10	0.04													0.15	0.29	0.2
Herklotsichthys quadrimaculatus									0.03										0.03	0.0
Hilsa kelee	0.25	0.03	0.64		0.01	0.01			0.01					0.01					0.98	0.8
Himantura uarnak	0.01												0.01						0.02	0.1
Johnius dussumieri					0.03														0.03	0.1
Leiognathus equula	0.07	0.49	6.62	0.18	1.03	1.22		0.03	2.11	0.09	2.56		0.07	0.77	1.30	1.54			18.06	0.1
Liza dumerilii	0.19	0.38	0.05	0.28		0.06		0.01	0.93			0.10		0.37	0.01	0.19			2.57	0.1
Liza luciae	0.03																	0.61	0.64	0.5
Liza macrolepis	0.06	0.72	0.31	0.30		0.04			1.16	0.01				0.47	0.17	0.84			4.08	0.1
Lutjanus argentimaculatus	0.03																		0.03	0.1
Lutjanus fulviflamma				0.01														0.10	0.11	0.1
Megalops cyprinoides														0.01					0.01	0.1
Monodactylus argenteus						0.02													0.02	0.0
Mugil cephalus	0.03	0.06							0.01		0.01			0.01					0.13	0.1
Oligolepis acutipennis		0.07							0.07	0.27			0.10	0.13	0.27	0.13		0.03	1.06	0.8
Oligolepis keiensis												0.20				0.03			0.23	0.1
Oreochromis mossambicus	0.07	0.03	0.03		0.03	0.01		0.16								0.01		0.30	0.63	0.5
Periopthalmus africanus								0.02											0.02	0.1
Platycephalus indicus				0.03										0.01					0.04	0.0
Pomadasys commersonnii	0.00								0.05					0.04					0.09	0.1
Pomadasys kaakan									0.20					0.01					0.21	0.1
Pomadasys olivaceum									0.10										0.10	0.1
Pomatomus saltatrix			0.01						0.01										0.03	0.0
Pseudorhombius arsius		0.03												0.03					0.07	0.1
Rhabdosargus holubi														0.02					0.02	0.0
Rhabdosargus sarba				0.30	0.03		0.10	0.02							0.13	0.03			0.61	0.1
Scomberoides lysan	0.01	0.01								0.03									0.06	0.0
Sillago sihama			0.03		0.05				1.01	0.07	0.05	0.60	0.15	0.05		0.04			2.06	1.6
Solea bleekeri							0.10	0.08						0.04	0.05				0.27	0.2
Sphyraena barracuda									0.13							0.01			0.14	0.1
Stolephorus indicus									0.13	0.17	0.10		0.01						0.41	0.3
Syngnathus asus			0.01	0.03															0.05	0.1
Terapon jarbua	0.27	0.79	0.65	0.03	0.25	0.10	0.10		0.45	0.41	0.65	0.40	0.90	0.03	0.17	0.11			5.32	0.1
Thryssa vitrirostris														0.03					0.03	0.0
Upeneus vittatus	0.00								0.15										0.15	0.1
Valamugil buchanani	0.01								0.04	0.20	0.01			0.03					0.29	0.2
Valamugil cunnesius	0.96	1.76	0.25	0.96	0.06	0.06		0.01	0.88	0.15	5.08		1.13	0.86	0.75	0.31			13.22	10.2
Valamugil seheli	0.20	0.87	0.48	0.11	0.17	0.01													1.84	1.4
Mullet fry		0.40		0.40	0.38	5.38		0.04											6.60	0.1
Total	10.4	7.7	9.7	3.6	2.9	7.4	0.5	1.1	45.2	2.8	9.5	3.5	9.0	4.3	4.3	6.3	0.0	1.7	129.9	
No of species	23	19	17	18	17	12	5	11	29	14	15	7	14	27	15	18	0	10	59	

Other numerically important species included *Terapon jarbua*, *Liza macrolepis* and the goby *Glossogobius tenuiformis*. Of the most abundant species in the system, *L. equula* (99%) and *V. cunnesius* (91%) were almost exclusively caught in the Mfolozi Estuary. Similarly, 86-87% of *A. gymnocephalus and A. natalensis* were recorded in this part of the system. During August 2007, the fish assemblage was characterized by a large catch (n=360) of early juvenile mullet ranging in length between 10 and 30 mm, indicating the extent of recruitment of this group into the Mfolozi/Msunduzi system prior to this sampling period. During 2008, however, no post-larval mullet were recorded in the system. Of the seven mullet species recorded in the system, *V. cunnesius* was by far the most abundant, accounting for 58% of the mullet caught, followed by *L. macrolepis* (18%) and *L. dumerilii* (11%).

Estuarine association

The fish assemblage of the Mfolozi/Msunduzi system during 2007 and 2008 was dominated by marine spawning species, with 42 of the 59 species recorded belonging to this category (Table 2, Figure 4). Of the remainder, 15 were estuarine resident species, while only two freshwater species were recorded. Marine spawning species consistently dominated the fish assemblage in terms of species numbers during all four sampling periods, with estuarine resident species only comprising between 21% and 31% of the species recorded (Figure 4). In contrast, the CPUE of estuarine species almost equaled that of marine spawning species, contributing 46% of the fish caught in the system. This suggests that, although fewer estuarine species were found in the system, they occurred in relatively high numbers. Marine spawning fish dominated the fish assemblage during three of the four sampling periods, comprising 61-83% of the fish caught, whereas, during March 2008, estuarine resident species contributed 62% of the catch. This was mainly due to very large catches of *A. gymnocephalus* and *A. natalensis* during this sampling period.

The importance of the Mfolozi/Msunduzi estuary as nursery habitat for marine spawning species is illustrated by the predominance of recently recruited juveniles in the system (Figure 5 and Figure 6). Most species showed a unimodal length frequency distribution, with most specimens in the 30-50 mm SL size classes. Juveniles of *L. equula* and *V. cunnesius* were particularly abundant in the system, being almost an order of magnitude more abundant than those of the other marine spawning species. Very few *L. equula* larger than 70 mm were recorded in the system, with 75% of all specimens in the size class 40-60 mm SL; while 16% were smaller than 40 mm SL. Similarly, 28% of the *V. cunnesius* specimens were in the 30-40 mm SL size class.

It is noteworthy that some species, such as *Rhabdosargus sarba*, *Gerres acinaces*, *G. methueni*, *G. filamentosus* and *L. equula,* comprised mainly early juveniles, with very few larger juveniles being recorded. In contrast, species such as *T. jarbua*, *V. cunnesius*, *L macrolepis* and *Liza dumerilii* comprised both newly-recruited and larger individuals. The mullet *L. macrolepis* comprised mainly larger individuals, the majority being in the 140-150 mm size class.

Table 2. Species, estuarine dependence (EDC), numerical CPUE per season and minimum and maximum body size (mm, SL) of fish recorded in the Mfolozi/Msunduzi system in 2007-2008. M = Marine spawning, E = Estuarine resident, F = Freshwater

	EDC	March 2007			August 2007			March 2008			August 2007		
		CPUE	Min	Max	**CPUE**	Min	Max	**CPUE**	Min	Max	**CPUE**	Min	Max
Acanthopagrus berda	M	**0.06**	60	240	**0.37**	10	350	**0.11**	20	160	**0.62**	20	200
Ambassis ambassis	E	**0.07**	40	60	**1.01**	30	100				**0.20**	30	60
Ambassis gymnocephalus	E	**5.10**	30	60				**28.67**	10	90	**1.08**	20	60
Ambassis natalensis	E	**4.10**	20	60	**0.13**	40	50	**11.91**	10	60	**2.05**	20	90
Argyrosomus japonicus	M	**0.14**	130	400	**0.04**	180	290	**0.01**	150	360	**0.03**	170	520
Atherinomorus sp.	M	**0.47**	30	40									
Awaous aeneofuscus	E							**0.10**	40	70			
Caranx ignobilis	M	**0.03**	40	170				**1.91**	30	200	**0.01**	140	140
Caranx sem	M	**0.04**	70	70				**0.01**	250	250			
Caranx sexfaciatus	M	**0.51**	40	140	**0.04**	90	140	**0.35**	40	100			
Carcharhinus leucas	M							**0.01**	740	850			
Congridae sp.	F							**0.05**	90	90			
Drepane longimana	M	**0.01**	70	70							**0.01**	70	80
Elops machnata	M	**0.01**	300	420	**0.01**	130	130						
Gerres acinaces	M	**0.07**	20	30				**3.20**	30	140	**0.03**	70	70
Gerres filamentosus	M							**0.30**	40	50	**0.21**	40	60
Gerres methueni	M				**0.48**	10	30				**0.11**	10	50
Gilchristella aestuaria	E	**0.30**	30	50				**0.17**	30	40	**0.03**	30	30
Glossogobius callidus	E							**0.57**	30	60	**0.01**	40	50
Glossogobius giurus	E				**0.01**	220	220	**0.07**	40	80	**0.24**	60	250
Glossogobius tenuiformis	E				**0.93**	10	50	**1.65**	10	50	**1.73**	10	60
Goby sp.	E				**0.14**	20	20				**0.15**	20	20
Herklotsichthys quadrimaculatus	M							**0.03**	50	50			
Hilsa kelee	M	**0.92**	50	220	**0.03**	100	140	**0.01**	170	170	**0.01**	60	80
Himantura uarnak	E	**0.01**	260	330				**0.01**	250	250			
Johnius dussumieri	M				**0.03**	30	30						
Leiognathus equula	M	**7.18**	20	110	**2.45**	30	100	**4.82**	20	80	**3.60**	30	130
Liza dumerilii	M	**0.61**	0	100	**0.35**	80	180	**1.03**	50	90	**0.58**	50	210
Liza luciae	M	**0.03**	120	320							**0.61**	120	120
Liza macrolepis	M	**1.09**	30	250	**0.33**	80	250	**1.18**	60	250	**1.48**	20	260
Lutjanus argentimaculatus	M	**0.03**	60	60									
Lutjanus fulviflamma	M				**0.01**	50	50				**0.10**	50	70
Megalops cyprinoides	M										**0.01**	100	100
Monodactylus argenteus	M				**0.02**	20	20						
Mugil cephalus	M	**0.09**	90	450				**0.03**	210	210	**0.01**	180	310
Mullet fry	M	**0.40**	30	70	**6.20**	20	40						
Oligolepis acutipennis	E	**0.07**	20	50				**0.43**	30	60	**0.56**	20	50
Oligolepis keiensis	E							**0.20**	30	40	**0.03**	40	40
Oreochromis mossambicus	F	**0.13**	60	120	**0.19**	60	150				**0.31**	50	200
Periopthalmus africanus	E				**0.02**	30	30						
Platycephalus indicus	M				**0.03**	90	90				**0.01**	110	180
Pomadasys commersonnii	M	**0.00**	150	150				**0.05**	60	220	**0.04**	120	450
Pomadasys kaakan	M							**0.20**	40	150	**0.01**	60	90
Pomadasys olivaceum	M							**0.10**	60	70			
Pomatomus saltatrix	M	**0.01**	110	280				**0.01**	180	180			
Pseudorhombius arsius	E	**0.03**	30	30							**0.03**	40	40
Rhabdosargus holubi	M										**0.02**	60	60
Rhabdosargus sarba	M				**0.45**	10	20				**0.17**	20	30
Scomberoides lysan	M	**0.02**	80	100				**0.03**	20	20			
Sillago sihama	M	**0.03**	40	40	**0.05**	100	130	**1.88**	30	130	**0.09**	70	100
Solea bleekeri	E				**0.18**	20	50				**0.09**	20	70
Sphyraena barracuda	M							**0.13**	110	180	**0.01**	250	250
Stolephorus indicus	M							**0.41**	30	40			
Syngnathus asus	M	**0.01**	100	100	**0.03**	100	100						
Terapon jarbua	M	**1.71**	20	130	**0.48**	10	90	**2.81**	10	90	**0.32**	30	120
Thryssa vitrirostris	M										**0.03**	90	140
Upeneus vittatus	M	**0.00**	120	120				**0.15**	70	80			
Valamugil buchanani	M	**0.01**	110	350				**0.25**	50	430	**0.03**	120	170
Valamugil cunnesius	M	**2.97**	30	190	**1.09**	80	180	**7.24**	30	180	**1.92**	20	190
Valamugil seheli	M	**1.55**	30	250	**0.29**	70	110						
Total CPUE		**27.9**			**15.4**			**70.1**			**16.6**		
Species count		**34**			**27**			**36**			**38**		

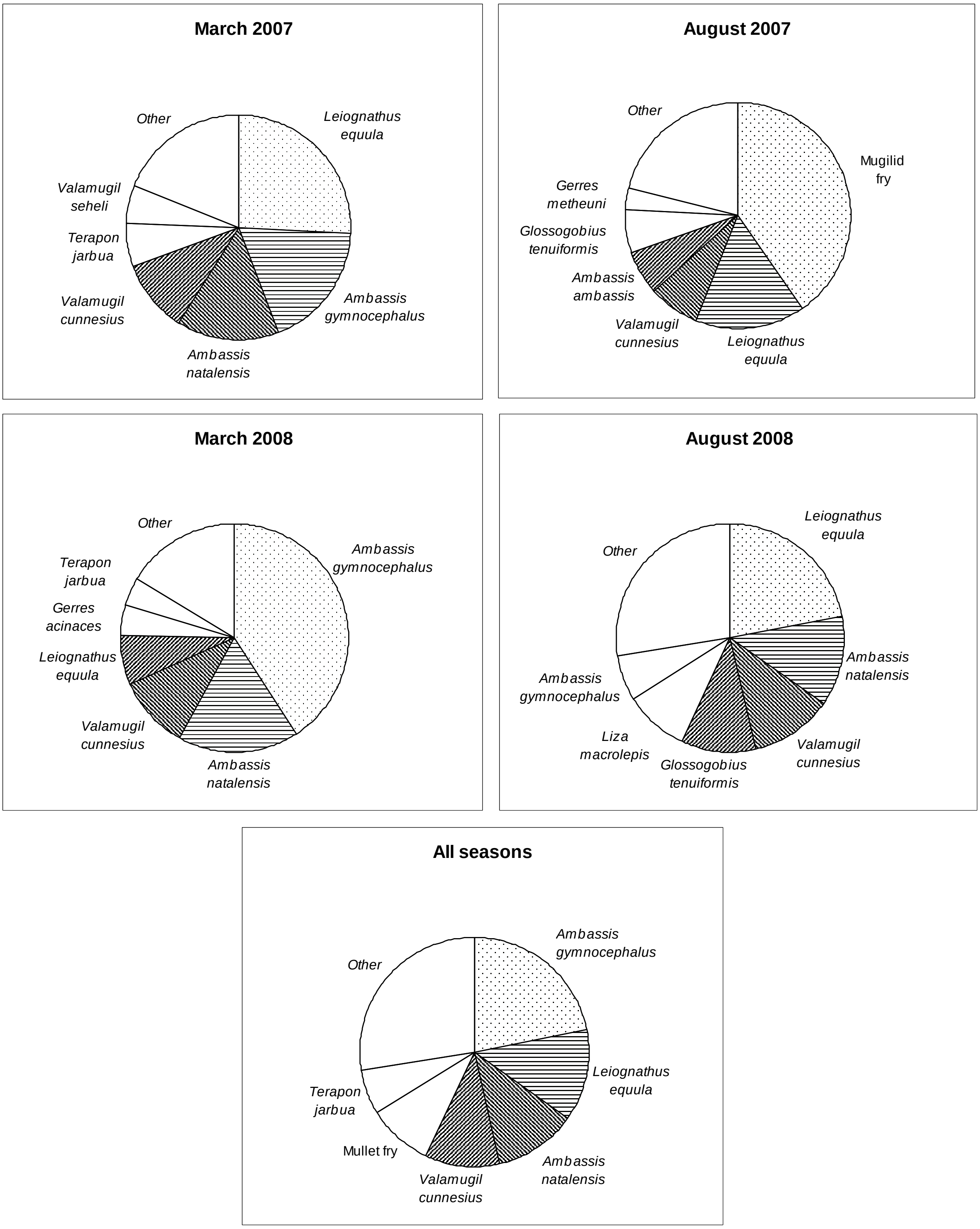

Figure 3. Fish species dominances recorded per sampling period and for all sampling periods combined in the Mfolozi/Msunduzi estuarine system in 2007 and 2008.

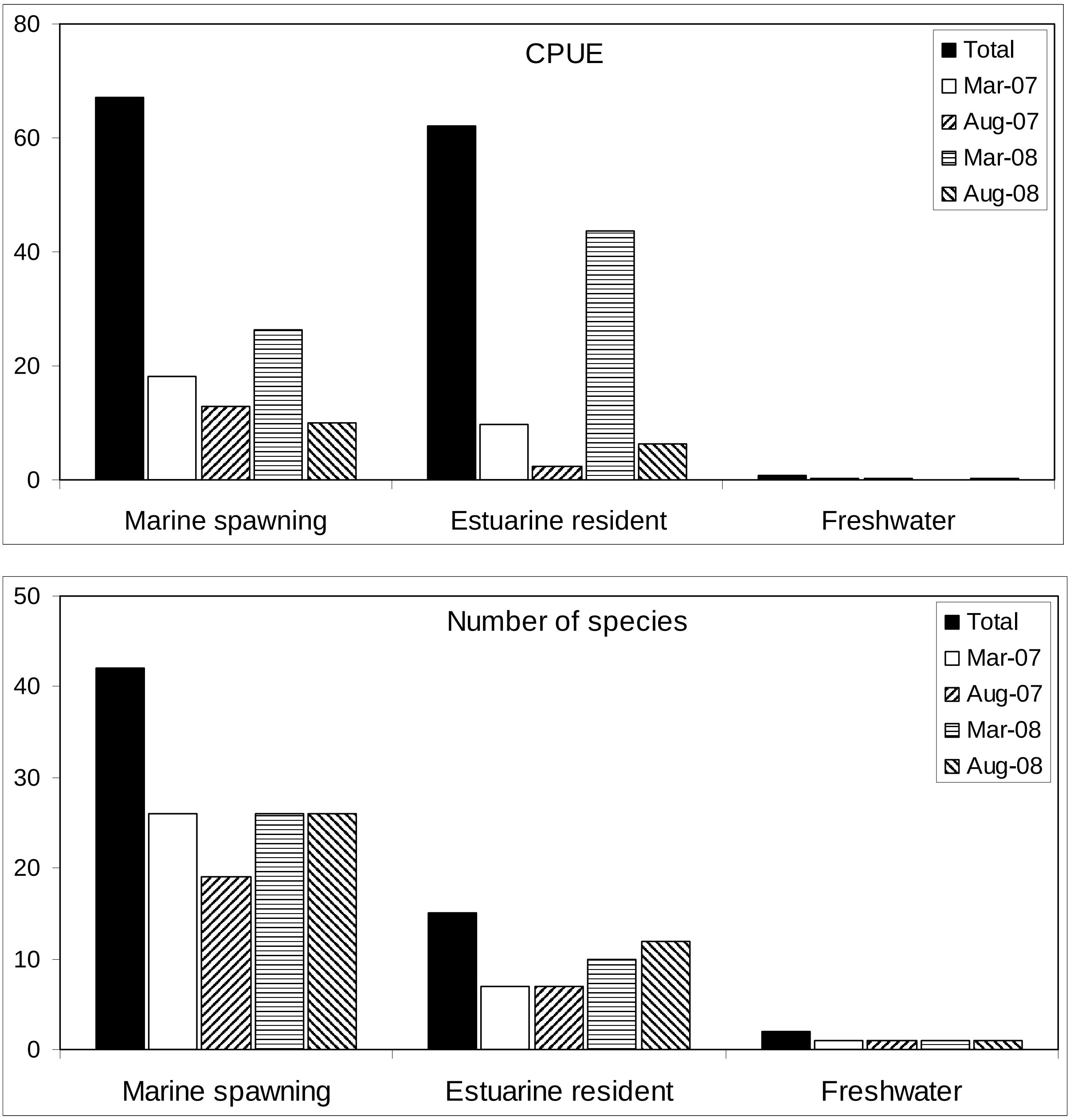

Figure 4. The CPUE and number of species of marine spawning, estuarine resident and freshwater fish species recorded during each sampling period, as well as the total CPUE and number of species, in the Mfolozi/Msunduzi estuarine system in 2007 and 2008.

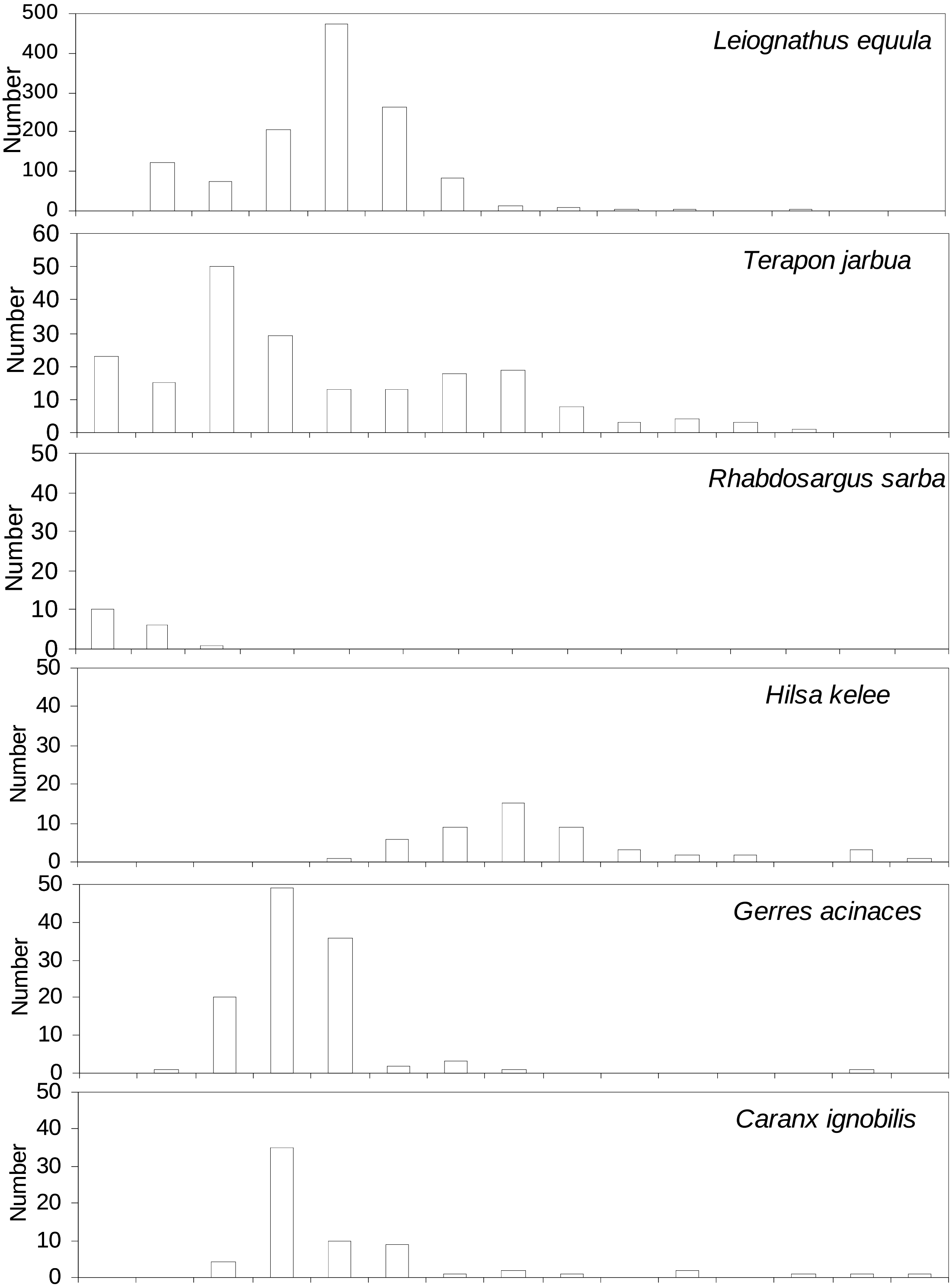

Figure 5. Length-frequency distribution of six marine spawning fish species in the Mfolozi/Msunduzi estuarine system in 2007 and 2008.

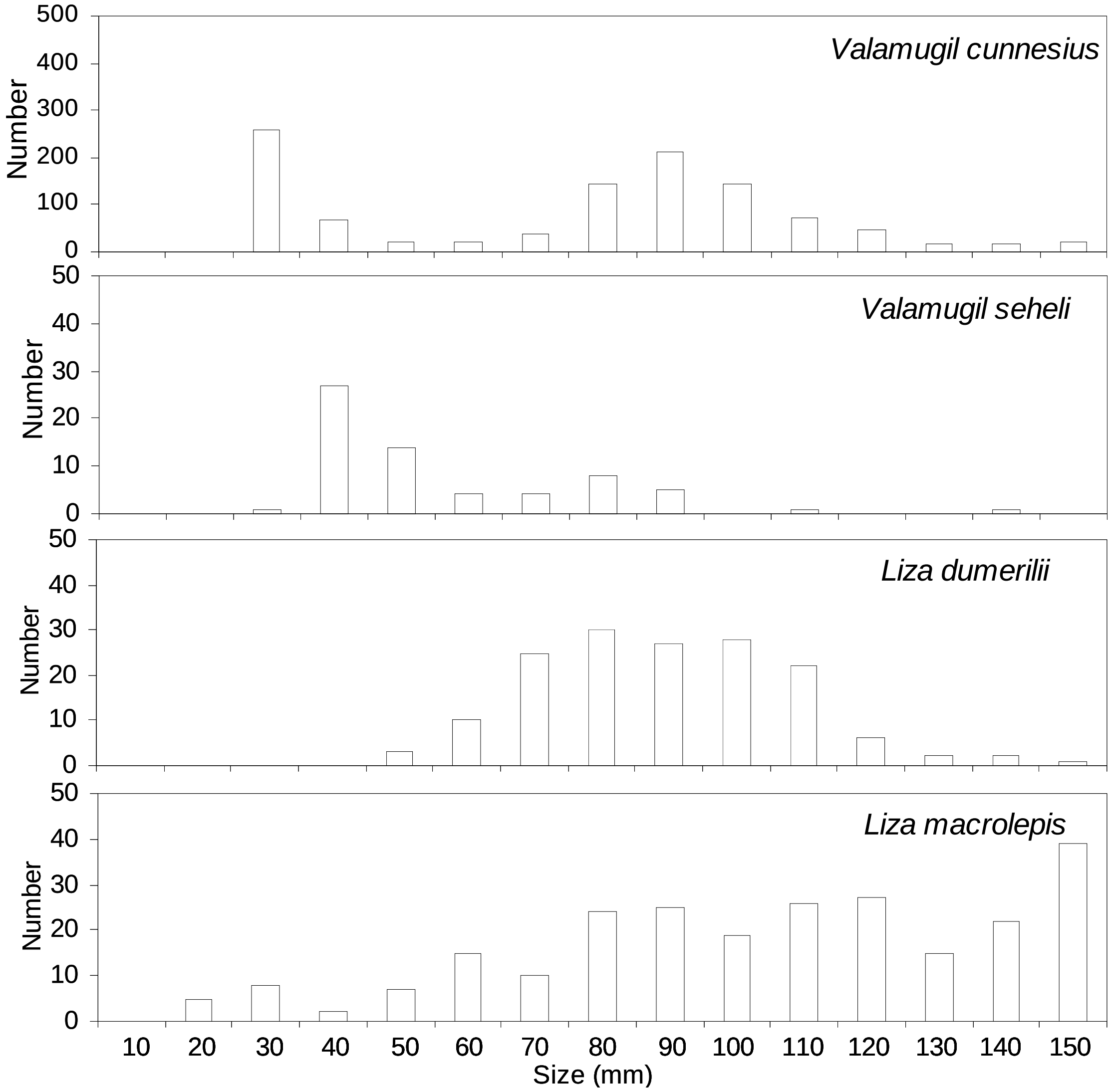

Figure 6. Length-frequency distributions of four mullet species in the Mfolozi/Msunduzi estuarine system in 2007 and 2008.

Temporal and spatial changes in the fish assemblage

Multivariate analysis revealed differences between the fish assemblages of the Mfolozi and Msunduzi estuaries as well as temporal shifts in the fish assemblage of the Mfolozi Estuary during the study period (Figure 7). With the exception of the Site S2 sample from March 2008, which was grouped with the Mfolozi samples, the Msunduzi fish assemblage was separated from that of the Mfolozi Estuary at a similarity of less than 30%, which is indicative of the extent to which the Msunduzi fish assemblage differed from that of the Mfolozi Estuary. This is due to the low number of species and CPUE recorded throughout the Msunduzi Estuary during August 2007 and 2008 and at Site S1 in March 2008. Analysis of similarity (ANOSIM) showed that the fish assemblage of the Mfolozi and Msundusi estuaries differed significantly (R = 0.49, p = 0.005) during the three sampling periods when both estuaries were sampled (August 2007, March 2008 and August 2008).

Within the Mfolozi Estuary the fish assemblage was predominantly structured by temporal changes, as the assemblage recorded during each of the two sampling years was distinctly grouped at a similarity of 42% (Figure 7). Within each sampling year, the assemblage was further grouped by sampling period, which suggested that temporal changes in the fish assemblage were more important in structuring the assemblage than were spatial differences along the length of the system. Using ANOSIM, it was shown that in the Mfolozi Estuary there were significant differences between the 2007 and 2008 fish assemblages (R = 0.52, p = 0.002) as well as between those of the four sampling periods (R = 0.79, p = 0.001). In contrast, there were no significant differences between sites across year groups or between sites across estuary groups.

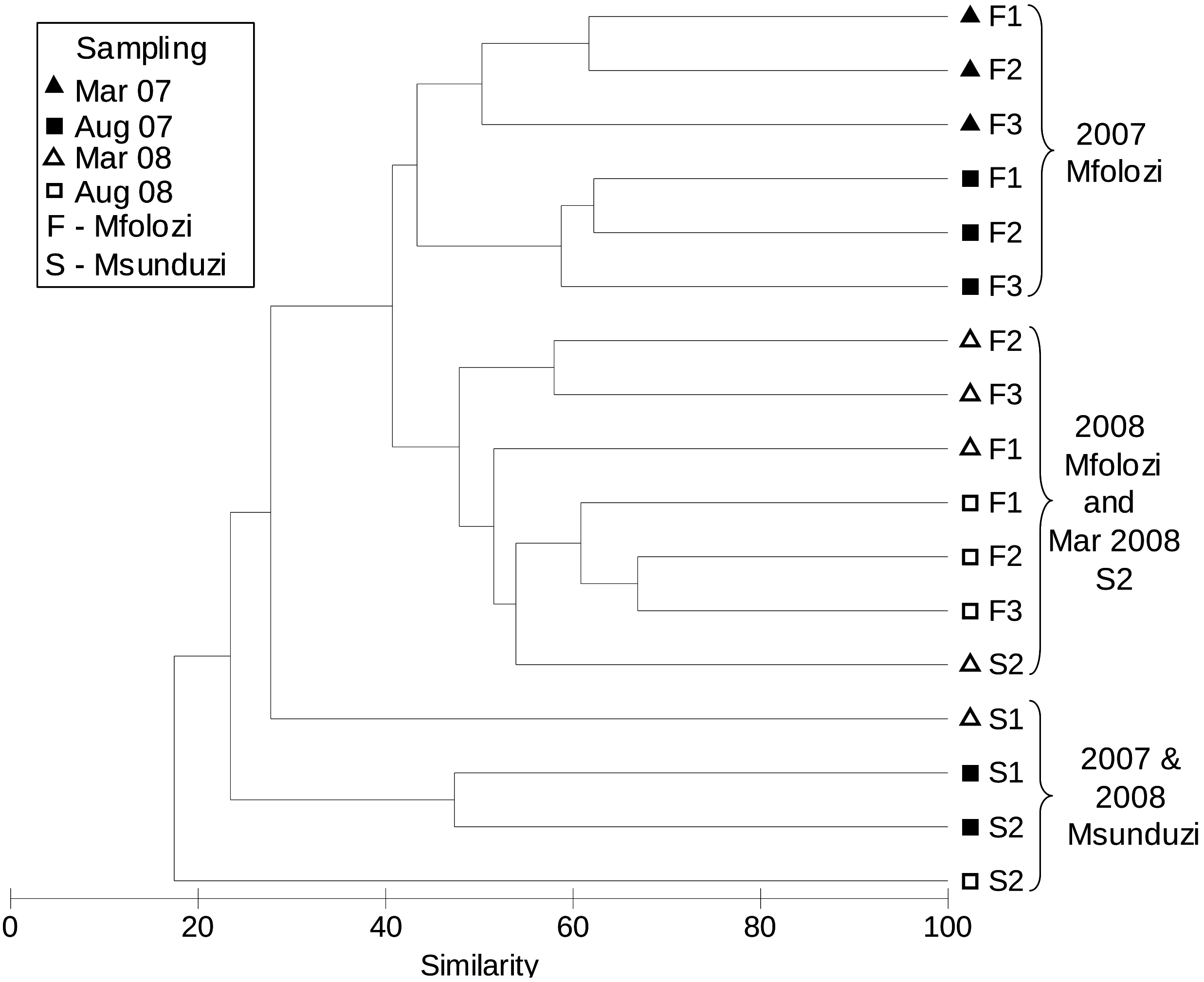

Figure 7. Cluster dendrogram of the fish assemblage recorded in the Mfolozi/Msunduzi estuarine system in 2007 and 2008.

The fish species most responsible for variation in species composition between estuaries, and between open (March) and closed (August) mouth conditions, were analysed using the SIMPER procedure, which determines the contribution of each species to the average Bray-Curtis similarity within a group (Table 3). The mean similarity within the Mfolozi and Msunduzi Estuary assemblages was 46% and 21%, respectively, indicating a much higher degree of similarity within the Mfolozi assemblage. There were distinct differences in the fish species characteristic of each estuary (Table 3). Of the eight species showing the highest degree of similarity within the Mfolozi Estuary fish assemblage, only three, *Terapon jarbua, Acanthopagrus berda* and *A. natalensis,* were also important in structuring the Msunduzi Estuary assemblage. *Leiognathus equula, V. cunnesius* and *G. tenuiformis* were most responsible for structuring the Mfolozi Estuary fish assemblage, accounting for 42% of the similarity within the estuary, but they were relatively unimportant in the Msunduzi Estuary.

A comparison between the open and closed mouth assemblages in the Mfolozi Estuary also showed that there were differences in the fish assemblage characteristic of each phase. *Caranx sexfaciatus, C. ignobilis* and *Gerres acinaces* were important in structuring the fish assemblage when the mouth was open, but not when the mouth was closed. Similarly, *G. tenuiformis, A. berda* and *Liza dumerilii* were important species in the fish assemblage under the closed mouth condition, but not when the mouth was open. In contrast, *L. equula, T. jarbua* and *V. cunnesius* were consistently among the four most important species under open and closed mouth conditions.

Correlation between species assemblage and water quality variables

Canonical Correspondence Analysis (CCA) provided insight into the relationship between the fish assemblage, water quality and sediment characteristics of the Mfolozi/Msunduzi system (Figure 8). Salinity, temperature, sediment grain size and organic content were the variables most responsible for structuring the fish assemblage, while sediment sorting coefficient, pH, turbidity, water depth and dissolved oxygen levels were of lesser importance. There was a strong correlation between temperature and salinity, which is understandable given that the estuary mouth was open during late summer and closed during late winter. There was a negative correlation between salinity and dissolved oxygen, with higher oxygen levels being recorded during the colder winter sampling period. The influence of salinity on the Mfolozi/Msunduzi fish assemblage can be seen in the separation between the March (open mouth) and August (closed mouth) samples, with the majority of samples collected during closed mouth conditions grouped towards the right of the ordination (Figure 8). The influence of sediment particle size and organic content on variation in the fish assemblage is not clear, since the entire system was very muddy, although higher turbidities were generally recorded during high flow conditions during March sampling when the mouth was open.

DISCUSSION

Despite its historical link with and close proximity to the well-researched St Lucia estuarine system, there is little information on the fish ecology of the Mfolozi/Msunduzi estuarine system (Whitfield *et al*., 2006). The recent regional drought conditions, which caused the mouth of the St Lucia system to remain closed for more than five years since 2002, have led to renewed interest in the importance of the much smaller Mfolozi/Msunduzi system as an alternate nursery area for post-larvae of marine spawning species when the St Lucia mouth is closed (Cyrus & Vivier, 2006; Vivier & Cyrus, 2009).

Table 3. Mean similarity, % contribution and cumulative contribution of the fish species making the highest contribution to the mean similarity in the fish assemblages and to those recorded under open and closed mouth conditions in the Mfolozi/Msunduzi estuarine system in 2007 and 2008.

Species	Mean Similarity	Contribution %	Cumumulative %
Between estuaries			
Mfolozi Estuary: Mean similarity within group: 45.9%			
Leiognathus equula	7.6	16.6	16.6
Valamugil cunnesius	6.0	13.1	29.6
Glossogobius tenuiformis	5.7	12.4	42.0
Terapon jarbua	5.0	11.0	52.9
Liza macrolepis	2.7	5.9	58.8
Ambassis natalensis	2.1	4.5	63.4
Acanthopagrus berda	1.8	3.9	67.3
Liza dumerilii	1.8	3.9	71.2
Msunduzi Estuary: Mean similarity within group: 21.4%			
Acanthopagrus berda	4.9	23.0	23.0
Ambassis natalensis	3.4	15.7	38.8
Terapon jarbua	3.2	15.1	53.9
Ambassis gymnocephalus	1.3	6.2	60.0
Ambassis ambassis	1.3	6.1	66.2
Solea bleekeri	1.2	5.8	71.9
Oreochromis mossambicus	1.1	5.2	77.1
Rhabdosargus sarba	0.9	4.1	81.2
Mean dissimilarity between groups= 71.3%			
Open and closed mouth conditions (Mfolozi estuary)			
Open mouth: Mean similarity within group: 46.0%			
Terapon jarbua	6.5	14.1	14.1
Valamugil cunnesius	6.3	13.8	27.8
Leiognathus equula	5.8	12.5	40.4
Caranx sexfaciatus	2.9	6.3	46.6
Liza macrolepis	2.6	5.6	52.2
Caranx ignobilis	2.4	5.1	57.3
Ambassis natalensis	2.3	5.0	62.3
Gerres acinaces	1.9	4.1	66.4
Closed Mouth: Mean similarity within group: 52.2%			
Leiognathus equula	8.5	16.3	16.3
Glossogobius tenuiformis	6.5	12.5	28.8
Valamugil cunnesius	6.0	11.4	40.2
Terapon jarbua	4.8	9.1	49.4
Liza macrolepis	3.7	7.1	56.4
Acanthopagrus berda	3.3	6.4	62.8
Liza dumerilii	3.0	5.8	68.7
Ambassis natalensis	2.3	4.4	73.0
Mean dissimilarity between groups= 57.9%			

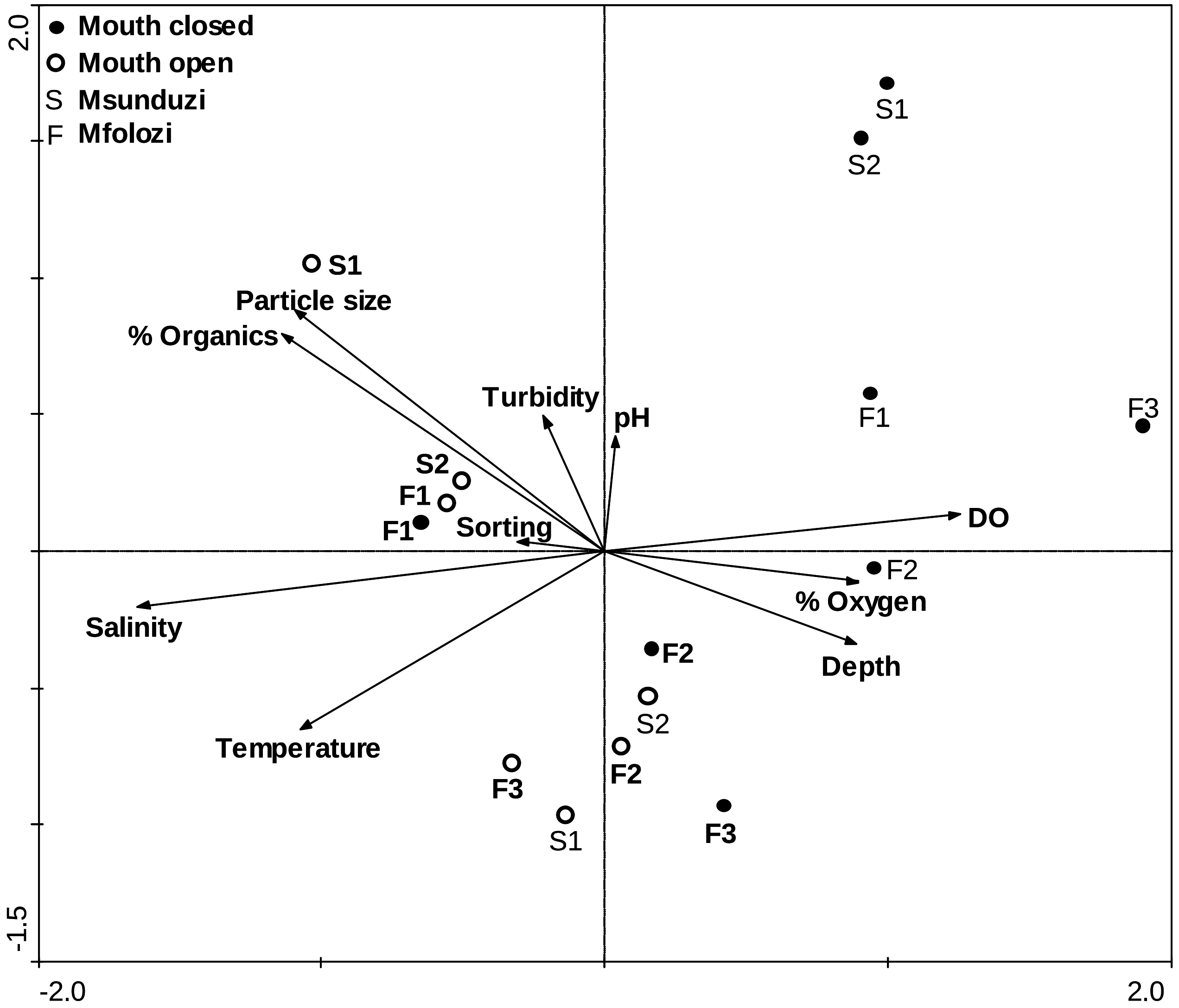

Figure 8. Canonical Correspondence Analysis (CCA) showing the relation between physical parameters and the fish assemblages recorded at the five sampling sites in the Mfolozi/Msunduzi system in 2007 and 2008.

In a once-off survey, Harrison *et al.* (2000) recorded only 31 fish species in the Mfolozi/Msunduzi system. A total of 59 species were recorded here during the present survey, this also being much higher than the 38 species recorded in the larger St Lucia system during 2004-2006, when the mouth of that system was closed (Cyrus & Vivier, 2006). Whitfield (1980) synthesised information from a number of studies and documented a total of 108 species from St Lucia, mainly under open mouth conditions. The Mfolozi/Msunduzi estuarine system is classified as a river mouth with a permanently open mouth, even though it was closed during sampling in August 2007 and 2008 (Whitfield, 2000). A comparison with other permanently open sub-tropical systems showed that the 59 species now recorded in the Mfolozi/Msunduzi system compares favorably with the numbers in much larger systems such as the Mhlatuze Estuary (n=72; Weerts & Cyrus, 1998) and Richards Bay Harbour (n=64;

Weerts & Cyrus, 2002). In comparison, Vivier & Cyrus (2002) reported only 40 fish species from the intermittently open Nhlabane Estuary after a four year seasonal study of the system.

There were notable differences in the fish species composition of the Mfolozi/Msunduzi system when compared to that reported from the adjacent St Lucia Estuary after three years of closed mouth and hypersaline conditions (Cyrus & Vivier, 2006). None of the dominant species in the Mfolozi/Msunduzi Estuary occurred in high numbers in the St Lucia Estuary. The St Lucia system was dominated by *Oreochromis mossambicus* (50%), followed by *Thryssa vitrirostris* (16%), *Silhouettea sibayi* (10%) and *Hilsa kelee* (9%), of which *S. sibayi* and *H. kelee* were not recorded in the Mfolozi/Msunduzi Estuary (Cyrus & Vivier, 2006).

We suggest that the relative abundance of species such as *L. equula*, *C. sexfasciatus* and *V. cunnesius* in the system during the present study is turbidity related. Cyrus & Blaber (1987) compared the ability of subtropical estuarine fish to withstand high turbidities and concluded that species such as *L. equula*, *C. sexfasciatus* and *V. cunnesius* are turbid-water species, whereas *T. jarbua* is indifferent to turbidity. In some species, such as *C. sexfasciatus*, juveniles are known to inhabit waters that are more turbid than those in which the adults occur (Cyrus & Blaber, 1987). In a highly turbid system such as the Mfolozi/Msunduzi, the importance of turbidity as a fish assemblage structuring factor cannot be underestimated. The influence of turbid estuarine water on the distribution of juvenile fishes has been suggested to include providing the juveniles with a form of cover through a reduction in light intensity and visually obscuring prey species from their predators (Cyrus & Blaber, 1987). Cyrus & Blaber (1987) also argued that higher food availability associated with turbid areas attracted large numbers of juvenile marine fishes, due to the higher benthic invertebrate biomass usually associated with more turbid systems, as compared to clear-water systems.

The Mfolozi/Msunduzi Estuary is recognised as one of the most turbid and muddy estuaries in South Africa. It is calculated that the sediment load coming down the Mfolozi River is so high that the Mfolozi/Msunduzi Estuary would fill with sediment in 1.5 years if it was cut off from the sea (Lindsay *et al*., 1996). The Mfolozi/Msunduzi estuary is much more turbid than the St Lucia Estuary which, by international standards, is regarded as a turbid system. The turbidity range recorded for KwaZulu-Natal estuaries was 0.5-1472 NTU, which is far greater than that recorded elsewhere in the world (Cyrus & Blaber, 1987). Major fluvial flood events help maintain the Mfolozi/Msunduzi Estuary depth profile by periodically pushing sediment seawards and scouring and maintaining the main flow channel in the estuary (Lindsay *et al*., 1996).

As pointed out by Vivier & Cyrus (2009), river flows carrying high suspensoid loads can, however, be lethal to both marine migrant and estuarine resident fish species. Whitfield and Paterson (1995) recorded extensive mortalities of both groups of fishes in the Sundays Estuary following a flash flood carrying a high suspensoid load. Although the suspended silt resulted in a clogging of the gills of fishes, it is also plausible that reduced oxygen levels associated with the turbid floodwaters contributed to the asphyxiation of fishes in this estuary. One of the notable characteristics of the Mfolozi fish fauna during 2007 was the absence of juveniles (>30 mm SL) of many species (Vivier & Cyrus, 2009). Dietary information indicates that these were all species that became benthic feeders after their planktonic copepod feeding phase (Whitfield, 1998). In contrast, species that became piscivorous or detritivorous feeders remained in the system. It is suggested that the reasons for the loss of benthic feeders is related to the impoverished zoobenthic community recorded in the Mfolozi system, caused by unstable substrata associated with frequent silt deposition (Vivier & Cyrus, 2009).

Most South African estuaries are dominated by euryhaline marine species that spawn at sea (Whitfield, 1994), in which the development of eggs and larvae occur at sea, followed by a mass migration of post-larvae and juveniles (10-60 mm SL) into the shallower waters of estuaries during spring and early summer, where the high temperatures and rich food supply favour rapid growth, and the shallow turbid waters provide protection from marine predators (Wallace, 1975). Estuaries thereby perform an important nursery function for large numbers of juvenile estuarine-dependent marine fish (Whitfield, 1994; Valesini *et al*., 1997). Of the 155 marine species commonly recorded in southern African estuaries, 135 are associated with subtropical estuaries along the KwaZulu-Natal coast (Whitfield, 2005). Harrison (2003) reported that, in open subtropical estuaries, estuary-associated marine species comprise by far the largest and dominant group, comprising 96 % of the total fish biomass, while 71% of the fish species in these estuaries show some degree of dependence on estuaries as nursery areas.

The importance of the Mfolozi/Msunduzi system as a nursery area for juveniles of marine spawning species was evident in the high number of marine species in the system during all sampling seasons, as well as the high numbers of juveniles of marine species. Of the 59 species recorded in the system, 42 were marine species, while 53 % of the total number caught comprised marine species. The system was dominated by the juveniles of turbid water species, notably *L. equula* and *V. cunnesius.* During August, mullet fry dominated the system, accounting for 38% of the fish caught. Vivier & Cyrus (1994) regarded the relative abundance of juveniles of marine spawning species in the Nhlabane Estuary as indicative of the importance of this estuary as a suitable nursery area in the life cycle of many marine species.

Larger, more frequently open, estuaries tend to have a higher nutrient input and more clearly defined salinity gradients. Closed phases in estuaries result in a low recruitment potential for juvenile marine fish and effectively prevent the emigration of adults back to sea (Whitfield, 2005). If the nursery function of an estuarine system is discontinued, regional marine fish populations will be adversely affected, with possible serious implications for commercial and recreational fisheries (Whitfield, 2005; Mann & Pradervand, 2007). A closed estuary mouth also results in the entrapment of sexually mature adults in the system, and hence in a reduction in the viable spawning population in that region.

The Mfolozi/Msunduzi mouth was open in March and closed in August during both sampling years. The Mfolozi/Msunduzi system is located in a summer rainfall area, with sporadic flooding events during summer causing the estuary mouth to open. Although there were slightly higher species numbers and CPUEs in March of both sampling years compared to August, the fish assemblage during the closed mouth conditions in August 2007 and 2008 was still dominated by marine spawning species, indicating that the marine species were able to withstand the low salinities recorded. The two environmental variables most responsible for structuring the fish assemblage of the Mfolozi/Msunduzi system were salinity and temperature. These two variables were directly related during this study, as the highest temperatures were recorded during March, which was also the time when the mouth was open and the highest salinities were recorded. Mouth condition can thus be regarded as the physical parameter that was most influential in structuring the fish assemblage in the Mfolozi/Msunduzi system. The key to maintaining estuarine biodiversity and the nursery function of estuaries lies in regular contact with the marine environment (Vorwerk *et al.*, 2003; Whitfield *et al*., 2006; Mann & Pradervand, 2007). This allows for successful recruitment of marine organisms into the estuary and the inflow of the sea water necessary for maintaining a salinity gradient and estuarine conditions.

Fluctuations in salinity are regarded as a major factor governing the diversity and abundance of fishes in estuaries (Harrison & Whitfield, 2006; Whitfield *et al*., 2006). Large-scale declines in fish densities, biomass and species diversity have occurred in estuaries where salinities dropped below 3, as was recorded in Lake St Lucia (Blaber & Whitfield, 1976). Data on the salinity tolerances of southern African marine fish species that commonly occur in estuaries (Whitfield *et al*., 1981) show that, of the 70 species investigated, 30 do not occur at salinities below 5. The salinities recorded during closed mouth conditions in August 2007 and 2008 in this study ranged between 1.2-5.4 in the Msunduzi and 4.5-5.5 in the Mfolozi. These low salinities, particularly those in the Msunduzi, could therefore be expected to affect the distribution and survival of marine fish, although marine species have been noted to congregate in large numbers in the vicinity of the Mfolozi mouth during periods of high freshwater outflow (Cyrus, 1991).

Marine fish species that enter southern African estuaries are divided into marine immigrants, which are marine species of which the juveniles and/or adults make extensive use of the estuarine environment and show varying degrees of dependence on estuaries, and marine stragglers, which are marine species that only occasionally enter estuaries or with only a small proportion of the overall population ever entering estuaries (Whitfield, 2005). Due to their dependence on estuaries for the completion of their life cycle, marine immigrants are generally more tolerant of extreme salinities than marine stragglers and, as such, the former group would have a higher chance of survival under low salinity conditions when the mouth was closed. The marine stragglers *Drepane longimana*, *Upeneus vittatus* and *Herklotsichthys quadrimaculatus* were recorded only during high-salinity open-mouth conditions. A number of marine immigrants, such as *Pomatomus saltatrix*, *Scomberoides lysan* and *Liza luciae*, were also recorded only during March, suggesting that they were unable to survive the low salinities during August. In a recent review of the effect of salinity on the fish ecology of the St Lucia system Whitfield *et al*. (2006) remarked that the optimum salinity for most fishes in Lake St Lucia is between 10 and 20, since notably higher fish abundances were recorded within this range. This salinity range also happens to encompass the isosmotic state for many marine and estuarine fish species (Blaber, 1974).

The relatively high species count, compared to that in other permanently open systems, the dominance of post-larvae of marine spawning species with varying degrees of dependence on estuaries, and the close proximity of the Mfolozi/Msunduzi system to the St Lucia system, emphasise the importance of the Mfolozi/Msunduzi system as a potential alternate nursery area when the St Lucia mouth is closed (Vivier & Cyrus, 2009). The total estuarine area of the Mfolozi/Msunduzi system is, however, only a fraction of that of the St Lucia system, and therefore the Mfolozi/Msunduzi system is incapable of substituting for the loss of the St Lucia nursery area, but can, at best, provide only limited alternative estuarine habitat for the marine recruits that would normally enter the St Lucia system when its mouth is open. In addition, the impoverished zoobenthic community recorded in the Mfolozi/Msunduzi system is regarded as a limiting factor in the extent to which benthic-feeding marine species can utilise the nursery habitat in the system. Prolonged closure of the St Lucia system, which comprises 80% of the estuarine area in KwaZulu-Natal, has adversely affected its fish assemblage and caused regional declines in populations of many marine fish species (Cyrus & Vivier, 2006; Mann & Pradervand, 2007). Recovery of the St Lucia fish community can only begin once the estuary mouth breaches and regular contact with the marine environment is re-established. Due to its close proximity to St Lucia, the Mfolozi/Msunduzi system will contribute towards the re-colonisation of marine fish species into the St Lucia system, and will therefore play an important role in the recovery of the St Lucia fish assemblage when its mouth re-opens.

The importance of the Mfolozi/Msunduzi system to the water budget of the St Lucia system has also been recognised and, in 2007, a project was initiated by Ezemvelo KZN Wildlife to divert Mfolozi/Msunduzi water into the St Lucia Estuary through a linking channel during low flow conditions. The benefits to be derived by the St Lucia system and its estuarine fauna, if this diversion is successful, will further highlight the need to re-establish the former Mfolozi-St Lucia link. Catchment degradation and socio-economic factors associated with sugar cane farming in the Mfolozi floodplain will, however, probably prevent large-scale re-establishment of the Mfolozi swamps, which is a prerequisite for the permanent re-linking of the Mfolozi to the St Lucia system.

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A RESOURCE ECONOMICS ANALYSIS OF THE SIGNIFICANCE OF REHABILITATION OF THE MFOLOZI FLOODPLAIN

Sandy van der Waal*

Affiliation:Environmental Science Department, Rhodes University, Grahamstown
**Email:collingsza@gmail.com*

INTRODUCTION

Lake St Lucia in northern KwaZulu-Natal, South Africa, experiences severe ecological stress during dry periods largely as a result of diminishing freshwater supplies and conditions of hypersalinity. Possible management intervention involves restoring the Mfolozi River flow into the St Lucia Lake system. However, due to perceived high sediment loading, water from the Mfolozi River requires considerable filtration before this link will be acceptable. One option, addressed in this report, would be to restore the existing sugarcane farmlands on the Mfolozi floodplain (~ 20 800 ha) to previous wetland conditions in order to re-establish a sediment removal function. Restoration of this kind will have a direct impact on the industries currently supported by the iSimangaliso Wetland Park and the Mfolozi floodplain (tourism, sugar and conservation). To understand the measure of such impacts, ecosystem services in the form of flood alleviation, water provision, water purification, sediment regulation, tourism, fisheries, vegetation for harvest, existence, cultural and research for both Lake St Lucia and the Mfolozi floodplain were analysed. This section summarises the research presented as a Masters dissertation by the author through Rhodes University, Grahamstown, South Africa.

The aim of the study was to provide an economic valuation of the current ecosystem services provided by Lake St Lucia and the Mfolozi floodplain and to determine the expected changes to these values brought about by two possible restoration scenarios for the Mfolozi floodplain; one involving about 20 800 ha and the other about 6 000 ha, that would allow the reintroduction of water from the Mfolozi River into Lake St Lucia. The objectives of the study were to:

- Identify existing ecosystem services in the Lake St Lucia system and in the Mfolozi floodplain and assess the monetary value of each.
- Using knowledge from specialists, determine the expected changes to ecosystem service values under the two potential restoration scenarios (partial and full restoration) of the Mfolozi Floodplain, currently being considered by management (Ezemvelo KZN Wildlife/iSimangaliso Wetland Park Authority) (R. Taylor, pers. comm.).
- Construct an empirical economic model as a framework into which data might be entered for computational purposes, thereby providing a decision-making tool for management.
- Use the model and calculate expected economic outcomes associated with restoration scenarios in the Mfolozi floodplain and highlight potential implications for management.

MAJOR FINDINGS

Economic valuation of ecosystem services

Nine ecosystem services were assessed for both the Mfolozi floodplain and the St Lucia system. These services included representatives of each or the four categories of ecosystem services proposed by the Millennium Ecosystems Assessment (MEA).

Table 1. Ecosystem services analysed in this study.

MEA category	**Service valued for the Mfolozi floodplain and the Lake St Lucia system**	**Service description**
Regulating	Flood alleviation	Mitigating impacts of flood events or storms; water regulation such as drainage
	Water provision	Water supply to users within the site
	Water purification	Pollution control and detoxification; specifically reducing nitrogen and phosphorus levels
	Sediment retention	Sediment retaining capabilities; prevention of damage from erosion and siltation
Supporting	Tourism	Enterprises based on tourism or recreation supported by natural habitat
Provisioning	Vegetation harvesting	Direct use values; harvesting raw materials for fuel use, building, manufacturing, food etc.
	Fisheries	Habitats as nursery grounds/refugia for national stocks, supply to recreational and commercial fishing
Cultural	Existence	Aesthetic; enjoyment of scenery, sense of place
	Cultural and education	Spiritual, artistic, historic and research, education

Where calculations involved a US dollar value, conversions were made to South African Rands using the Rand/Dollar exchange rate of approximately 1 US$: R10 (December 2008). Due to the availability and nature of data, certain values for ecosystem services for the ‘St Lucia System’ were determined for the area within the iSimangaliso Wetland Park boundary, others were determined for the St Lucia Lake and one was calculated for the town of St Lucia only. Methods for valuing ecosystem services included a replacement cost method, market value, benefit transfer and the assigning of a proxy value (Table 2). For information regarding the way in which the data were calculated, refer to Appendix Table A and Collings (2007).

Table 2. Valuation methods and data sources for ecosystem service valuation for the St Lucia system and Mfololzi floodplain.

ECOSYSTEM SERVICE	**METHOD**	**SOURCE**
ST LUCIA SYSTEM		
Flood alleviation	Benefit transfer	Taylor *et al*. (2006), Costanza *et al*. (1997)
Water provision	Replacement cost	DWAF (2008), Bate & Taylor (2007)
Water purification	Benefit transfer	Taylor *et al*. (2006), Costanza *et al*. (1997)
*Sediment retention	Management costs	Ezemvelo KZN Wildlife (2008)
*Tourism	Tourism proxy	Statistics South Africa (2009)
*Vegetation harvesting	Market value	Ezemvelo KZN Wildlife (2008)
Fisheries	Benefit transfer	Lamberth & Turpie (2003), Taylor *et al*. (2006)
*Existence	Benefit transfer	Mucina & Rutherford (2006), Turpie (2003)
*Cultural and Education	Benefit transfer	Ezemvelo KZN Wildlife (2008), Mucina & Rutherford (2006), Costanza *et al*. (1997)
MFOLOZI FLOODPLAIN		
Flood alleviation	Replacement cost	Mfolozi Cooperative Sugar Planters (UCOSP), 2009.
Water provision	Market value	DWAF (2008), UCOSP (2008/9)
Water purification	Benefit transfer	Costanza *et al*. (1997)
Sediment retention	Replacement cost	UCOSP (2008)
Tourism	Tourism proxy	Statistics South Africa (2009)
Vegetation harvesting	Benefit transfer	Ezemvelo KZN Wildlife (2008), UNESCO (2008), Collings (2007)
Fisheries	Benefit transfer	Lamberth & Turpie (2003)
Existence	Benefit transfer	Mucina & Rutherford (2006), Turpie (2003)
Cultural and Education	Benefit transfer	Mucina & Rutherford (2006), Costanza *et al*. (1997)

*Values derived using the area of iSimangaliso Wetland Park

Results (Table 3) showed a current annual minimum value for the Mfolozi floodplain and Lake St Lucia as greater than R21 x 10^6 yr^{-1} and R1.1 x 10^9 yr^{-1} respectively. This equates to approximately 90.76% and 2% of the Umkhanyakude District gross geographic product (GGP) for 2000 (Haley Sharpe Southern Africa, 2003) for the St Lucia System and Mfolozi floodplain respectively.

Resultant annual economic values showed that cultural and educational services were the greatest for both the St Lucia system (R325 x 10^6 yr^{-1}) and the Mfolozi floodplain (R8 x 10^6

yr^{-1}), following which, regulating services were the highest (Table 3). These included water purification (R231 x 10^{6} yr^{-1}), flood alleviation (R197 x 10^{6} yr^{-1}) and water provision (R160 x 10^{6} yr^{-1}) for the St Lucia system and flood alleviation (R5 x 10^{6} yr^{-1}) and water provision (R4.6 x 10^{6} yr^{-1}) services for the Mfolozi floodplain.

Fisheries and tourism, important industries in the district were valued at 13 and 3% of the total economic value for the St Lucia System respectively. The current fisheries value for the Mfolozi floodplain was calculated as 3% of the total economic value of the floodplain and a tourism value about 8% of the total. In comparison to other ecosystem services, under the current land use, the Mfolozi floodplain offers a relatively low economic value for its sediment retention and water purification function.

Regulating ecosystem services flood alleviation, water provision and water purification, among the highest valued services for the system, were calculated for Lake St Lucia. This is important to note, because at the present time the lake experiences major stress during drought periods. Should environmental conditions deteriorate further in the future, ecosystem services may be adversely affected, thereby impacting on associated economic values.

Table 3. Economic values of ecosystem goods and services for the Mfolozi floodplain and St Lucia system. Values for the St Lucia system were calculated for the St Lucia Lake, the iSimangaliso Wetland Park or the town of St Lucia.

MEA	**Ecosystem Goods and Services**	**Current Annual Economic Value (R)**		
		Mfolozi floodplain	**St Lucia system**	
Regulating	Flood Alleviation	5,000,000	196,610,400	Lake
	Water Provision	4,604,700	160,000,000	Lake
	Water Purification	144,900	230,592,400	Lake
	Sediment Retention	500,000	2,000,000	Park
Supporting	Tourism	1,659,300	35,824,800	St Lucia
Provisioning	Vegetation Harvesting	196,400	3,582,600	Park
	Fisheries	740,500	143,990,000	Lake
Cultural	Existence	401,400	9,069,200	Park
	Cultural and Education	7,959,800	324,672,200	Park
	Total Annual Value	**21,948,400**	**1,106,341,600**	

Note: Totals may not add up due to rounding.

Outline of Restoration Scenarios

Following the valuation of ecosystem services for both the Mfolozi and St Lucia systems, the response of these values was investigated under three different Mfolozi Floodplain restoration scenarios.

Current land use: No restoration

The first scenario considered the current environmental conditions of the Mfolozi River and St Lucia system should the situation remain as it is currently, with no restoration of the Mfolozi floodplain. Therefore, no link between the Mfolozi River and Lake St Lucia would be established under this scenario.

Partial reinstatement

Partial restoration considers re-establishing the wetlands in low-lying areas of the floodplain along the Mfolozi River channel as delineated by Collings (2007). Low-lying areas have the highest risk of flooding and therefore are considered to be the most suitable for wetland restoration. This concept was first raised in the 1980s by van Heerden (2001) (Figure 1). This area of about 6 000 ha includes approximately 1 800 ha of sugarcane (Collings, 2007).

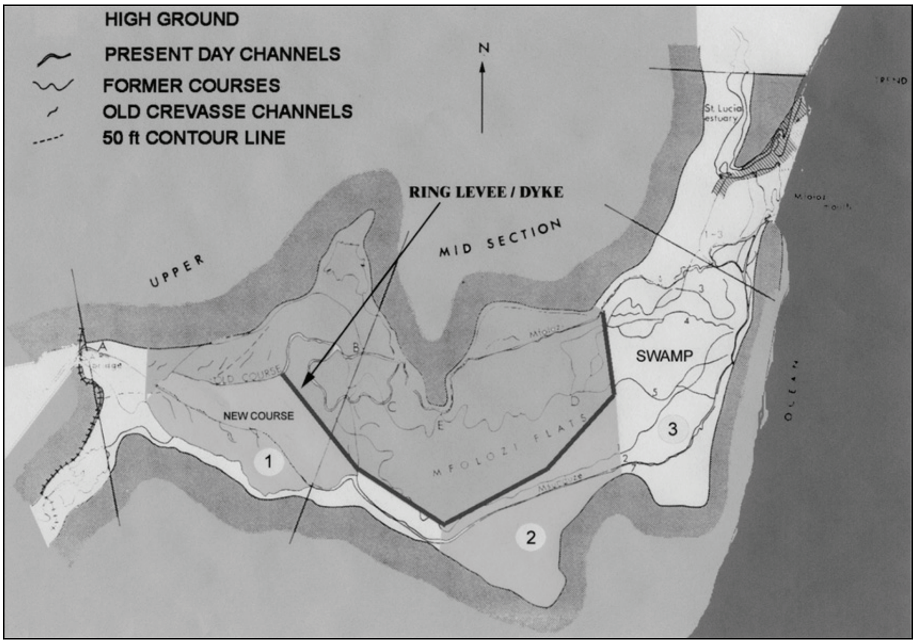

Figure 1. The Mfolozi floodplain as a sediment trap (‘the van Heerden concept’).

With an increase in freshwater supply to Lake St Lucia, although temporary in this scenario, environmental conditions could be expected to improve. Salinity levels in the lake would not reach the upper extremes recorded in recent years and the St Lucia mouth would breach more frequently. However, although this scenario allows for the Mfolozi River to provide supplementary waters to Lake St Lucia, this may only occur during high flows in summer.

Therefore, this scenario may not provide adequate alleviation of the stress experienced by the St Lucia System during periods of drought and particularly periods of extended drought.

Full restoration

This scenario considers the potential restoration of all land in the demarcated floodplain area of approximately 20 000 ha, of which 8 000 ha is currently under sugarcane (Collings, 2007). In this scenario it is assumed that all privately owned land would be purchased and included into the iSimangaliso Wetland Park or alternatively into a separate conservation area.

This scenario assumes that restoring the floodplain will reinstate sufficient filtration of silt and mud from the water of the Mfolozi River to allow the establishment of a permanent link with Lake St Lucia. It is further assumed in this scenario that the volume of freshwater input to the lake system during high flow months would be sufficient to maintain efficient ecological functioning into drought periods as is likely the case under the "natural" condition. It is thus expected that the St Lucia system would no longer experience the present wide fluctuations in salinity along with other ecological stresses during drought periods. The increased freshwater supply would alleviate pressures on the local biota as well as support tourism activities. The St Lucia mouth would again be expected to breach more frequently than is currently the case.

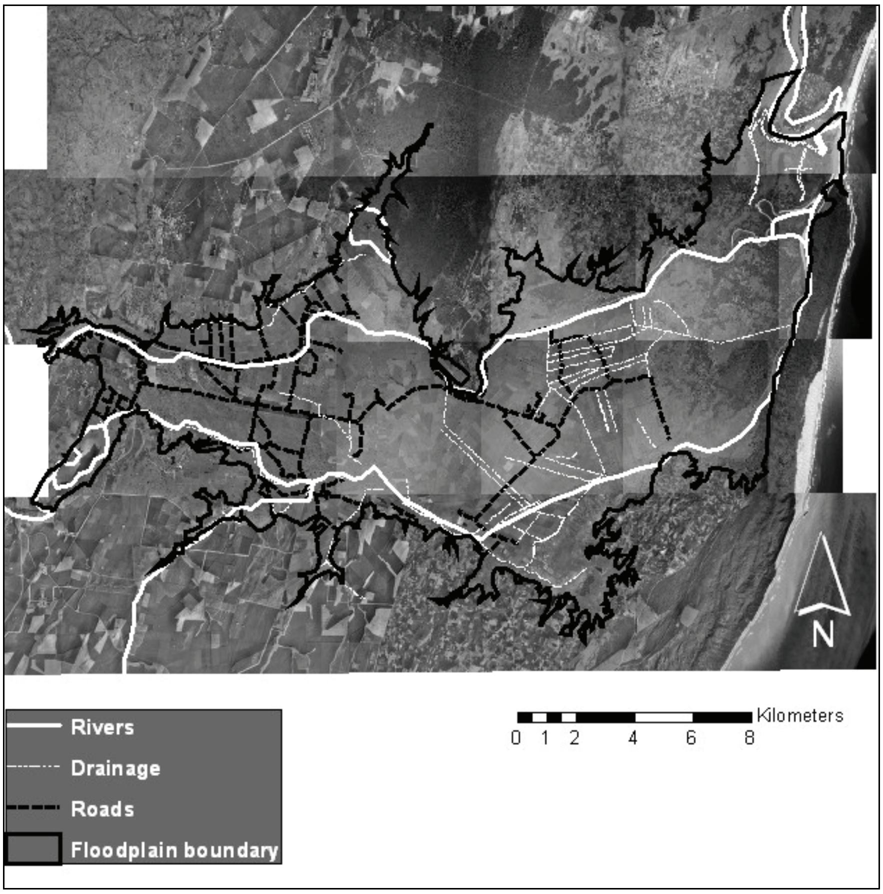

Figure 2. GIS delineation of the Mfolozi floodplain with major infrastructure (after Collings, 2007).

Land use in of the Mfolozi floodplain would shift from intensive sugarcane to natural habitat. This scenario involves the removal of all drainage and infrastructure to accommodate wetland restoration. The restored natural habitat, along with an expected increase in biodiversity, would attract nature based tourism enterprises as well as vegetation harvesting.

Specialist estimates of ecosystem service value change

Eight specialists, each recognized as having more experience or knowledge of a particular ecosystem service than others, provided input in order to estimate potential changes to ecosystem services under each restoration scenario. These specialists were required to indicate their estimates of change (percentage increase or decrease) to given economic values of ecosystem services that would be expected under each scenario. Specialists were asked to provide a rating from 1-3 of their confidence regarding their answers for each ecosystem service. A score of 1 indicated weak confidence in the response, 2 represented moderate confidence and 3 indicated strong confidence. 'Confidence' points were used to weight each specialist's estimates of change to ecosystem service values using MS Excel. The weighted averages of percentage changes to ecosystem services from specialist responses were applied to the initial monetary values for each service for both the partial and full restoration scenarios, in order to assess the economic value of different restoration scenarios.

Table 4. Specialists who contributed to the study.

Name	**Area of Expertise**	**Organization**
Janine Adams	Estuarine ecology, Estuarine Environmental flow requirements	Water Research Commission, Nelson Mandela Metropolitan University, Port Elizabeth
Maura Andrew	Social Scientist	CES, Grahamstown
Fred Ellery	Wetland ecology and rehabilitation	Rhodes University, Grahamstown
Suzanne Grenfell	Geomorphology and Mfolozi Sediments	University of Exeter, UK
Christo Marais	Biodiversity protection, Water management and Resource economics	Working for Water, DWA
Ricky Taylor	Regional ecologist	Ezemvelo KZN Wildlife, St Lucia Estuary
Damien Walters	Wetland ecology and rehabilitation	WESSA Mondi Wetlands Programme, KwaZulu-Natal
Alan Whitfield	Ichthyology, Biological oceanography, Marine ecology, Estuarine ecology	SAIAB, Grahamstown

In order to provide a measure of the change to overall economic value of each study site under each scenario, the sum of economic values for every ecosystem service was considered. It is important to note however, that these figures do not represent a total economic value (TEV) as referred to in the literature (Turpie & Lannas, 2007; Edwards & Abivardi, 1997). A number of variables required for calculating such a TEV were not included in the analyses in this study (*e.g.* option value). Furthermore, the values of ecosystem services were calculated using different scales for the St Lucia system (Table 2) and therefore cannot provide a total economic value for a specific area. Thus, the sum of the ecosystem service values presented does not provide a TEV for each system but rather can only be considered indicative of the overall economic value. With the exception of the water provisioning service, every ecosystem service on the Mfolozi floodplain had a greater percentage increase than did the St Lucia System under both restoration scenarios (Figure 3).

Partial Restoration

Ecosystem Service

Mfolozi floodplain

Under the partial restoration scenario, the sum of all ecosystem service values increased by approximately 26 % from the current land use value (Figure 4). The results showed existence value, tourism, fisheries and vegetation harvesting, each increased by over 80 % (Figure 3).

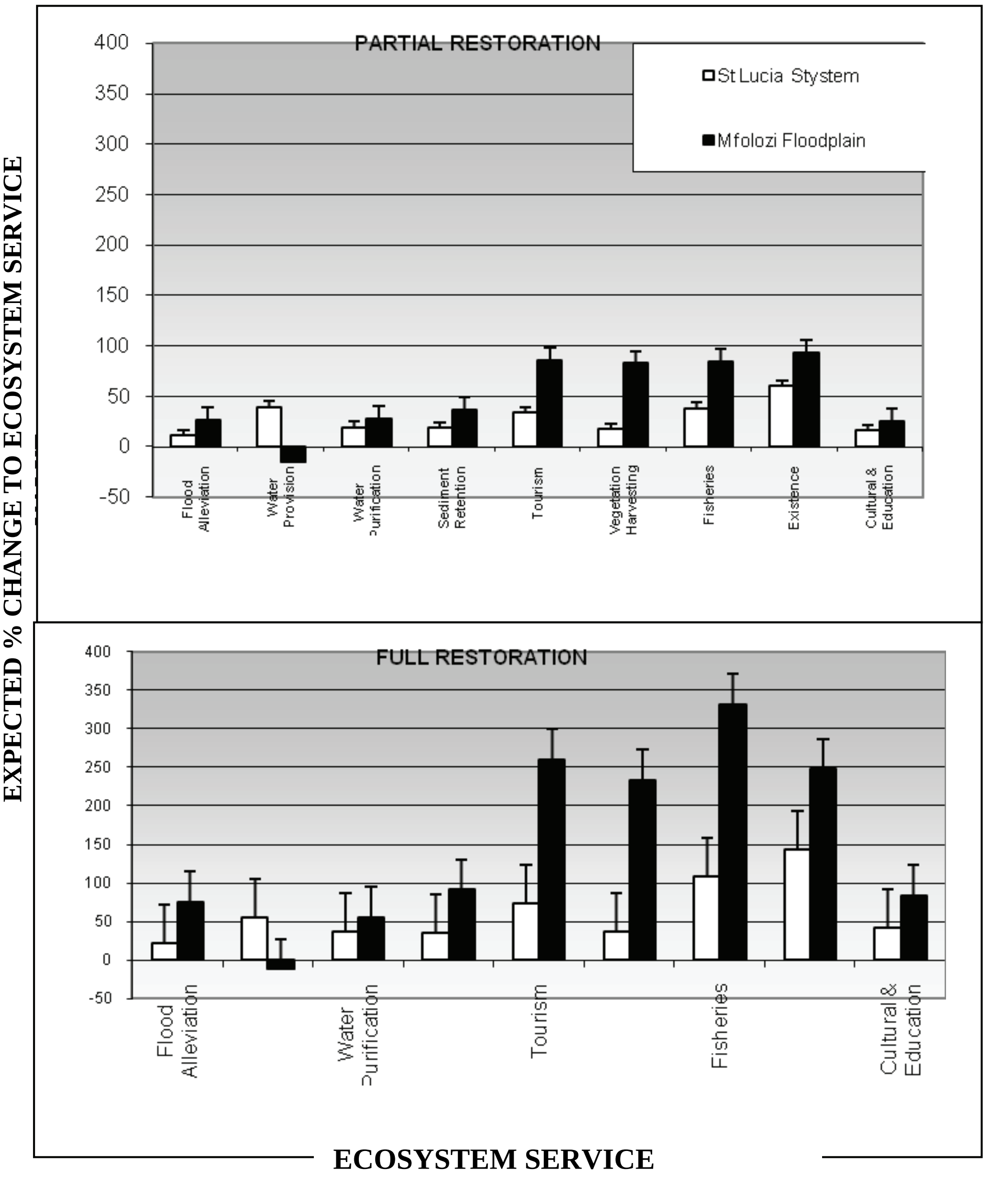

Figure 3. Expected percentage changes to ecosystem services in each study site under the partial (above) and full (below) restoration scenarios.

Restoration of wetland habitats in the lower lying areas of the floodplain would reduce the risk of downstream flooding due to the available habitat into which flood waters would be dissipated. Wetland vegetation in these restored areas would increase the filtering action of sediments as well as purifying the water flowing through the system. Annual economic values for these regulating services, flood alleviation, water purification and sediment retention, would increase under this scenario by 25-40 % (Figure 4). The additional natural habitat would also provide greater opportunities for cultural and educational activities and increases of about 26% might be expected. The value of water provision to the Mfolozi floodplain, however, was expected to decline by approximately 14%, due to the reduction in irrigation water under this scenario.

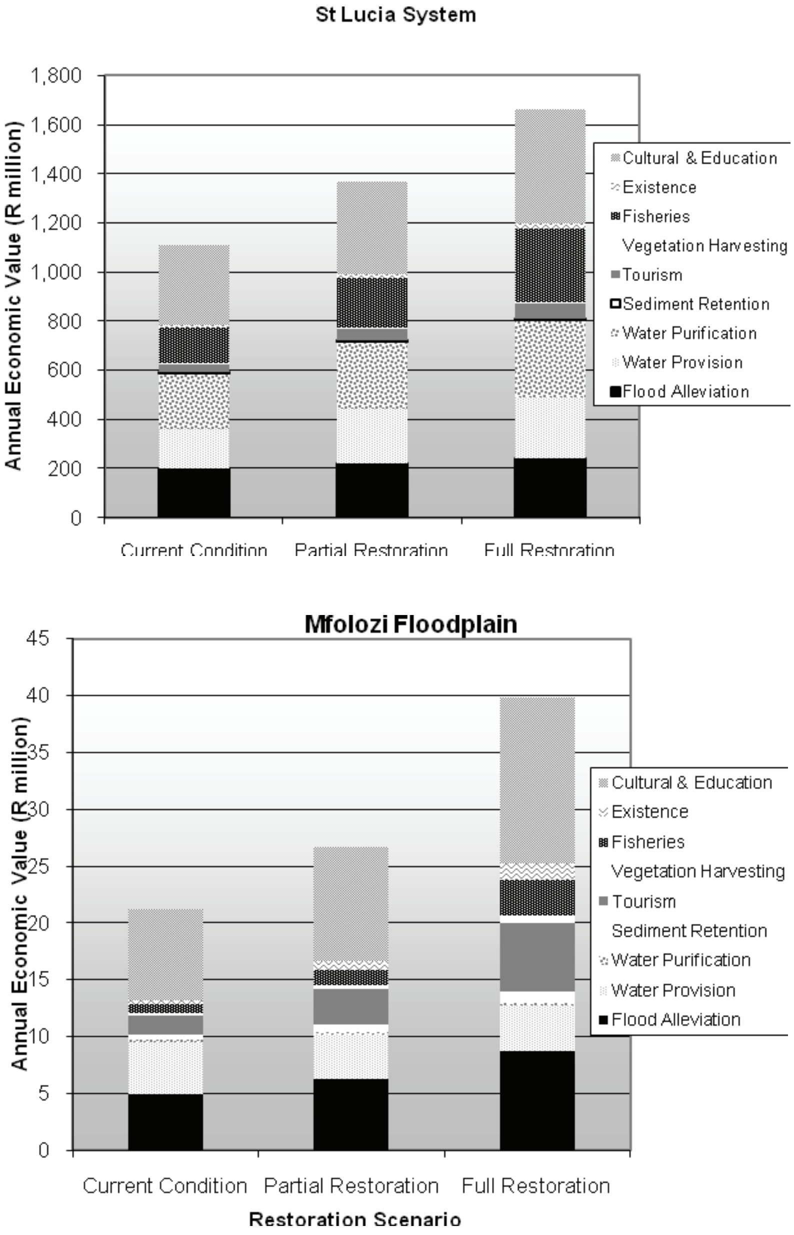

Figure 4. The total annual ecosystem service values for each restoration option. Percentages indicate the expected change under each scenario from the present total economic value.

St Lucia system

The total ecosystem service value was expected to increase by about 24 % from the current situation (Figure 4). The existence value of the St Lucia system would experience the greatest percentage increase (61%) following partial restoration of the floodplain. Additional water supply from the Mfolozi River in this scenario, although temporary, would increase the water provision service value by 40 % (Figure 3). Returning freshwater volumes to the St Lucia Estuary, along with regular flushing of the system due to the mouth opening more frequently, would re-establish vital nursery grounds for estuary dependent marine fish. This would impact positively on the country's fisheries, as the case would also be for the Mfolozi Estuary under this scenario. The results showed an approximately 40 % increase in the value for fisheries under this scenario. Concern was raised among the specialists, however, that the increased freshwater inflow might also increase the flood risk to the town of St Lucia. The annual value of tourism was also expected to increase by approximately 34%. Results showed economic values for flood alleviation, water purification, sediment retention, vegetation harvesting and cultural and education would each increase by less than 20% under this scenario.

Full Restoration

Mfolozi floodplain

Restoring the entire floodplain area is expected to increase the sum of current ecosystem service values by approximately 88 % (Figure 4). Fisheries would increase by 330%, which is more than double the expected increase following a partial restoration of the floodplain. Opportunities for tourism would also improve substantially, increasing the value of tourism by about 260%. Further, the additional habitat restored under this scenario would increase the supply of natural resources available for harvesting, growing in economic value by 230%. The change from sugarcane to natural wetland habitat would see the existence value of the floodplain increase by approximately 250%. Flood alleviation, water purification, sediment retention and cultural and education services would increase more than 75% under this scenario. Following the decrease in downstream users in the floodplain, water provision is expected to decrease by about 10%.

St Lucia system

Total added ecosystem service values for the St Lucia system would increase by 50% if the Mfolozi floodplain was fully restored (Figure 3). The existence value would experience the greatest percentage change of over 140% under this scenario (Table 6). The permanent link with the Mfolozi River under this scenario would provide the freshwater inflow required to alleviate the severe ecological stress currently experience by the lake system. Salinity and water temperatures would be expected to stabilise and the St Lucia mouth would open more frequently, re-establishing nursery grounds for estuary dependent marine fish as experienced under a partial restoration scenario. Greater hydrological and chemical stability is also expected to influence tourism activities positively. Results show fisheries and tourism values increasing by 109% and 73% respectively. An increase in the value of cultural and education service (40%) is also expected. Given the greater volumes of water that would be entering the system from a link with the Mfolozi River, the value of water provision was expected to increase by 55%. However, increasing the available water supply to the St Lucia system may also increase flood risk to St Lucia Town. The flood attenuation value was thus estimated to only increase by about 20% in this scenario. Greater water levels in the lake and the possible submergence of shoreline vegetation is not expected to provide greater opportunities for the harvesting of vegetation. However, these conditions may still provide increased purification of water together with a greater retention of sediments. Water purification, sediment retention and the harvesting of vegetation values are expected to increase by between 30-40%.

Table 5. Ecosystem services listed from the highest to the lowest expected percentage change in economic value under each restoration scenario.

Rank	**MFOLOZI FLOODPLAIN**		Rank	**ST LUCIA**	
	Partial Restoration	**Full Restoration**		**Partial Restoration**	**Full Restoration**
1	Existence	Fisheries	1	Existence	Existence
2	Tourism	Tourism	2	Water Provision	Fisheries
3	Fisheries	Existence	3	Fisheries	Tourism
4	Vegetation Harvesting	Vegetation Harvesting	4	Tourism	Water Provision
5	Sediment Retention	Sediment Retention	5	Water Purification	Cultural and Education
6	Water Purification	Cultural and Education	6	Sediment Retention	Water Purification
7	Flood Alleviation	Flood Alleviation	7	Vegetation Harvesting	Vegetation Harvesting
8	Cultural and Education	Water Purification	8	Cultural and Education	Sediment Retention
9	Water Provision	Water Provision	9	Flood Alleviation	Flood Alleviation

This interdisciplinary research has addressed efforts to conserve the ecological health of one of South Africa’s most pristine regions whilst recognising the direct conflict with other industries and current political agendas. The field of environmental economics has provided a tool by which the contribution of ecosystems to the economy may be communicated. It is emphasised that many of the country’s industries should be conscious of the preservation of and the long-term health of the country’s natural capital, upon which they are delicately reliant.

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THE VALUE OF ESTUARIES IN NORTHERN KWAZULU-NATAL WITH PARTICULAR REFERENCE TO THE MFOLOZI AND ST LUCIA SYSTEMS

Jane Turpie* & Sabrina Chesterman

Affiliation: Anchor Environmental Consultants, Tokai, Cape Town
**Email: jane@anchorenvironmental.co.za*

INTRODUCTION

The St Lucia/Mfolozi estuarine system is the largest in South Africa and of extremely high conservation significance. However, relatively little is known of the economic value of this system or the estuaries of northern KwaZulu-Natal in general. This study formed part of a larger study funded by the Department of Water Affairs to determine the economic value of all rivers, wetlands and estuaries of three Water Management Areas (WMAs), including the Usutu-Mhlatuze WMA (DWA, 2010). Nine estuaries are included in the latter WMA, which includes the coastal stretch from Kosi estuary to the Richard's Bay/Mhlatuze Estuary system. Although estimates are made on a course scale and need further refinement they do provide first cut estimates of the values of a range of estuaries along this short stretch of coast.

The nine estuaries within the Usutu to Mhlatuze WMA are, from north to south, the Kosi, Mgobezeleni, St. Lucia, Mfolozi, Nhlabane, Richards Bay/Mhlatuze, Mlalazi, Siyaya and the Matigulu/Nyoni (Figure 1). In fact they should strictly be considered as eight estuaries, since the St Lucia/Mfolozi is naturally a single estuary system. Nevertheless, these have been considered separately in this study as they are artificially separated at present.

None of the estuarine systems has been accurately mapped to date. Based on the current botanical database for South African estuaries (J. Adams *in litt*., 2010), the nine estuaries cover an area of approximately 43 000-65 000 ha, depending on data source, ranging in size from 8 ha to the 38 500-48 000 ha extent of St Lucia, South Africa's largest estuary (Table 2). The recent Ezemvelo KZN Wildlife land cover data suggest that some of the systems may be considerably larger than our earlier estimates. For example, a more inclusive estimate of the St Lucia Estuary puts it at close to 48 000 ha, with a water area close to 36 000 ha. Estimates of the size of the Kosi system range, depending on where the upper limit of the estuary is defined, from 416 ha to over 4600 ha (the whole lake system). According to Broekhysen (1959), the estuarine area does not include the lakes, which suggests that the smaller estimate is probably the more accurate. In the case of the Nhlabane Estuary, it should be noted that the estimate does not include the approximately 1000 ha lake, which is not currently estuarine in function because it has been cut off from any marine input. In most cases, the differences between the land cover data and the estuary habitat data based on aerial photographs is probably due to a more inclusive categorisation of the latter, including associated freshwater wetland habitats. In the case of Mfolozi, the categorisation of habitats in the landcover data, which included 3450 ha of floodplain grass, 2063 ha of reed/sedge marsh and 1435 ha of mangrove forest, suggested that the latter were highly unreliable for this site.

Table 1. Physical classification and size of estuaries in the Usutu to Mhlatuze WMA. Size ranges are based on botanical database and the KZN Wildlife landcover data. Note: *larger estimate not reliable.

Estuary	**Classification**	**Catchment Size (km^2)**	**Area of estuary (ha)**	**MAR ((m^3 x 10^6)**	**Health**
Kozi	Estuarine Lake	500	416-4615	-	Good
Mgobezeleni	Estuarine Lake	33	15-234	-	Good
St Lucia	Estuarine Lake	9 542	38 582-47 981	295	Good
Mfolozi	River Mouth	11 318	138-7109*	1 060	Fair
Nhlabane	Estuarine Lake	107	14-1181	20	Fair
Richards Bay/Mhlatuze	Estuarine Bay	4 373	3550-3735	616	Fair
Mlalazi	Permanently open	507	101-239	139	Good
Siyaya	Temporarily open/closed	18	8-9	-	Fair
Matigulu/Nyoni	Permanently open	900	127-562	186	Good

Table 2. Estimated area (ha) of estuarine habitat types in the study area, based on aerial photographs (source: J. Adams, Botanical database 2010).

	Inter-tidal salt marsh	**Supra-tidal salt marsh**	**Submerged macrophytes**	**Reeds & sedges**	**Mangroves**	**Sand/mud banks**	**Channel**	**Rocks**	**Swamp forest**	**Total**
Kosi	0	0	0	100	61	18	200	12	25	416
Mgobezeleni	0	0	0	5	5	1	1	0	4	15
St Lucia	516	1706	181	3789	571	206	31610	0	3	38582
Mfolozi	0	0	0	78	26	20	9	0	5	138
Nhlabane	0	0	1	8	0	0	5	0	0	14
Mhlatuze/ Richard's Bay	112	0	5	514	919	621	1548	0	16	3735
Mlalazi	0	39	0	20	61	20	96	0	3	239
Siyaya	0	0	0	5	0	0	1	0	1	8
Matigulu/ Nyoni	0	0	1	2	0	1	122	0	2	127

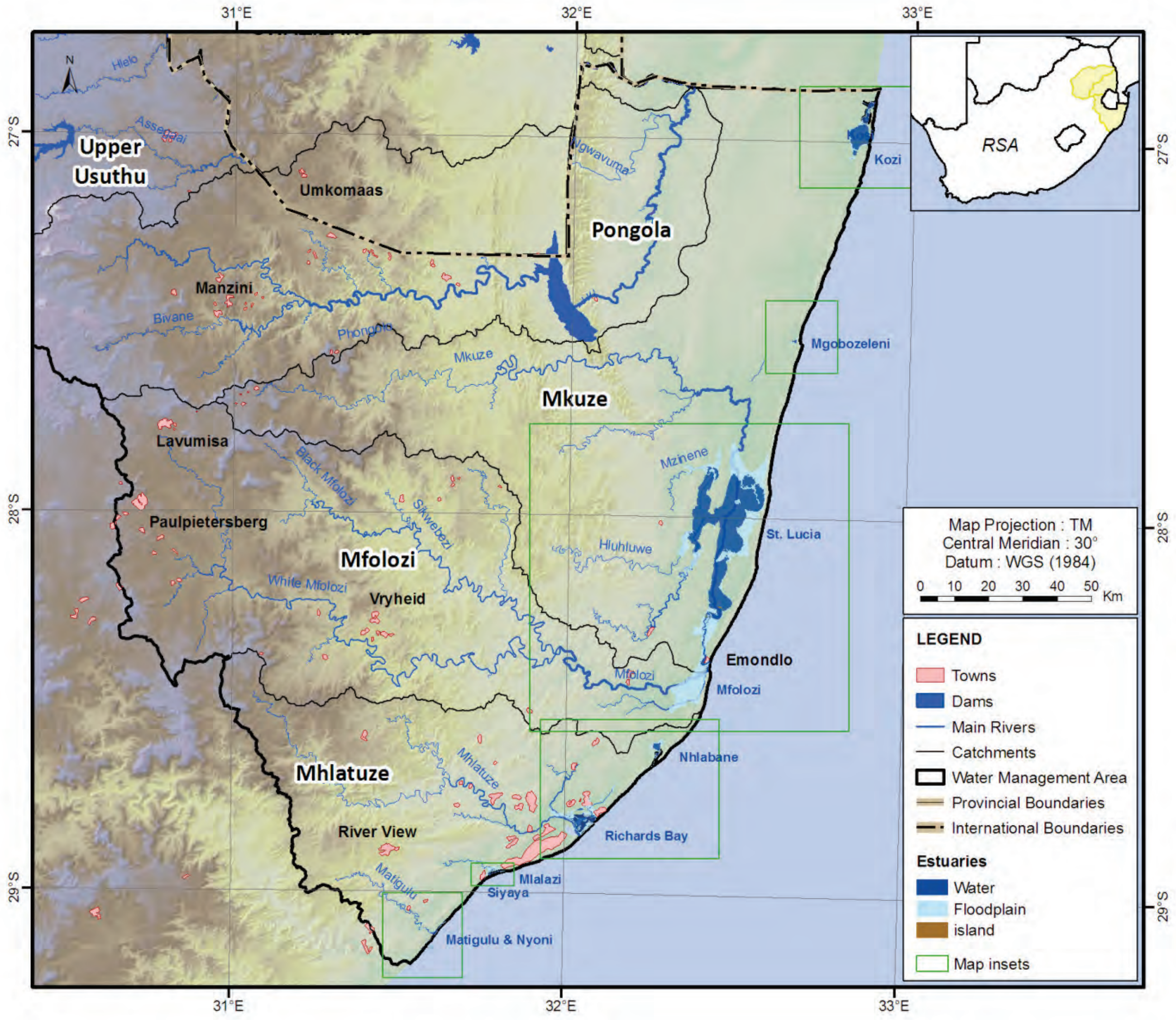

Figure 1. Location of estuaries in the Usutu to Mhlatuze WMA.

The area of estuarine habitats that have been recorded for each estuary are summarised in Table 2. The St Lucia system not only dominates in terms of open water area, but also has by far the largest areas of other habitats, apart from mangroves and swamp forest (Table 3).

CONSERVATION IMPORTANCE

Estuaries have been recognised for their productive fish and invertebrate fisheries, biodiversity and the range of important functions they perform such as nursery areas for marine fish, conduits for species which move between oceans and rivers, as well as important staging sites for populations of migratory birds (Turpie, 1995). In addition, estuaries support a number of southern African endemic species, of which some are dependent on estuaries for their survival (Turpie *et al*., 2002). Through these attributes estuaries have fundamental importance with regards to their conservation status.

The estuaries located along the KwaZulu-Natal coast are some of the most important in terms of their conservation status across the country. All the estuaries in the WMA, except for the Siyaya, were placed within the top 50 South African estuaries ranking their conservation importance. The size of the estuaries in the region was an important contributing factor with Kosi, St Lucia, Mhlatuze and Nhlabane all scoring 100 for this attribute (Table 4).

Table 3. Estuary importance scores within the Usutu-Mhlatuze WMA, extracted from Turpie & Clark (2007).

Estuary	Size	Habitat	Zonal type rarity	Biodiversity	Conservation importance
Kosi (including lakes)	100	100	70	100.0	97.0
Mgobezeleni	10	80	70	37.0	40.3
St Lucia	100	100	70	98.5	96.6
Mfolozi	90	100	70	92.5	91.1
Nhlabane	50	50	70	86.0	61.0
Richard’s Bay*	100	0	80	85.0	69.3
Mhlatuze*	100	100	80	53.5	86.4
Mlalazi	90	90	30	94.0	85.0
Siyaya	30	60	10	47.0	39.8
Matigulu/Nyoni	90	70	30	89.0	78.8

**For the purposes of scoring these systems were considered independently*

In terms of zonal type rarity the Mfolozi with a score of 70, is one of only 12 river mouths in South Africa and one of four closed-fresh-turbid systems in South Africa. The Kosi, Mfolozi and St Lucia also scored highly for their biodiversity importance. The St Lucia system scored 100 for its habitat diversity which includes mangroves and extensive freshwater marshes. It also scored highly for its biodiversity relative to other South African estuaries taking into account scores for plants, invertebrates fish and birds. In addition many of these systems are important for the services they provide, notably the Mfolozi which is critical to the St. Lucia system.

A more recent assessment of conservation importance focuses on the Estuarine Health Index (EHI) scores of the different estuaries (van Niekerk & Turpie, 2010). The EHI assesses the degree to which the current state resembles the reference (*i.e*. natural) condition. Once the natural hydrological conditions have been described, an assessment into the condition of the estuaries in terms of a range of biophysical variables is carried out by specialists. The current state is then scored for each of these variables on a scale of 0 (no resemblance to original state) to 100 (same as natural state). The health scores and overall scores for the estuaries within the Usutu-Mhlatuze WMA are summarised in Table 5.

The overall health score of 34.6 of the St Lucia system (2004) translates into a Present Ecological Status of an E, which was classed as a highly degraded system (Table 6). The Nhlabane was also classified as highly degraded, with the Mfolozi and Richard’s

Bay/Mhlatuze estuaries falling into the largely modified category. The St Lucia system had a relatively poor water quality score in relation to the other estuaries within the WMA, this was similar for its habitat and biological scores. It scored well for its physical habitat and for its other water quality attributes.

Table 4. Estuarine Health Score of estuaries within the Usutu-Mhlatuze WMA.

	Hydrology	Hydrodynamics	Other Water quality	Salinity	**Total WQ Score**	Physical habitat	**Habitat Score**	Microalgae	Macrophytes	Invertebrates	Fish Final	Birds	**Biological Score**	Ecological Category (Mean)	**EHI SCORE (Min)**
Kosi	85	90	95	80	**89**	80	**86.0**	87.5	70	90	70	70	**77.5**	B	**77.5**
Mgobezeleni	85	70	95	75	**87**	85	**81.75**	82	90	90	60	95	**83.4**	B	**81.75**
St Lucia	35	40	75	30	**57**	65	**49.25**	53	30	10	40	40	**34.6**	D	**34.6**
Mfolozi	80	70	30	70	**46**	60	**64.0**	50	30	50	45	40	**43.0**	D	**43.0**
Nhlabane	65	10	80	10	**52**	10	**34.25**	41	40	50	40	60	**46.2**	D	**34.25**
Richards Bay	80	100	60	50	**56**	30	**66.5**	66	20	30	45	80	**48.2**	D	**48.2**
Mhlathuze	80	100	70	50	**62**	30	**68.0**	72	40	60	50	40	**52.4**	C	**52.4**
Mlalazi	90	90	75	90	**81**	90	**87.75**	80	50	80	55	80	**69.0**	B	**69.0**
Siyaya	10	10	20	10	**16**	20	**14.0**	14	10	10	10	5	**9.8**	F	**9.8**
Matigulu/ Nyoni	90	80	85	80	**83**	80	**83.25**	87	80	80	55	85	**77.4**	B	**77.4**

Table 5. Relationship between Estuarine Health Score, Present Ecological Status (PES) classification, and how it is understood.

EHI Score	**PES**	**General description**
91-100	A	Unmodified, natural
76-90	B	Largely natural with few modifications
61-75	C	Moderately modified
41-60	D	Largely modified
21-40	E	Highly degraded
0-20	F	Extremely degraded

South Africa is a signatory to various international conventions, including the RAMSAR Convention on Wetlands and is consequently obligated to conserve its biodiversity. Under the Ramsar Convention, South Africa currently has 20 designated wetlands of international importance, seven of which are in the KwaZulu-Natal province. The St Lucia and Mfolozi estuaries have RAMSAR status and are conserved as a World Heritage Site. They comprise the oldest conserved estuary system in the World. Despite this protection status it is recognised these systems have been increasingly influenced by anthropogenic interaction and stresses, which has led to their designation as 'significantly modified' systems. Consequently it has also become imperative to elucidate the economic value of these and other estuaries in order to ensure that their future health is improved and maintained.

ECOSYSTEM SERVICES

Estuaries, like other ecosystems, offer a range of goods, services and attributes that generate value and contribute to human welfare (Barbier, 1994). The concept of ecosystem goods and services stems from the perception of ecosystems as natural capital which contributes to economic production. Goods include harvested resources, such as fish, services are processes that contribute to economic production or save costs, such as water purification and attributes relate to the structure and organisation of biodiversity, such as beauty, rarity or diversity, and generate less tangible values such as spiritual, educational, cultural and recreational value. Goods, services and attributes are often referred to collectively as 'ecosystem services', or 'ecosystem goods and services'. More recently, the Millennium Ecosystem Assessment (MA) (2003) categorized the services obtained from ecosystems as follows:

- Provisioning services such as food and water.
- Regulating services such as flood and disease control.
- Cultural services such as spiritual, recreational, and cultural benefits.
- Supporting services, such as nutrient cycling, which maintain the conditions for life on Earth.

The first three align well with the definitions of goods, services and attributes described above. The fourth, supporting services, has created some controversy as inclusion of these 'services' in a valuation study can lead to double counting. It does, nevertheless, highlight the fact that the other services cannot be generated without these underlying processes.

Ecosystem valuation has generally been undertaken within the framework of Total Economic Value (TEV; Pearce & Turner, 1991), which includes direct use, indirect use and non-use values. Direct use values result from economic activity and are generated through the consumptive or non-consumptive use of natural resources. Indirect use values result from regulating services which may either generate outputs that form inputs into production processes elsewhere (in other words the benefits are realised off-site), or they result in engineering cost savings by performing functions that would otherwise require costly infrastructure or man-made processes. Option value is the estimated future value of resources and services offered by ecosystems such as possible medicinal, leisure, agricultural or industrial uses (Pearce & Turner, 1991). Existence value is the value of simply knowing that natural resources or biodiversity are protected (Pearce & Turner, 1991).

Provisioning services

Plant resources

Estuaries provide several resources which can be harvested, including raw materials (e.g. mangroves, reeds and sedges), wild foods and medicines. Some of the more important plant resources include Ncema rushes (Juncus kraussii) used to make traditional Zulu sleeping mats, reeds (Phragmites spp.) used in the building of traditional walls, sedges used for craft work, mangroves used to make fish traps, and fuel wood (mainly Syzigium cordatum).

Ncema is a valuable resource that has been completely overexploited outside protected areas (Kyle, 2010). Ncema collection is allowed around the St. Lucia estuary over a ten day period during winter. It also occurs all year round in the northern portions of the Park where control is difficult (Kyle, 2010). About 305 568 kg of Ncema was harvested during 2009 from the coastal areas of the Park. This was concentrated around Kosi Bay (34.3%), St. Lucia mouth (18.5%) and Cape Vidal (17.7%). The number of people utilising the resource was estimated at 25 per day at the time of the study and had increased from five in 1980. Kyle (2010) estimated the value harvested from coastal reserves and protected areas during 2009 to be in the region of R1.2 million.

Table 6. Types of services provided by inland wetlands, based on Costanza et al. (1997) and the Millennium Assessment (2003).

Types of Services		**Description**
Provisioning services	**Water**	Provision of water for livestock or domestic use
	Food, medicines	Production of wild foods and medicines
	Grazing	Production of grazing for livestock
	Raw materials	Production of fuel, craftwork materials, construction materials
	Genetic resources	Medicine, products for materials science, genes for resistance to plant pathogens and crop pests, ornamental species
Regulating services	**Climate regulation**	Carbon sequestration. Wetlands are believed by some to be carbon sinks that contribute towards reducing carbon emissions
	Water regulation	Flood attenuation – Reduction of the amplitude and velocity of flood waters by wetlands, reducing downstream damage
		Groundwater recharge – Differential recharge to groundwater relative to surrounding vegetation types
		Dry season flows – Moderating the seasonality of downstream flows
	Sediment retention	Retention of soil and fertility within an ecosystem
	Waste treatment	Breaking down of waste, detoxifying pollution; dilution and transport of pollutants
	Regulation of pests & pathogens	Change in ecosystem health affects the abundance or prevalence of malaria, bilharzia, liver fluke, black fly, invasive plants, etc.
	Refugia	Critical breeding, feeding or watering habitat for populations that are utilized elsewhere
Cultural services	**Abundance, rarity and beauty of species, habitats and landscapes**	Providing opportunities for : Cultural activities and heritage Spiritual and religious activities and wellbeing Social interaction Recreational use and enjoyment Research and education

Reeds are primarily collected in a number of northern protected areas, particularly Western Shores, Ozabeni and Kosi Bay (Kyle, 2010). The collection of reeds is on an *ad hoc* basis, making it difficult to accurately predict precise details of collection. Kyle (2010) estimated the value harvested from coastal reserves and protected areas during 2009 to be in the region of R840 000. Some 557 639 kg of sedge was harvested in 2009, with 96% located in Ozabeni (in the iSimangaliso Wetland Park) and Sodwana Bay (Kyle, 2010).

The estimated value of plant resource use for Kosi, St Lucia, Mlalazi, Siyayi and Matigulu were obtained from Kyle (2010), and the values for the remaining estuaries were estimated on the basis of average value per ha (Table 7).

Small-scale fisheries

Local indigenous people have fished in the Kosi lakes for many generations using traditional methods such as fish traps, spears and baskets. About 90% of the fish caught in traps were of marine origin, with several mullet species and spotted grunter the most important species caught, although the catch composition varied annually. Fishing in the reserve has been found to be sustainable in the past (Kyle, 1999). There are about 120 trappers operating 150 traps (Lamberth & Turpie, 2003). In addition to traditional fishing, there are about 45 gillnet permits rotating amongst approximately 90 people in Kosi Bay, plus about 90 regular illegal gillnetters (Lamberth & Turpie, 2003). In 2009, the fishery catches were estimated at 104 tonnes of fish, 3.8 tonnes of crabs and 1 tonne of prawns, worth about R3.33 million in total (Kyle, 2010). Kosi Bay is the site of the only-small scale commercial bait fishery, located within a protected area in South Africa (Kyle, 2010). The fishery is focused on pumping sandprawn Callianassa kraussi which are sold to recreational anglers in the Kosi Bay area. The focus of this small scale fishery is around the Makawulani and Mpungwini lakes, which generated R 81 600 in value from the sale of 1020 kg of bait (Kyle, 2010).

Illegal gillnetting has been taking place in Lake St Lucia since the 1960s (Mann, 1993). Most of the fish caught are consumed locally, although some species such as prawns are sold further afield. Results of a study that commenced in 1990 indicated that some 72 people were involved in gillnetting and they owned some 10 km of gill nets. In 1992 the estimated annual catch was between 90 and 130 tonnes with some 50% of the catch composed of detritivorous species such as mullet. Using the findings from Kosi Bay, these catches might be expected to be worth in the order of R1.35 million. Based on the success of the legal gillnetting system in Kosi Bay as described above, a similar project was launched on an experimental basis in Lake St Lucia, with an initial 30 nets of 30 m in length permitted. In 2002 there were an estimated 37 gillnet permits with an additional 270 people operating illegally (Lamberth & Turpie, 2003). In 2009, total fish catch was estimated to be only 8 tons, worth R240 000 (Kyle, 2010). However, the fishery would have been badly impacted by prolonged mouth closure up to the present time (end 2010).

There is also a small experimental gillnet fishery in the Msunduzi/Mfolozi system with about 28 fishers. There is one seine netting permit in Richards Bay. Illegal seine netting takes place in the Richards Bay, Mhaltuze, Amatikulu/Nyoni, Mlalazi, Nhlabane and Mfolozi estuaries. Very little is known about these fisheries, however. Kyle (2010) estimated the Umlalazi and Amatikulu fisheries to be worth about R60 000 and R27 000, respectively. Values for the remaining estuaries were estimated on the basis of average value per ha of water area, including intertidal and mangrove habitats (Table 7). Note that older information was used to estimate the value of St Lucia, since the most recent data are from a period of extreme drought and may not include illegal fishing.

Table 7. Provisioning values of estuaries in R millions (2009). Values apply to the more inclusive estuary areas (Table 1).

Estuary	**Fuel and other wood**	**Non woody plant resources**	**Fisheries**	**Total**	**Total R/ha**
Kosi	685 250	604 338	3 131 010	4 420 598	958
Mgobezeleni	0	0	0	0	0
St Lucia	0	1 046 825	1 350 000	2 396 825	50
Mfolozi	0	303 621	46 506	350 127	49
Nhlabane	0	50 440	398 198	448 638	380
Mhlathuze/RB	0	151 618	1 196 954	1 348 572	380
Mlalazi	0	8 860	60 000	68 860	682
Siyaya	20	0	0	20	2
Matigulu/Nyoni	0	8 860	27 000	35 860	64

Regulating services

Regulating services provided by estuaries relate to their functional capacity to regulate essential ecological processes through bio-geochemical cycles and other natural ecological processes (de Groot *et al*., 2002). The regulating services estuaries where a tangible value can be derived include carbon sequestration, nursery and refugia functions as well as sediment and nutrient exports.

Carbon sequestration

Climate change caused by increases in the emissions of greenhouse gases will carry a cost of about 2-7% of Gross Domestic Product (GDP) by 2050 (Fankhauser & Tol, 1997). The value of carbon sequestration by ecosystems is derived from the damage caused by increasing atmospheric carbon and resultant global climate change that can be offset through carbon uptake in these ecosystems.

Estuarine wetlands are especially efficient at carbon storage, without a significant release of greenhouse gases due to the inhibition of methanogenesis by sulphates (Magenheimer *et al.,* 1996). As distance from the tidal source increases carbon densities have been shown to increase whereas accretion rates have been shown to decrease (Chmura *et al.,* 2001). Therefore the estuarine wetlands contained within the study region can be assumed to be net sinks for carbon, and valued accordingly for this service.

Mangroves are also of significant value in sequestering carbon dioxide due to their high productivity (Ayukai, 1998). The key carbon sinks associated with mangroves are the fixation of carbon in local or adjacent systems and photosynthetic uptake of carbon through net growth of forest biomass (Bouillon *et al.,* 2009). High carbon fixation rates in mangrove sediments is significantly aided by low anoxic, low pH conditions in mangrove ecosystems (Ayukai, 1998). The long term rate of carbon accumulation in sediment by mangroves has been estimated at 139 g C m^{-2} y^{-1} (Laffoley & Grimsditch, 2009).

Using estimates from the literature for mangroves, swamp forest, floodplain grassland and sedge/reed marshes, the carbon sequestration capacity of the estuaries of the study area was estimated on the basis of habitat areas. The value of the service was based on the average global trade price for carbon sequestration between 2005 and 2009, of about US$20 per ton (Arntzen 2010; $1 = R7.43).

The total value of carbon sequestration by estuaries of the Usutu to Mhlatuze catchment was estimated to be in the order of R3.5 million per annum (Table 9). St Lucia Estuary has the highest estimated carbon sequestration value, of over R2.4 million per annum. Other estuaries with a high value were the Richards's Bay and Mfolozi estuaries, with values of R294 450 and R511 328 respectively. However, note that the latter includes a much greater area than the strictly estuarine area, which may be as small as 138 ha. The Nhlabane and Siyaya estuaries probably have negligible value in this regard.

The value of this service therefore arises as a result of avoided damage as well as revenue generating opportunities. There are already existing markets for carbon, both in terms of voluntary and certified credits and new financial mechanisms includes funding that is as a result of Reducing Emission from Deforestation and Degradation (REDD). In addition there is emerging architecture on ‘credits’ that have financial value in terms of additional services provided by ecosystems, for example water purification and biodiversity habitats. The scale of the St. Lucia estuary and its tourism and conservation importance to South Africa means it is poised as potential case to pilot these emerging markets.

Table 8. Total value of carbon sequestration by estuaries within the study area, using the more inclusive estuary areas.

Estuary	**Total Ha**	**Carbon sequestered (tons/y)**	**Total (R/y)**
Kosi	4 615	1159	168 504
Mgobozeleni	234	434	64 444
St Lucia	47 981	16 282	2 411 370
Mfolozi	7 108	3 625	511 328
Nhlabane	1 181	0	0
Richards Bay/Mhlatuze	3 550	2 007	294 450
Mlalazi	101	99	13 819
Siyaya	8.9	0	0
Matigulu/Nyoni	562	12	1 843
Total	**65 340**	**23 619**	**3 465 758**

Exports to marine ecosystems

Fish exports

An important value of estuarine systems is their contribution to commercial and recreational fisheries in the inshore marine area. Lamberth & Turpie (2003) estimated the value of the contribution made by estuaries to inshore marine fisheries in South Africa (not including prawn fisheries). This value was estimated to be about 21% of the total value of fisheries, based on the proportion of estuarine species in the catch and their degree of dependence on estuaries. For KwaZulu-Natal, the value of inshore marine catches attributable to estuaries was 26.2%, and thus higher than the national average.

Inshore marine fishing takes place by recreational shore-angling, recreational boat-angling, recreational spear-fishing and commercial fishing operations through boat-based line fishing, gill netting and beach-seine netting. It was estimated that total shore-angling effort amounts to approximately 2 778 000 days per annum, with 53% of this taking place in KwaZulu-Natal. Data were not provided at a provincial level for the other inshore fishing activities. It was estimated that there were 2 747 tons of inshore marine catches in KwaZulu-Natal per annum, with recreational fishing being relatively more important than commercial catches.

Lamberth & Turpie (2003) estimated the total contribution of all South African estuaries to coastal and inshore marine fisheries to be R490 million in 1997 Rands (R995 million in 2009 Rands), of which the 73 estuaries of the KZN coast were estimated to contribute R89.3 million per year (R181 million in 2009 Rand). Given the total estuarine water area of 46 811 ha in KZN, this translates to about R3 873 per ha per year in 2009 Rands. This does not include the direct value of estuary fisheries, discussed under the section on provisioning services. The nine estuaries of the Usutu to Mhlatuze WMA make up some 96.7% of the total KZN estuarine area, and hence have a total estimated nursery value of R176.9 million. In order to estimate how this value is spread among the estuaries of the KZN coast, and within that, of the Usutu to Mhlatuze WMA, the value was divided among estuaries on the basis of their contribution to the total estuarine area. When apportioning the value across the area, it is important to note that not all systems function optimally and will therefore likely differ in the true value of exports from the system.

Prawn exports

Five species of penaeid prawns are found within the St Lucia lake system, namely; white prawns, tiger prawns, speckled prawns, ginger prawns and green prawns. White prawns are the most abundant and make up 84% of the population (Joubert & Davies, 1966). In 2003 the KwaZulu-Natal crustacean fishery was estimated to be worth some R40 million (Turpie & Lamberth, 2004), equivalent to about R56 million in 2009 Rands. Inshore prawn catches were estimated to contribute about a 23% of this value, and offshore prawn catches contributed 50% and the remaining value is from other crustaceans and bycatch. Kyle (2010) estimated the prawn harvesting that occurs in the protected areas, especially within the coastal regions of iSimangaliso Wetland Park during 2009 amounted to R81 600.

Both the inshore and offshore populations are reliant on sediment and nutrient outputs from rivers and (or via) estuaries. It is sediment outputs from these systems that have created and continue to maintain the banks from which the prawns are fished, and the nutrient outputs from these systems are a critical input in an otherwise nutrient-poor environment. Reductions in outputs from these estuaries will thus lead to a slow decline in the fishery. In the past few years, the inshore, shallow water fishery has effectively collapsed as a result of poor catches, these declines being largely attributed to the loss or inaccessibility of nursery grounds.

Along the KZN coast three systems provide the majority of the suitable nursery habitat for penaeid prawns (*viz.* St Lucia, Richards Bay and the Mhlatuze Estuary), all of which fall within the study area and all of which have been impacted in one way or another. Penaeids have been recorded in many other estuaries but are not found in high numbers and therefore these are not considered to constitute significant nursery areas (DWAF, 2004). Based on expert experience of the prawn populations of these estuaries, it can be assumed that the three estuaries mentioned above each historically contributed about a third of the nursery function to the inshore prawn species (N. Demetriades, pers. comm.).

Sediment and nutrient exports

An additional important service that can be valued is the provision of sediment and nutrient outputs, which both the inshore and offshore populations are dependent upon. Rivers north of Durban that provide significant sediment and nutrient outputs to the coastal zone include the Umgeni, Umvoti, Mlalazi, Thukela and Mfolozi. Although the smaller systems provided fairly regular inputs to the coastal zone, the Thukela system dominates, providing more than 50 % of the total run off from all KZN rivers in most years (DWAF, 2004). The value provided by the individual systems is proportional to the volume of their water outputs.

Prawns are economically important as they are harvested commercially offshore on the Tugela Banks. The prawn-bait fishery which operated for 40 years in the St Lucia Narrows was closed down in 1995. The prolonged closure of the St Lucia Estuary mouth during the past decade has had a devastating impact on the migration of prawns into and out of the system, and illustrates the vital role of marine connectivity in the life cycles of these and other estuary-associated invertebrates (Joubert & Davies, 1966). In addition, the Mean Annual Run-off (MAR) from rivers in the region may also have an influence on the productivity of the prawn fishing banks and the current percentage contribution of each system is shown in Table 10.

Table 9. Simulated natural and present-day MAR for the estuaries that have an influence on the prawn fishing banks, and the current % contribution of each estuary (DWAF, 2004).

Catchment Name	**MAR (1980-1989)**			
	Natural MAR	**Present-day MAR**	**% of Natural**	**% of Total**
Mkuze River	407.57	192.95	47.3	2.85
Mzinene River	42.93	42.93	100.0(2)	0.63
Hluhluwe River	79.99	79.99	100.0(2)	1.18
Nyalazi River	78.22	78.22	100.0(2)	1.15
Mfolozi River	1366.23	1309.11	95.8	19.33
Mhlathuze River	648.56	201.37	31.0	2.97
Mlalazi / Siyai Rivers	183.78	183.78	100.0(2)	2.71
Matigulu / Nyoni Rivers	274.28	274.28	100.0(2)	4.05
Thukela River	4674.17	3353.23	71.7	49.50
Mvoti River	454.33	456.98	100.6(3)	6.75
Tongati River	115.04	115.25	100.2(3)	1.70
Mgeni River	908.58	485.55	53.4	7.17
Total	**9233.68**	**6773.64**	**73.4**	**100.00**

Notes: (1) *Surface Water Resources of South Africa 1990 (1920-1989)*
(2) *Only WR90 data available*
(3) *ACRU data used*

Total export value

The reliance of the industry on two types of functions produced by different systems necessitated a double-counting valuation approach. This means that the sum of the values attributed to estuaries does not equal the value of the industry, but the value of an individual system represents the value that would be lost if the estuary were lost. Values estimated for each estuary are summarised in Table 10. These amounted to a total estimated value of R206 million per annum.

Table 10. Estimated export values associated with each of the estuaries of the Usutu to Mhlatuze WMA (2009 Rands).

Estuary	**Water area (ha)**	**Fish exports (R/y)**	**Sediment & nutrient exports (R/y)**	**Prawn exports (R/y)**	**Total R/y**
Kosi	4238	18 352 653			**18 352 653**
Mgobezeleni	7	30 313			**30 313**
St Lucia	33084	143 270 214	3 253 600	3 966 667	**150 490 481**
Mfolozi	55	238 177	10 824 800		**11 062 977**
Nhlabane	6	25 983			**25 983**
Richard's Bay/Mhlatuze	3205	13 879 248	1 663 200	3 966 667	**19 509 115**
Mlalazi	177	766 498	1 509 074	3 966 667	**6 242 239**
Siyaya	1	4 330	8 526		**12 856**
Matigulu/Nyoni	124	536 982			**536 982**

Cultural services

The aesthetic and cultural values of ecosystems are derived from their attributes such as beauty and rarity. These attributes determine whether an area is suitable or attractive for recreational use, religious ceremonies or spiritual fulfilment. Some of the more intangible aspects of these values are extremely difficult to estimate, even when applying best-practice comprehensive survey methods. However, some of the more measurable manifestations of these values include the expenditure that people incur in order to view or visit estuaries (tourism value), and the extra amounts, or premiums, that people pay for properties in order to have access to or views of an estuary (property value).

TOURISM AND RECREATION

Estuaries are a major drawcard for tourism and recreational activities within South Africa. The value derived from tourism manifests itself in two main ways in the economy. Namely the expenditure by visitors in terms of trade sector turnover and investment in property through real estate turnover. In order to derive the corresponding the contributions, estuaries need to be isolated. Focusing on the tourism sector turnover, the visitor expenditure attributed to estuaries is between 20-30% of total tourism expenditure in coastal resort areas (Turpie & Joubert, 2005; Turpie, 2006).

Estuary angling

St. Lucia was one of the most popular recreational angling destinations in the country, attracting over 150 000 anglers per year (Mann, 1993). The indirect financial benefits of this industry include tourism, tackle, boats, vehicles, and bait, however, they have not yet been evaluated (Mann, 1993). In 1989, recreational angling was reportedly increasing by 6% per annum, which raised concerns about the sustainable use of St. Lucia's fish resources. In the past decade fish kills in Lake St Lucia arising from the extreme hypersalinity and evaporation of surface waters have had a major negative effect on the recreational fishery in the area.

Lamberth & Turpie (2003) estimated that the recreational angling effort for two of the estuaries in the study area were 10 000 boat-angler outings per annum in Kosi Bay and 30 000 boat-angler outings and 18 000 shore-angler outings in St Lucia. While recreational angling may occur on some of the other systems, this is unlikely to be to a significant degree. Based on the average value per angler day in Lamberth & Turpie (2003), inflated to 2009 values, the recreational angling value of Kosi Bay and St Lucia were estimated to be about R11 million and R52.8 million, respectively. This is a conservative estimate, in that it does not take into account the changing angling effort that might have occurred in the intervening period.

Nature based tourism

Creemers *et al*. (1995) made a rough estimate of the economic contribution of tourism in the iSimangaliso Wetland Park (previously the Greater St. Lucia Wetland Park) to refute an estimate by the environmental impact assessment (Anon, 1993) for the proposed mining in St Lucia which placed a value for tourism benefits due to mining at between R30 and R70 million. Creemers *et al.* (1995) argued that St. Lucia's high biodiversity value, its World Heritage Site and RAMSAR status rank it amongst the key protected areas in the country for tourism, and estimated that its tourism value could be in the order of R300 million per annum rather than the lower figure presented in the EIA (equivalent to R711 million in 2009 Rands).

Turpie (2005) estimated the total number of visitor beds in the Greater St Lucia Wetland area (St Lucia, Eastern and Western Shores, Ozabeni, Sodwana and Kosi) to be about 15 000 in 2004. Based on an assumed average occupancy of 44% and an average expenditure of R200 per person per night, the turnover in the accommodation sector was estimated at being in the region of R500 million, or R690 million in 2009 Rands. This is in keeping with the magnitude of the Creemers *et al*. (1995) estimate.

A visitor survey conducted by Turpie (2005) established the degree to which the visitor experience was derived from different habitats in the park, including the estuaries. Based on these findings the overall tourism value of the estuaries of Isimangaliso Wetland Park was estimated to be in the order of R170 million per annum (Table 12).

The iSimangaliso Wetland Park has been identified as one of the five most important ecotourism destinations in South Africa (Parris *et al.*, 1992), with anglers making up approximately 60% of all visitors in the late 1980s. Fish are thus a valuable resource to St Lucia in terms of its natural functioning as well as for ecotourism. Bird watching tours for overseas visitors are also a major industry and fish populations contribute to the maintenance of a diverse and abundant bird life.

Table 11. Estimated tourism value of the estuaries of the Isimangaliso Wetland Park (IWP), based on survey data presented in Turpie (2005).

Area	**Estimated % of the IWP beds**	**% of visitor experience attributed to estuaries**	**General tourism value attributed to estuaries (Rm/y)**	**Estuary**	**Estuary value (Rm/y)#**
Kosi	8%	42	21.9	Kosi	22.2
Sodwana	14%	4	3.8	Mgobezeleni	0.00012
Cape Vidal	2%	9	1.1	St Lucia	148.1
St Lucia town	64%	20	91.0		
Inland St Lucia	13%	60*	52.6		
Total			**170.4**		**170.4**

* No data, estimated in this study.

the value to Sodwana visitors was distributed to the area of all estuaries in the park.

Based on a survey of over 500 bird watchers conducted during 2009 it was estimated that 4.5% of national birding time in South Africa was spent in KwaZulu-Natal estuaries, translating to a value of R39.5 million per annum. Apportioning this value among the estuaries of the province, this amounts to just under R550 per ha per year, with the estuaries of the study area having most of the value (Table 13). In order to avoid double counting, however, the values associated with the Isimangaliso estuaries (Kosi, Mgobezeleni and St Lucia) were assumed to be included in the general nature-based tourism value estimated for the wetland park above. Thus the total value of tourism in estuaries was estimated to be R177 million (Table 13).

Table 12. Estimated value of bird watching and overall tourism value attributed to each of the estuaries of the study area.

Estuary	**Size (ha) (inclusive estimate)**	**Total birding value R/y**	**Total tourism value**	**R per ha**
Kosi	4 615	2 526 981	22 263 604	4824.48
Mgobezeleni	234	127 980	127 980	547.59
St Lucia	48 209	26 398 693	148 149 414	3073.08
Mfolozi	7 108	3 892 342	3 892 342	547.59
Nhlabane	1 181	646 539	646 539	547.59
Richard's Bay/Mhlatuze	3 650	1 999 091	1 999 091	1 095
Mlalazi	9	4 889	4 889	547.59
Siyaya	562	307 741	307 741	547.59
Total		**35 904 256**	**177 083 859**	

SCIENTIFIC AND EDUCATION VALUE

Placing a tangible measure on the scientific and educational value of the aquatic ecosystems in the area is difficult. In the absence of a direct metric to quantify scientific and educational value, government payment for research output was taken as a proxy for calculating the scientific value of the key aquatic ecosystems in the area. Payment for academic output stems from the Policy for Measurement of Research Output of Higher Academic Institutions, under the Department of Education. The purpose of the policy is to encourage research productivity by fiscally rewarding research output from public higher education institutions, to the tune of R80 000 per peer reviewed publication. In order to obtain an estimation of scientific value within a relevant timescale, a literature research of journals was carried out between 2005-2010, for all relevant articles on aquatic ecosystem resources within the study area, using three search engines (Web of Science; Africa-Wide: NiPad – which includes the South Africa Studies database; and Water Resources World Wide). This yielded an average annual output of R0.4 million per year.

Total value

The total value of the estuaries in the study area was estimated to be in the order of R396 million per annum (Table 14). Regulating services were the most important value, amounting to some R209.5 million. Cultural services amounted to at least R175 million, with the majority of this derived from tourism activities. The lowest value of estuaries came in terms of their provisioning services, namely fishing in the estuaries which derived a value of R6.9 million. St Lucia accounted for nearly 80% of the value.

Table 13. Value of provisioning, regulating and cultural services from the nine estuaries.

	Provisioning		***Regulating***		***Cultural***		
	Plants	**Fishing (Rm)**	**Carbon sequestration (Rm)**	**Nursery & export (Rm)**	**Tourism (Rm)**	**Scientific (Rm)**	**Total (Rm)**
Kosi	1.3	3.1	0.2	13.6	22.3	0	40.5
Mgobozeleni	0.0	0.0	0.1	0	0.1	0	0.2
St Lucia	1.0	1.4	2.4	155.5	148.1	0.2	308.6
Mfolozi	0.3	0.0	0.5	11.5	3.9	0	16.2
Nhlabane	0.1	0.4	0	0.1	0.6	0	1.2
Richards Bay/Mhlatuze	0.2	1.2	0.3	19.1	2.0	0.1	22.8
Mlalazi	0.0	0.1	0	5.4	0.0	0	5.5
Siyaya	0.0	0.0	0	0.1	0.3	0	0.4
Matigulu/Nyoni	0.0	0.0	0	0.7	0.0	0	0.7
Total	2.9	**6.2**	**3.5**	**206**	**177.4**	**0.4**	**396.3**

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THE ST LUCIA MFOLOZI/MSUNDUZI INDABA: A REVIEW AND CONSIDERATION OF FUTURE RESEARCH NEEDS

AT Forbes*

Marine & Estuarine Research, Durban
**Email: ticky@mer.co.za*

INTRODUCTION

The above meeting took place at the Ezemvelo KZN Wildlife offices at St Lucia over the period 3-5 May 2010. Sponsorship was provided by the South African Water Research Commission (WRC) and the workshop was convened under the aegis of the Consortium for Estuarine Research and Management (CERM) and organized under the leadership of Prof. Alan Whitfield and co-ordinated by Prof. Guy Bate. South African estuarine specialists who had information on physical, biological, management, conservation or economic fields relating to the Mfolozi/Msunduzi system, were invited to attend the workshop. In addition, representatives from the local Mfolozi sugar cane industry and interested CERM members were invited to attend. All delegates were given the opportunity to make oral presentations and to provide written submissions for ultimate inclusion in a WRC report.

The original intention of the workshop was to focus on the Mfolozi and Msunduzi estuarine complex for which, particularly from a biological point of view, there was less information available than existed for the relatively well-worked St Lucia Narrows and Lake. However, the conditions in the Narrows and the Lake, including the closure of the mouth from 2002 onwards and the unprecedented drying up of the lakes during the last 10 years was also discussed. In addition, the controversy over mouth manipulation generated a momentum towards focusing on the role and significance of the Mfolozi/Msunduzi complex on the functioning of the greater St Lucia wetland system.

The workshop incorporated the following major components:

- history of the system, with particular emphasis on the changes ascribed to canalisation and farming on the Mfolozi floodplain;
- five presentations dealt with various aspects of the sedimentology and geomorphology of the Mfolozi floodplain and mouth, mouth dynamics and hydrology;
- five presentations dealt with the biota of the two estuaries;
- two presentations dealt with the resource economics of the Mfolozi floodplain and also with the greater Lake St Lucia complex in a comparative context with other north-eastern KwaZulu estuaries.

At the request of the Mfolozi sugar industry representatives at the workshop, the Chair of the meeting granted their representative an opportunity to present their ideas on possible solutions to the problems of St Lucia. Their contribution is included in this report.

The workshop concluded with a question and answer session during which presenters were given the opportunity to clarify aspects of their contributions. Delegates were then asked individually to contribute any ideas that they considered worthy of research effort. They were further asked to select three priority ideas from all those presented and these were subsequently scored and ranked.

This section will provide a commentary on the presentations listed above and conclude with a summary and synthesis of what were regarded by the delegates to be prime and necessary research fields.

COMMENTARY

The historical perspective provided some useful background and an account of human activities, particularly in the Mfolozi floodplain, as well as those involved in mouth manipulation and engineering actions and developments.

What might be called the ‘physical’ contributions were highlighted by the submissions of van Heerden and Lawrie, Chrystal and Stretch, particularly in relation to their respective dealings with sediment dynamics on the floodplain and mouth region, as well as the modeling of mouth behaviour and salinity in the greater system under different mouth conditions. These papers also provided corroborating evidence for the fate of Mfolozi sediments which were not recorded in the Narrows or Lake. Van Heerden’s elegant analysis and description of the processes involved in sediment settlement and compaction on the floodplain, the fate of transported material arriving on the Mfolozi floodplain during Cyclone Domoina in 1984 and the subsequent erosion of the Maphelane dune and the Honeymoon Bend area during the cyclone, is a model of field data collection and intelligent interpretation. The conclusive demonstration of a metre or more of subsidence in large areas of the eastern sector of the cultivated floodplain as a result of clearing, drainage and isolation from sedimentary inputs, provided a graphic explanation as to why these areas had become more susceptible to flooding during spring high tides when the mouth is open or following mouth closure and backflooding. When coupled with sea level rise, and the inevitability of further subsidence under present conditions, this will obviously become a major consideration in future management plans for the area.

A significant aspect of the van Niekerk & Huizinga submission was that it indicated a substantial variation in suspended sediment carried by the Mfolozi, ranging from 2-3 g l^{-1} during summer highflows to less than 0.1 g l^{-1} during winter. Possibly more significantly, and which was corroborated by van Heerden, was the huge variation in Mfolozi River flow. Both agree on a mean annual runoff (MAR) in the region of 900 x 10^6 m^3 but van Niekerk & Huizinga refer to a flow equivalent to 14% of the MAR in 1982 followed by 420% in 1983. Seasonal flows range from 7% of the MAR during June-August to 47% between January and March. At the other end of scale van Heerden refers to 55 years of data between 1921 and 1975 when the MAR was exceeded during each of 20 single months.

Despite the above variability there is no historical record, legend or folk story to say that the drying up of the lake in the early 2000s had any precedents. Longer periods of below average rainfall have occurred in the past (*vide* Lawrie, Chrystal & Stretch) when the lake apparently did not disappear, and it is highly significant that the drying up of the lake this century occurred within three years of the onset of the present dry period. Definitive data on flows in the four rivers feeding directly into the lake, which might give an indication of anthropogenic flow reduction, unfortunately do not appear to be available. It is therefore not immediately possible to assess the extent to which any reduced flow in these rivers exacerbated the impacts of the isolation of the Mfolozi, or conversely the extent to which unmodified flows might have mitigated the impact of the isolation of the Mfolozi. The model developed by Lawrie, Chrystal & Stretch suggests that with separate mouths for the Mfolozi and St Lucia systems and an Mfolozi input via the back channel, the St Lucia mouth would have been closed 83% of the time, thereby seriously impacting on fish and invertebrate migrations and consequent nursery functions.

The submissions on the biota of the Mfolozi/Msunduzi estuarine zones, especially those on the benthos and fish, provide very valuable insight on these environments. The botanical contribution is significant in that the dominance in the wetland areas by reeds and swamp forest (rather than mangroves) is indicative of a system which has historically closed and subsequently backflooded as a result of continued riverine inputs, thereby favouring the reed/swamp forest complex which can survive these conditions. Although not mentioned in the submissions, the absence of the burrowing crustaceans *Callianassa kraussi* – the sandprawn and *Upogebia africana* – the mudprawn, also correlates with a temporarily open/closed mouth condition. *U. africana* has a marine larval phase in the life cycle and mouth closure during migration periods would disrupt the life cycle (Wooldridge, 1991; Wooldridge & Loubser, 1996). *C. kraussi* can breed in temporarily closed estuaries but requires a minimum salinity of about 50% seawater for successful reproduction (Forbes, 1973, 1978). As both species occur in estuaries to the north and south of the St Lucia complex, it is arguably the conditions resulting from periodic mouth closure and prolonged low salinity that excludes these species. However, without long-term observations on mouth state, it is obvious that the length of these closed periods can only be a guess.

The contributions from the Coastal Research Unit of Zululand (CRUZ) are significant in that they provide a preliminary answer as to whether the Mfolozi/Msunduzi is presently acting as a mini St Lucia lake system (particularly as a nursery ground for fish and invertebrates) and also whether the non-migrant benthic fauna in these systems could serve as a source of replacement for species lost from the main St Lucia environment. A total of 50 fish species was recorded in the Mfolozi/Msunduzi system and attention was drawn to the species size composition which was dominated by the juveniles, with very few adults present. Zoobenthic feeding fish were generally poorly represented and the juveniles of these species declined in abundance following the dietary switch from zooplankton to zoobenthos, as might have been expected on the basis of the relatively impoverished benthic fauna. The absence of molluscs from the system was a feature and contrasts with the abundance of this taxon in Lake St Lucia. Overall it appears that the combined Mfolozi/Msunduzi system does play a role as an estuary and provides estuarine nursery grounds for selected species. However, even for these taxa this role is limited when compared to the greater St Lucia environment. There is also strong evidence provided by Bickerton's contribution that the role of the Mfolozi system as a source of freshwater prawns (*Macrobrachium* spp.) to the Narrows and Lake St Lucia has been severely compromised by the artificial separation of the Mfolozi/Msunduzi system from St Lucia.

The presentation by the farmer/engineer consortium was focused on freshwater availability and provided several potential options focused on engineering possibilities, mainly inter-basin transfer and the damming of tributary rivers with the aim of stabilising freshwater inputs to Lake St Lucia.

FUTURE RESEARCH POSSIBILITIES

The discussions at the end of the workshop culminated in the formulation of 45 suggestions for further research, many of which had some degree of commonality, *e.g.* sediments loads, sediment transport, natural mouth dynamics, mouth manipulation, etc. Subsequent voting by the delegates on which suggestions they considered more (or most) important provided a priority listing and also generated 16 zero scores (presumably indicating less significant suggestions).

For practical reasons only the top 10 research topics will be given further consideration, namely:

- Data requirements: Digital elevation model, bathymetry, topography.
- Adaptive management protocol for immediate implementation.
- Vegetation map with digital elevation model and LIdar with bathymetry.
- Options for introducing Mfolozi/Msunduzi water, including use of dams.
- Abiotic consequences: Sediment processes in the catchment and floodplain.
- Recruitment study: Mangroves, fish and invertebrates, including all manner of connectivity, *e.g.* back-channel, mouths and overwash of seawater into the estuary.
- Estuarine Water Reserve: Estuarine health assessment for the Greater St Lucia system.
- Implications of sea level rise and climate change to subsistence agriculture.
- Biotic response of introducing Mfolozi/Msunduzi water into St Lucia.
- In the case of a combined mouth, what would be the role of the Mfolozi/Msunduzi?

Top priority was allocated to “data requirements” incorporating a “digital elevation model, bathymetry and topography” of the Mfolozi/Msunduzi. An “adaptive management protocol for immediate implementation” was the second priority. In the absence of any additional clarifying information, this presumably refers to the development of a protocol which will allow the implementation of immediate short-term interventions designed to alleviate the current condition, especially relinkage of the Mfolozi system to St Lucia. The third priority was for a vegetation map of the Mfolozi/Msunduzi floodplain incorporating a digital elevation model and bathymetry of the area. The fourth priority was for an investigation of the options for restoring Mfolozi/Msunduzi water to Lake St Lucia and the possible significance of dams in this option. This could probably be linked to the 10th priority which referred to the “role” of the Mfolozi/Msunduzi in a combined mouth situation. The 5th priority was for the investigation of historical and present sedimentary processes in the catchment and floodplain. Priorities 6-10 included studies of the immigration/emigration of fishes and invertebrates, dispersal of animals through increased water connectivity, the transport of mangrove propagules and the influence/significance of the introduction of Mfolozi/Msunduzi water to the St Lucia system. Further recommendations were for an estuarine health assessment of the “Greater St Lucia system” and an investigation of the effects of sea-level rise and climate change on the Mfolozi/Msunduzi floodplain in particular.

Lower ranked questions could at times be considered to fall within the ambit of some of the perceived priorities listed above but it was notable that aspects such as nutrient dynamics, particularly flow reduction in the rivers feeding directly into the lake, were not highlighted. This may be because the brief of the workshop was to focus on the Mfolozi/Msunduzi system and not Lake St Lucia.

Although not rated highly by comparison with the physical and biological aspects, it is worth noting that other suggestions for research or investigation included the socio-economic aspects of restoration attempts (or lack thereof) on the sugar industry, tourism and subsistence farming. Biologically oriented suggestions included studies of Mfolozi/Msunduzi microalgal communities, meiofauna, invertebrate nurseries and the assessment of possible invasive aliens, particularly in the event of any interbasin water transfer to St Lucia.

CONCLUSIONS

It was encouraging, given the current situation at St Lucia, that although possibly slightly ambiguous in the wording, the second priority reflected research focused on “adaptive management....” and “...immediate implementation”. The first priority, however, emphasised data requirements and one must perforce question how much more data will be required before action is taken. Rather than trying to extend existing data-bases it would seem that monitoring and data collection would be far better employed to assist in the adaptive management of the re-connection of the Mfolozi and St Lucia systems.

What has happened at St Lucia can only be described as a national estuarine catastrophe with already visible ripple effects in terms of the collapse of the offshore shallow-water prawn fishery and the reduction in recruitment to populations of estuary-associated marine migrant fish. These effects will certainly be felt for several years at least, beyond the point of any restoration or recovery of the St Lucia system. Resident species have lost huge areas of habitat while critical normal estuarine function in terms of the provision of nursery grounds for migrant fish and invertebrates and feeding grounds for piscivorous birds in the largest estuarine habitat in the country has been lost. The socio-economic aspects of the collapse of the St Lucia system are also significant, *e.g.* the recreational fishery associated with the Lake has collapsed and St Lucia town has had to change its marketing strategy for tourism.

While hindsight is an exact science and there has long been an acceptance or assumption that engineering structures such as mouth groynes and link canals could be used to manage systems such as St Lucia (and maintain them in some sort of acceptable state), this perception was shattered by Cyclone Domoina in 1984. Therefore any future management actions need to make allowances for such episodic events and to plan accordingly.

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LIST OF ACRONYMS

<	less than
± SE	plus/minus the Standard Error
°C	degrees Centigrade
$\mu g\ l^{-1}$	microgram per litre
μg	micro gram
μM	micro mole
$10^6\ m^3$	millions of cubic metres
amsl	above mean sea level
ANOVA	Analysis Of Variance
Arc GIS	Arc ® Geographical Information System (product of ESRI)
BAS	Best Attainable State
BCWL	Back Channel Water Level
BOD	Biological Oxygen Demand
BP	Before Present
CCA	Canonical Correspondence Analysis
CERM	Consortium for Estuarine Research and Management
Chl a	Chlorophyll-a
cm	centimetres
CPUE	Catch Per Unit Effort
CRUZ	Coastal Research Unit of Zululand (University of Zululand)
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
df	degrees of freedom
DWAF	Department of Water Affairs and Forestry
EHI	Estuarine Health Index
EIA	Environmental Impact Assessment
EKZNW	Ezemvelo KZN Wildlife
EMWL	Estuary Mean Water Level
F	Statistical F-ratio
ft	feet (Imperial system)
g	gram
GEF	Global Environmental Facility
GGP	Gross Geographic Product
GMSL	Geodetic mean sea level
ha	hectare
HWS	Spring High Tide
$ind\ m^{-2}$	individuals per square metre
$kg\ a^{-1}$	kilograms per annum
km	kilometre
KZN	KwaZulu-Natal
LiDAR	Light Detection And Ranging
LWS	Low Water Spring tide level
m	metre
$m^3\ day^{-1}$	cubic metres per day
$m^3\ s^{-1}$	cubic metres per second

MAE	Mean Annual Evaporation
MAR	Mean Annual Runoff
MCM	Marine and Coastal Management
MDS	Multi-Dimensional Scaling
MEA	Millennium Ecosystems Assessment
MFBL	Mfolozi Breaching Level
mg l^{-1}	milligram per litre
mm	millimetres
>	more than
MS	Microsoft
MSL	Mean Sea Level
n	number of samples
NMMU	Nelson Mandela Metropolitan University
NPB	Natal Parks Board
NRIO	National Research Institute for Oceanography
NTU	Nephelometric Turbidity Units
^{o}E	degrees east latitude
^{o}S	degrees south latitude
p	statistical level of significance
pers. comm.	personal communication
PES	Present Ecological Status
pH	measure of acidity/alkalinity
PSU	Practical Salinity Unit
R	Regression coefficient
RAMSAR	Ramsar International Convention on Wetlands (Iran, 1971)
RBM	Richards Bay Minerals
REC	Recommended Ecological Category
REDD	Reducing Emission from Deforestation and Degradation
SAIAB	South African Institute for Aquatic Biodiversity
SBA	Stemele Bosch Africa
SD	Standard Deviation
SIMPER	Similarity Percentage(s)
SL	Standard Length
SLBL	St Lucia Breaching Level
SRTM	Shuttle Radar Topography Mission
t	Student's t-test
t km^{-2} a^{-1}	tonnes per square kilometre per annum
TEV	Total Economic Value
TIN	Triangular Irregular Network
TOCE	Temporary Open/Closed Estuary
UCOSP	Mfolozi Cooperative Sugar Planters
UK	United Kingdom
UNESCO	United Nations Educational, Scientific and Cultural Organization
USM	Umfolozi Sugar Mill (Pty) Ltd
WMA	Water Management Area
WRC	Water Research Commission
www	world wide web
YSI	Yellow Springs Instruments

MFOLOZI/MSUNDUZI PROJECT TEAM

The core specialist team involved in this project was as follows:

Expertise	Name	Contact details
Project leader	Prof. Alan Whitfield	SA Institute of Aquatic Biodiversity, Grahamstown a.whitfield@saiab.ac.za
Organiser	Prof. Guy Bate	Nelson Mandela Metropolitan University, Port Elizabeth guy.bate@nmmu.ac.za
Ecologist	Dr Ricky Taylor	EKZN Wildlife, St Lucia taylorr@kznwildlife.com
Geohydrology	Prof B Kelbe	University of Zululand, , KwaDlangezwa bkelbe@pan.uzulu.ac.za
Vegetation	Prof. Janine Adams	Nelson Mandela Metropolitan University, Port Elizabeth janine.adams@nmmu.ac.za
Fish	Prof. Digby Cyrus	University of Zululand, KwaDlangezwa dcyrus@pan.uzulu.ac.za
Water chemistry	Dr Leon Vivier	University of Zululand, KwaDlangezwa lvivier@pan.uzulu.ac.za
Zooplankton and macrocrustaceans	Dr Hendrik Jerling	University of Zululand, KwaDlangezwa hjerling@pan.uzulu.ac.za
Civil Engineering and hydrodynamics	Prof. Derek Stretch	University of KwaZulu-Natal, Durban stretchd@ukzn.ac.za
Civil Engineering and hydrodynamics	Ms R. Lawrie	University of KwaZulu-Natal, Durban lawrie@ukzn.ac.za
Civil Engineering and hydrodynamics	Mr Clint Chrystal	University of KwaZulu-Natal, Durban chrystal@ukzn.ac.za
Economics	Ms S van der Waal	Coastal and Environmental Services, Grahamstown collingsza@gmail.com
Ecological evaluation	Dr Jane Turpie	Anchor Environmental, Cape Town jane@anchorenvironmental.co.za
Management	Mr J Gerber	EKZN Wildlife, St Lucia

Other contributors who did not make oral presentations, but who have made a written contribution to this report following earlier work on the system, include Dr Ivor van Heerden from the Department of Civil & Environmental Engineering, Louisiana State University, USA (exnatalia@aol.com) and Mr Iain Bickerton (ibickert@saol.com) who had worked on the system for his MSc degree through the University of Natal, Durban.

APPENDIX 1

Evaluation of the short-term link between the Mfolozi Estuary and St Lucia Lake

iSimangaliso
Wetland Park

World Heritage Convention Act 1999 (Act. No. 49 of 1999)
Proclamation Number 4477 of 2000
Dated 24 November 2000
Regulations 1193 dated 24 November 2000

iSimangaliso Wetland Park Authority
The Dredger Harbour, St Lucia, 3936
Private Bag X05, St Lucia, 3936
Telephone: +27 (35) 590 1633
Fax: +27 (35) 590 1602
wetlandauthority@isimangaliso.com
www.isimangaliso.com

EVALUATION OF THE SHORT-TERM LINK BETWEEN THE MFOLOZI ESTUARY AND ST LUCIA LAKE

BY
ROBYNNE LAWRIE
BSCENG MSCENG
(RESEARCH ENGINEER)
&
DEREK STRETCH
BSCENG MSCENG PHD (CANTAB)
(DIRECTOR)

UNIVERSITY OF KWAZULU-NATAL
SCHOOL OF CIVIL ENGINEERING, SURVEYING & CONSTRUCTION
CENTRE FOR RESEARCH IN ENVIRONMENTAL, COASTAL & HYDROLOGICAL ENGINEERING
(CRECHE)

AUGUST 2008

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UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

School of Civil Engineering, Surveying & Construction

FINAL REPORT

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BY

ROBYNNE LAWRIE
BSCENG MSCENG
(RESEARCH ENGINEER)
&
DEREK STRETCH
BSCENG MSCENG PHD (CANTAB)
(DIRECTOR)

CENTRE FOR RESEARCH IN ENVIRONMENTAL, COASTAL & HYDROLOGICAL ENGINEERING
(CRECHE)

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Glossary of Terms and Abbreviations

Back Channel	Man-made link between the St Lucia and Umfolozi estuaries
BCWL	Back Channel Weir Level
BC Weir	Back Channel Weir
Breaching level	Level in the Estuary above which the mouth will breach
C_dQ_o	Characteristic Flow Scale for the Mouth (m^3/s)
CPI	Current Precipitation Index (mm)
DRDEU	Daily Rainfall Data Extraction Utility
EMWL	Estuary Mean Water Level (m)
EMSL	Estuary Mean Sea Level (same as EMWL)
EKZN Wildlife	Ezemvelo KwaZulu-Natal Wildlife
FDC	Flow Duration Curve
g	acceleration due to gravity (9.81 m/s^2)
GMSL	Geodetic Mean Sea Level (m)
H	Water depth above the crest of a Broad Crested Weir (m)
HRU	Hydrological Research Unit
HWS	High Spring Tide Water Level (m)
HWSE	High Spring Tide Water Level in the Estuary when open (m)
LWS	Low Spring Tide Water Level (m)
m	Exponent
MFBL	Umfolozi Breaching Level (m)
MSL	Mean Sea Level (m)
Pan factor	Factor that relates Pan Evaporation to Actual Open Pan Evaporation
"Present inflows"	After abstractions, damming and afforestation
R	Rainfall (mm)
STBL	St Lucia Breaching Level (m)
Threshold flow	Flow below which the combined mouth would close
Q	Flow (m^3/s)
V	Lake Volume (m^3)
V_B	Lake Volume at the Breaching Level (m^3)
V_c	Critical Lake Volume (m^3)
"Virgin inflows"	Prior to significant anthropogenic influence
V_o	Lake Volume when Mouth Discharge is Zero (m^3)
Weather SA	Weather South Africa
ρ	Memory coefficient

Executive Summary

Lake St Lucia has been subjected to many artificial changes over the past century. These include:

- a decrease in inflows from its main feeder catchments (particularly the Mkuze river) due to abstractions
- the artificial separation of the Umfolozi mouth from the St Lucia mouth in 1952 - ostensibly to address the perceived threat of siltation from silt-laden Umfolozi waters
- the artificial maintenance of an open mouth between 1952 – 2002 by dredging and other measures (such as the construction of groynes in the late 60's)
- Since 2002, the management strategy has been to cease the artificial manipulation of the St Lucia mouth state and allow the system to close during drought periods, while continuing to keep the Umfolozi mouth separate
- Most recently a "back-channel" has been used to allow a limited link with the Umfolozi that diverts some fresh-water into the closed St Lucia system. This strategy is similar to that of a "link canal" that was previously explored, and unsuccessfully implemented in the 70's. In terms of mouth management, the management strategy remains to keep the Umfolozi mouth separated to prevent silt influxes into St Lucia when the Umfolozi floods. In practice the strategy is to maintain a weak point in the spit near Maphelane so that the Umfolozi will breach and form a separate mouth when it floods.

A series of modelled scenarios are presented, focusing on the management strategy of maintaining a separate Umfolozi mouth while allowing a managed flow of water via the back-channel into St Lucia to maintain the ecosystem during drought periods.

Firstly, long-term simulations have been used to illustrate the consequences of the artificial changes that have been implemented in the past and continue to be part of the current management strategy. The key result of these simulations is the conclusion that the separation of the Umfolozi and St Lucia mouths is by far the most significant anthropogenic intervention in terms of long-term impacts on the functioning of the St Lucia system. The addition of 5Mm^3 per month of fresh water from the Umfolozi to the St Lucia via the back-channel can restore *virgin* fresh water inflows into the system, but has no significant effect on the mouth state of the St Lucia system. This indicates the importance of re-establishing a combined mouth so that the Umfolozi can resume its historical role of providing a more stable mouth state for the system.

Secondly, short-term simulations, using forecast rainfall, are used to predict the state of the system for the next nine months. They suggest that below average or even average rainfall will result in hypersaline conditions and very low water levels. Above average rainfall will see water levels increasing slowly and salinities dropping. The supply of additional freshwater via the back-channel (if the Umfolozi mouth is closed) can significantly reduce or delay the onset of hypersaline conditions (and associated low water levels) in the lake. However this strategy is only likely to be effective during the periods of low flow in the Umfolozi (typically from June through September) - the onset of spring rains will generally lead to a rapid rise in water levels in the Umfolozi basin with subsequent breaching of the berm. Preliminary hydraulic analysis of the back-channel has led to recommendations for the heights of the required key control points, in particular a crest height of the "weir" controlling the back-channel flows, and the breaching level for the Umfolozi estuary.

In summary our primary recommendations are:
1. The back-channel link should be maintained essentially as it is, with some adjustment of the control point elevations if required, since its effects are beneficial to the system in its current state.
2. The management strategy should move away from persistent intervention towards a new strategy of non-intervention, but with detailed monitoring. This includes allowing the re-establishment of the historical configuration of a combined Umfolozi/St Lucia mouth. The monitoring program and future research should focus on the uncertain issues concerning siltation and mouth dynamics.

1 Background

Extensive scientific research has been carried out on St Lucia, most of which has been focused on biological components of the system. The hydrology and physical dynamics of the system has received much less research attention, the most significant of which has been the work at the Hydrological Research Unit (HRU – University of Witwatersrand) reported by Hutchison and Pitman (1977), Hutchison and Midgley (1978). The HRU study used a water balance model to simulate the functioning of the system and to investigate the efficacy of various management options to mitigate the effects of extreme hypersaline conditions that occur during drought conditions. These measures included the importing of fresh water using various forms of link canal, which was a preferred option. It should however be noted that the HRU modelling did not include any attempt to predict the mouth state of the system: it was simply specified based on available historical observations.

Figure 1.1 Lake St Lucia with insert showing magnified view of the mouth region (Google Earth, 2005)

Lake St Lucia receives a mean annual rainfall of 890 mm (Hutchison and Pitman, 1973) and loses on average 1470mm to evaporation per annum. The surface area of the lake is roughly 300 km^2 (at average water levels) with an average depth of 1m. The high surface area to volume ratio, makes the system vulnerable to evaporative losses during drought conditions when catchment inflows reduce. The total supply of freshwater to the lake is estimated to be about 600Mm^3 per annum on average, and the total loss due to evaporation about 400Mm^3 (Hutchison, 1976). However, these values are highly variable, depending on erratic wet and dry cycles. Episodic floods contribute an immense quantity of fresh water, much of which is lost to the sea when the mouth opens. These floods act to periodically "reset" the system by flushing out salt and accumulated sediments.

Figure 1.2 Aerial view of the St Lucia/Mfolozi mouth region (Google Earth, 2008)

It is widely believed that the extensive accumulation of sediments at the mouth by the early 1950s was caused by the canalization of the Umfolozi swamps (starting in 1911) which in turn increased the silt loadings in the Mfolozi (Taylor, 2006). It should however be noted that the area experienced a prolonged drought starting in the mid 40s (one of the longest on record) which persisted until floods in 1956. In 1952 a separate Umfolozi mouth was dredged open to address the siltation issue and to protect sugarcane farms in the Umfolozi floodplain from flooding (Taylor, 2006). We note that while there appears to be a widely held perception that Umfolozi silts have been deposited into the main St Lucia lake basin there is no scientific evidence yet linking the two. After 1952, the management strategy was, and still is, to keep the two mouths separate. Management actions were also directed at maintaining a sea-estuary link and the St Lucia mouth was kept open during drought conditions. In the 1970s extensive dredging operations took place in the Narrows to increase flows. The perception seems to have been that the removal of accumulated sediment from the Narrows would cause the St Lucia mouth to stay mostly open. A sand trap was also constructed at the estuary mouth to inhibit marine sediments from closing the mouth. The management strategy of maintaining an open mouth was changed in 2002 and the mouth was allowed to close in July 2002.

In the past, when St Lucia formed a combined mouth with the Umfolozi, a narrow north extending spit developed from the Maphelane bluff due to the prevailing littoral transport patterns. An aerial photograph of the combined Umfolozi and St Lucia mouth taken in the 1930s is shown in Figure 1.3. Note the constricted mouth with a well-developed flood delta. Large floods in the Umfolozi would generally destroy this spit and the Umfolozi would discharge out to sea. Littoral transport would then re-build the spit and the mouths would recombine. When the combined mouth was closed, fresh water from the Umfolozi would have flowed into St Lucia replenishing water lost due to evaporation thus diluting salinities.

Figure 1.3 An aerial photograph illustrating the combined St Lucia and Umfolozi mouth in the 1930s (provided by Taylor, 2007)

The current drought cycle has had a severe impact on St Lucia. The mouth has remained continuously closed with extreme hypersaline conditions (and desiccation) developing in the upper reaches of the lake. Although the system has been extensively researched in the past, we believe that the re-current management crises, particularly concerning issues of mouth manipulation and catchment management, indicate a need for further research to develop our understanding of the physical and biological dynamics of this system with the aim of providing improved tools for the ongoing management of this key resource. The conservation of this wetland system relies on the implementation of appropriate management decisions informed by models based on scientific research.

Key management questions include: should the mouth be kept open artificially or be allowed to remain closed during drought conditions (Taylor *et al*., 2006); and should the Umfolozi mouth be linked back into the St Lucia system (Taylor, 2006) as in the past (refer to Figure1.3)?

1.1 Objectives

The brief of this study was to investigate the following:

- The importance, or not, of fresh water supplied via the back-channel for the maintenance of the St Lucia ecosystem. This must consider cases where the Umfolozi mouth is open or closed, with the St Lucia mouth closed, and cases where the Umfolozi mouth is open or closed, with St Lucia mouth open.
- St Lucia water levels and salinity states (via modelling and the development of scenarios) for the next nine months, with and without fresh water from the

Umfolozi/Umsunduze via the back-channel, with and without "average" spring rain, indicating probabilities of outcomes of salinity levels becoming intolerable.

- Probabilities attached to the flow of fresh water from the Umfolozi/Umsunduze for the next 9 months, taking cognisance that should the Umfolozi come down in flood, the Umfolozi mouth will have to be breached near Maphelane, and water will no longer flow down the back-channel into the St Lucia system.
    - The probability that even a minor flood in the Umfolozi River will force the opening of the Umfolozi mouth to the sea.
    - The quantity of water that is likely to be available to flow into St Lucia
    - The evaporative losses that can be expected in St Lucia over this time period and how much of this evaporative loss will be offset by the inflowing Umfolozi/Umsunduze water.
- The deepening or widening of the back-channel to allow increased fresh water flow from the Umfolozi/Umsunduze rivers into St Lucia, with provision for the rapid closing of the Back-channel in the event that the Umfolozi river comes down in flood.

1.2 Outline of the Report

The following chapters included in this report are outlined as follows:

- Chapter Two presents the methodology. The various parameters included in the water balance model are introduced.
- Chapter Three presents the results of the various simulations. A validation of the model is included and the objectives of the report are investigated. A sensitivity analysis of key parameters is also included.
- Chapter Four presents the conclusions of the study followed by
- Recommendations regarding management strategies and for further research are considered in Chapter Five.

2 Methodology

The freshwater inputs to the St Lucia Lake system comprise 1) rainfall, 2) river inflow mainly from the Mkuze, Hluhluwe, Mzinene and Nyalazi Rivers and 3) groundwater seepage along the Eastern Shores. The mouth state is a major driver of the functioning of the system. Closed mouth conditions allow fresh water to accumulate, but losses due to evaporation exceed the inputs during dry periods. Open mouth conditions on the other hand allow the inflow of seawater thereby modulating the water level in the lake. Water levels and salinities are key influences on the biological functioning of the system.

The water balance model developed for the study is similar to the model developed by Hutchison and Midgley (1978), but incorporates the mouth dynamics. The various components of the model are introduced in the following section. Due to the lack of measured river flows, inflows were simulated using the Pitman (1973) model, and a method based on flow duration curves (Smakhtin and Masse, 2000). The model was validated using measured monthly salinities provided by EKZN Wildlife. In order to estimate what may ensue in the next nine months, rainfall data was forecast for different scenarios and the corresponding flows simulated. A sensitivity analysis was performed to assess the effects of uncertain parameters on the modelling results.

2.1 Water Balance Model of the Lake System

The water balance model includes the ability to simulate the intermittent closing and breaching of the mouth. The model operates according to a monthly time step. Mouth state, average salinities and average water levels can be simulated to test various management strategies.

For simplicity, the model represents St Lucia Lake as one unified basin. Simulated salinities and water levels are therefore averaged over the whole lake system. Data inputs for the model include monthly rainfall, evaporation, river inflows, mouth discharge and Umfolozi flows. A few key parameters must be specified for the model and will be discussed in the following sections.

2.1.1 Volume, surface area and water level relationship for the St Lucia basin

The morphology of the lake was analysed by Hutchison (1974) based on a bathymetric survey carried out in the 70's. The analysis yielded relationships between water level, surface area and volume. The same relationships were used for the present model, but it is recognized that significant changes may have occurred. This input data can and should be updated as soon as new measurements become available.

2.1.2 Freshwater inflows

The model has been set-up to use simulated inflows for both "*virgin*" and "*present*" conditions as defined by Hutchison and Pitman (1977). *Virgin* conditions refer to a state prior to significant anthropogenic influence. *Present* conditions include the effects of abstractions, dams and afforestation. Hutchison and Pitman (1977) suggested that these have led to a roughly 20 % reduction of fresh water inflows into the lake (a total reduction of 60Mm^3 of fresh water, or 5Mm^3 per month). Changes since the 1970s are not known and require further investigation.

Flow gauges of the rivers that feed Lake St Lucia are located some distance from the lake and provide relatively limited or incomplete/unreliable data. Therefore, Hutchinson and Pitman (1973) used the rainfall-runoff model developed by Pitman (1973) to simulated monthly inflow from each of the surrounding catchments for the period 1918 to 1971. In order to extend this information, observed rainfall data from the same surrounding fifty-seven weather stations were extracted from the Daily Rainfall Data Extraction Utility (DRDEU, developed by Kunz, 2004). These were supplemented with recent data provided by Weather SA.

Average monthly evaporation data given by Hutchison (1976) was adopted unchanged for the present model.

A method based on flow duration curves (FDCs) and following Smakhtin and Masse (2000), was used to extend the Pitman simulated inflows to the present. A Current Precipitation Index (CPI) was computed from the rainfall data using Equation 2.1, namely

$CPI_t = \rho \, CPI_{t-1} + R_t$ **Equation 2.1**

where ρ is a memory coefficient (ρ <1) and R_t is the current monthly rainfall. The CPI is a proxy indicator of catchment wetness. The duration curve for the CPI was then used to infer the corresponding flow from the FDC by matching their exceedance probabilities (refer Figure 2.1). The value of ρ was chosen to produce the best correlation with the target flows (ρ = 0.7 for the Lake catchment and ρ = 0.6 for the Mfolozi catchment).

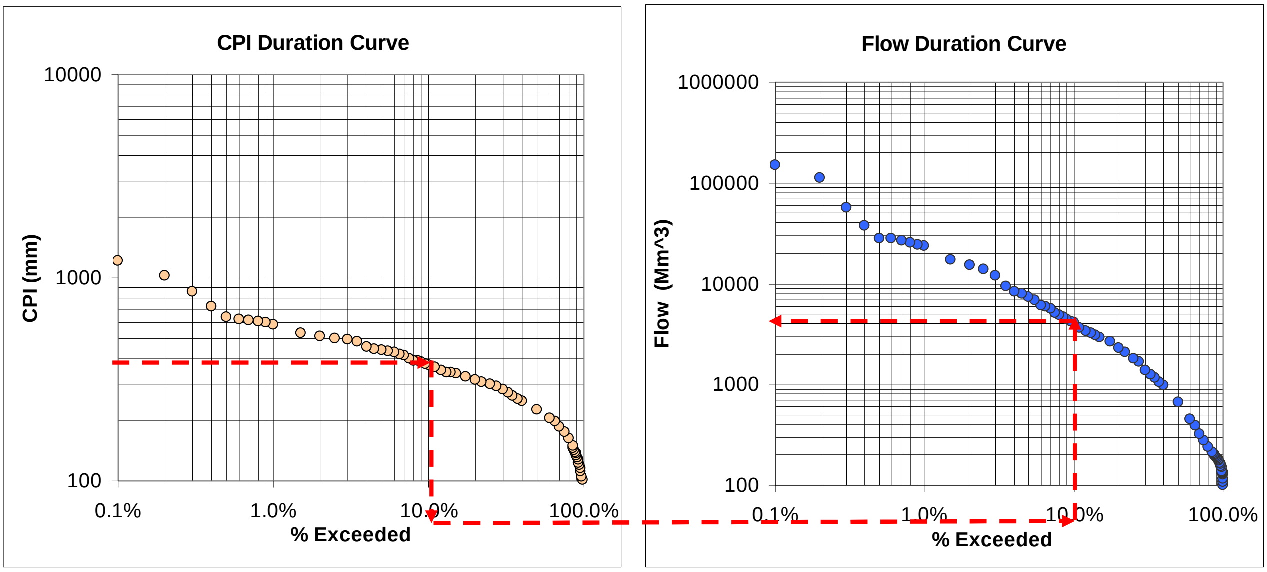


Figure 2.1 Flow and CPI duration curves used to simulate flow into the St Lucia Lake.

Figure 2.2 compares the FDCs of the inflows simulated by Hutchison and Pitman (1973) with those simulated using the method described above. It can be seen that the flow duration characteristics are accurately preserved by this technique.

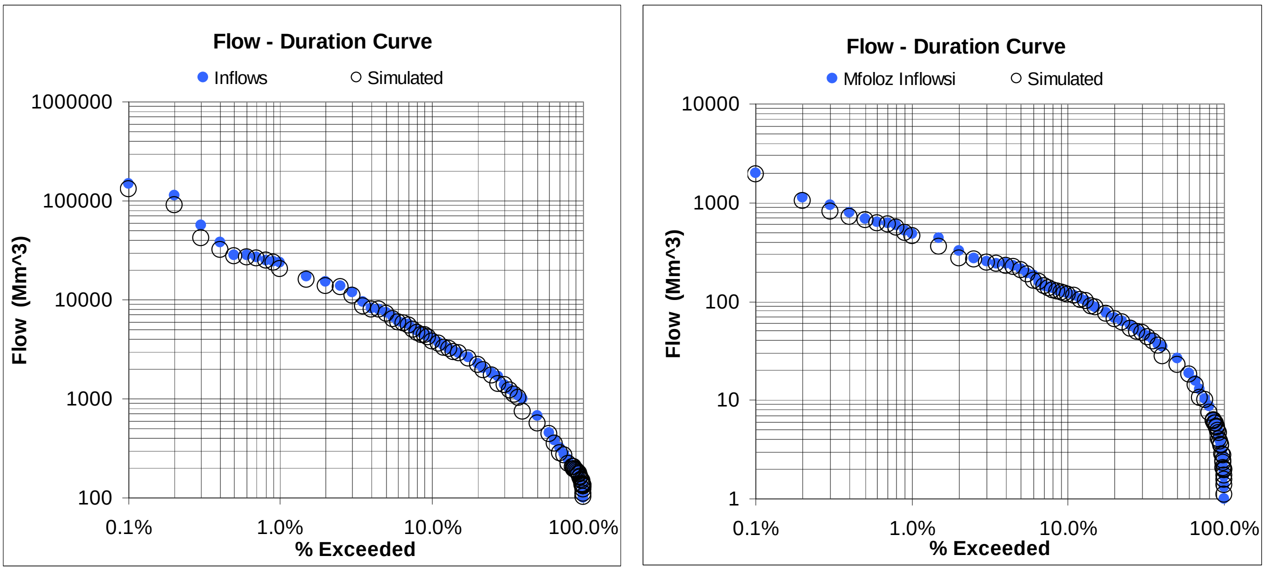


Figure 2.2 Comparison of the FDCs of the inflows simulated by Hutchison and Pitman (1973) and the inflows simulated using the FDC method.

2.1.3 Linkage to the Umfolozi

The model is designed to simulate various degrees of linkage between St Lucia and the Umfolozi. These range from completely separated systems to one where the mouths are combined. With the systems fully separated, the water in the Umfolozi plays no role in the water balance of St Lucia, and also has no influence on its mouth state. With the systems sharing a common combined mouth, the Umfolozi can contribute both to the water balance and the mouth state of the system. Details of the mouth state model are given in section 2.1.5. When a combined mouth closes, the model assumes that fresh water from the Umfolozi can flow into St Lucia, diluting salinities and increasing water levels. When a combined mouth is open, the model assumes that fresh water from the Umfolozi is mainly lost to the sea through tidal exchange flows. The facility to add a source for imported fresh water with specified flow rates, has been included in the model e.g. to simulate the effects of the back-channel.

2.1.4 Estuary mouth inflows and outflows

The inflows and outflows through the estuary mouth (when it is open) are pivotal in modulating the salt and water balance of the lake and also govern the mouth state of the system. Therefore in order to simulate the salinity and water level of the lake accurately, it is important that the exchange of flows between the lake and the sea are modelled. Hutchison and Midgley (1978) reported a relationship between lake water levels and average mouth discharges. This relationship was based on some (limited) tidal prism measurements and on simulations using a one-dimensional tidal propagation model. For the present study a weir-type equation was fitted to the reported mouth outflows and used to relate these outflows to lake volumes V, whence

$$Q = [C_d.Q_o].\ (V/V_o - 1)^m \qquad \text{for } V \geq V_o \qquad \textbf{Equation 2.2}$$

In this equation $[C_d.Q_o]$ is a characteristic flow scale for the mouth that, together with the exponent m, is chosen to best fit the predicted mouth discharges. The volume V_o is the lake volume when discharges are zero - V_o corresponds approximately to the volume when the lake water level is at the average level during open mouth conditions (i.e. estuary mean water level or EMWL). When lake volumes are less than V_o (water levels below about EMWL) there is a nett inflow from the sea into the lake, which is assumed to be independent of water levels and equal to $14Mm^3$ per month. This inflow volume is based on measurements of the tidal prism reported by Hutchison (1976). More recent measurements of tidal exchange flows by Chrystal and Stretch (2008), carried out after the breaching event in 2007, have confirmed that the nett inflows at low lake water levels are in the range 500000 to 1000000 m^3 per day, depending on the tidal amplitude: this corresponds to 15 – 30 Mm^3 per month. The inflow rate at low lake levels is an adjustable parameter in the model.

2.1.5 Mouth state model

As already noted, the link with the sea via the estuary is pivotal in modulating the salt and water balance of the estuary e.g. the closure of the mouth in June/July 2002 followed by ongoing drought conditions ultimately lead to very low water levels and hypersaline conditions. The modelling of the mouth state allows us to simulate water levels and salinities under various mouth management strategies, and is a key new feature of the present water balance model.

Three key parameters are assumed to control the mouth state. They are the volume (or water level) at which the mouth will breach and the volume (or water level) below which the mouth closes. In addition, if the Umfolozi/St Lucia has a combined mouth, the Umfolozi flow rates are assumed to provide another mechanism for modulating the state of the combined mouth. The determination of the mouth state is summarized in Table 1.

Table 1 Mouth state model

If the St Lucia mouth is:	It will remain so if:	Otherwise it:
Open	The volume in the lake exceeds a specified critical level, V_c	Closes
Closed	The volume of the lake remains below the specified breaching level, V_B	Opens
If the combined mouths are:	They will remain so if:	Otherwise it:
Open	The Umfolozi flow rates or lake volume are above a specified critical flow rate or volume respectively	Closes
Closed	The volume of the lake remains below the specified breaching level, V_B	Opens

Data concerning the mouth state under natural conditions is scarce. Due to the lack of measured data, estimates of the mouth model parameters were based on comparing predicted mouth states with recorded historical observations for the period 1918 to 1952. The threshold flow in the Umfolozi to maintain an open combined mouth was thus estimated to be about 4 Mm^3 per month and the threshold lake volume at closure of the mouth was estimated to be about 300 Mm^3 (with a corresponding lake level of -0.1m below EMWL). The threshold volume in the lake at which the mouth would breach naturally was assumed to be about 1175 Mm^3, which corresponds to a water level of +2m EMWL (2.25m above actual MSL). The effects of artificially breaching the system at lower water levels, or of other natural breaching levels can (and were) investigated by simply changing the relevant parameter.

2.1.6 Additional fresh water inputs via the back-channel

The model is configured to incorporate additional fresh water inflow via the back-channel or another source. For the present study, the fresh water link used in the simulations was assumed constant throughout the year, but variable flows can be accommodated if required. During open mouth conditions the model allows for a specified dilution of the sea water inflows where the mouth inflows are assumed to mix with fresh water from the source while outflows will flush the fresh water out to sea.

2.1.7 Salinity and water levels

Since the lake is represented as one unified basin, during extreme drought periods when water levels decrease drastically and different parts of the lake start to be isolated, the model will not accurately represent the actual situation.

Salinities are modelled using a salt balance which incorporates increases in salt loading when there are inflows from the sea (when the mouth is open and water levels are low, $V < V_o$), as well as the flushing effect of outflows via the mouth when water levels are higher ($V > V_o$).

2.1.8 Back-channel analysis

A detailed analysis of the functioning of the back-channel requires coupled water balance models for both the Umfolozi and the St Lucia basins that can simulate the Umfolozi estuary functioning under various scenarios. To build this model requires a bathymetric survey of the Umfolozi basin in order to establish its water-level/surface-area/volume relationship. Since this is not currently available, changes in water levels were simply inferred from.

Water level change = (Inflow volume)/(surface area of basin) **Equation 2.3**

where the surface area was assumed to be approximately 1.2km^2 (Lindsay *et al.*, 1995).

The back channel discharges into St Lucia were assumed to be controlled by a broad crested weir at the downstream end, where critical conditions give the corresponding maximum flow that is possible:

$$Q = 0.385 \times \mathrm{SQRT}(gH)\ H\ B \qquad \textbf{Equation 2.4}$$

where, g is gravity (9.81m/s^2), H is the water level relative to the crest of the weir and B is the width of the weir. Friction losses in the back channel were estimated with a uniform flow model.

2.1.9 Data Forecasting

In order to predict what may happen in the next nine months, a statistical analysis of the monthly rainfall data of the lake and the Umfolozi catchment was performed. Monthly mean, median, minimum, maximum, 75th, 25th and 10th percentiles were calculated. A rainfall forecast option for the next nine months was incorporated into the model where the user is able to select average monthly rainfall, below average monthly rainfall (e.g. 25th percentile) or above average monthly rainfall (e.g. 75th percentile).

2.1.10 Sensitivity Analysis

In order to give an indication of the sensitivity of the model to the parameters, a sensitivity analysis was performed. The breaching level was originally set at a threshold volume of 1175 Mm^3 (corresponding to a water level of 2 m EMWL). The effect of changing the breaching level to 1 m and 3 m EMWL was investigated as the breaching level is an important parameter that will influence inundation of adjacent agricultural lands. The sensitivity of the system was evaluated by comparing changes in the average salinity, water level and percentage mouth closure. The sensitivity analysis was performed both with and without a separate Umfolozi mouth.

2.2 General Approach of this study

The general approach in this study was to use long-term simulations to provide a broad perspective of the functioning of the lake. By simulating the functioning of this system over roughly a century, the long-term consequences of different management options and scenarios can be illustrated. These simulations are supplemented by short-term predictions for the next nine months. It is important to note that in order to relate the results of the long-term model simulations to the current state of the system (which is essentially a consequence of the management interventions that have taken place recently) requires that the system be “reset” by a significant flood event. We estimate that under current conditions, this would occur if the system experienced a flood with a return period of 10 years or more. Another important point to make regarding the resetting of the system is that if the St Lucia Estuary were to breach under natural conditions (i.e. from a water level of about +2mEMWL), a peak outflow through the mouth of about 1000Mm^3 per month (i.e. 380m^3/s) could occur. These outflows are of a similar magnitude to those of a very large flood (return period of 50 years or more) and would result in massive scouring of accumulated sediment built up in the mouth and narrows. Without the large flows of a natural breach such as this, sediment could continue to accumulate in the narrows and mouth. These natural breaching events, which have been prevented by artificial manipulation of the mouth state, would probably have played a significant role in the maintenance of the system prior to human intervention.

3 Simulation Results

The simulation results of the water balance model are presented in this chapter. The chapter begins with the validation of the model using measured and simulated salinities. Results of long-term simulations are presented in order to give the overall behaviour of the system under various management scenarios. Short-term simulations of the future are then presented to give an educated guess at what may happen in the next few months. The sensitivity of the model to certain key parameters is also discussed.

3.1 Validation of the Model

Salinities of North Lake, False Bay and South Lake have been measured by EKZN Wildlife since 1958 and are shown in Figure 3.1. The dashed line represents the salinity of sea water (35 ppt). Lake salinities vary spatially - the salinity gradient between the northern and southern parts of the lake are shown in Figure 3.1. Note that a positive gradient indicates increasing salinities from South to North and vice versa. During drought periods hypersaline conditions are associated with a significant increase in the salinity gradient. During wet periods there is typically a negative salinity gradient (up to about 24ppt).

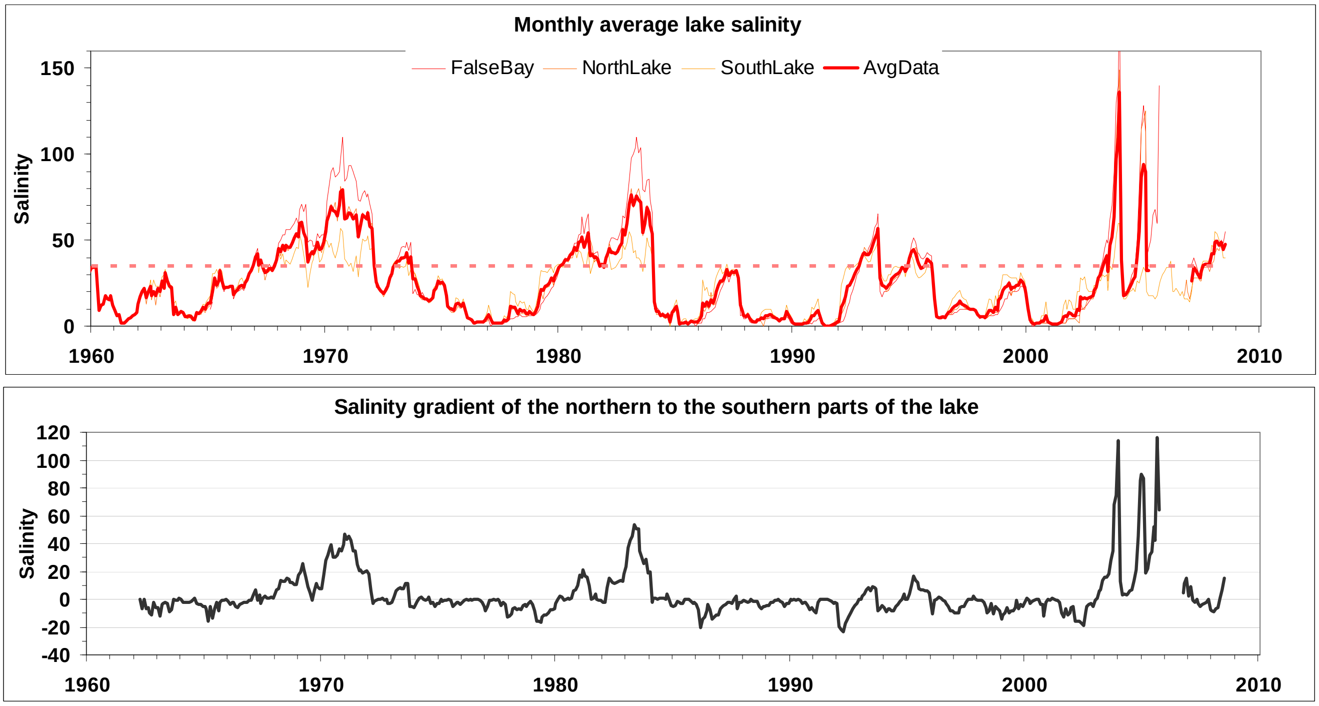


Figure 3.1 Measured monthly average lake salinities and salinity gradient between the northern and southern parts of the lake (courtesy of Ricky Taylor and Caroline Fox).

To validate the model, monthly lake salinities from 1950 until July 2008 were simulated under permanently open mouth conditions and compared to measured monthly average salinities (see Figure 3.2). The model represents the lake as one unified basin and therefore simulates average lake salinities and does not account for spatial variability. Measured monthly average salinities are also included in Figure 3.2 for comparison. It is important to note that the management strategy at the time (from 1955 until 2002) was to artificially keep the mouth open. The Umfolozi mouth has been separated since 1952. Monthly average lake salinities were simulated for both *present* and *virgin* inflow conditions (see section 2.1.2).

Notice how simulated salinities clearly mimic the measured salinities, increasing in the drier cycles and decreasing during the wetter cycles. These trends are caused by the increase in salt loading during dry periods as seawater flows into the system to modulate water levels and vice versa in wet periods. Since the lake is represented as one unified basin, the simulated average salinities deviate substantially from the mean in different parts of the lake during drought periods. The discrepancy in salinities after 2002 is due to the fact that the mouth was closed from mid June 2002 until March 2007 and then again from September 2007 until present (August 2008). Salinities during this period are better represented when the mouth dynamics are included (see below). Notice how *virgin* salinities are consistently lower then *present* salinities indicating the effect of the reduced fresh water inflows on the water and salinity balance. Adding a constant 5Mm^3/mth of additional fresh water to the *present* inflows makes the modelled salinities for that case correspond nearly perfectly with those of the *virgin* case.

Overall, the agreement between the measured and modelled average lake salinities is excellent and provides confidence in the basic input data that drives the water balance model. Note that for the simulations shown here, there are no adjustable model parameters, since the mouth state is fixed at open.

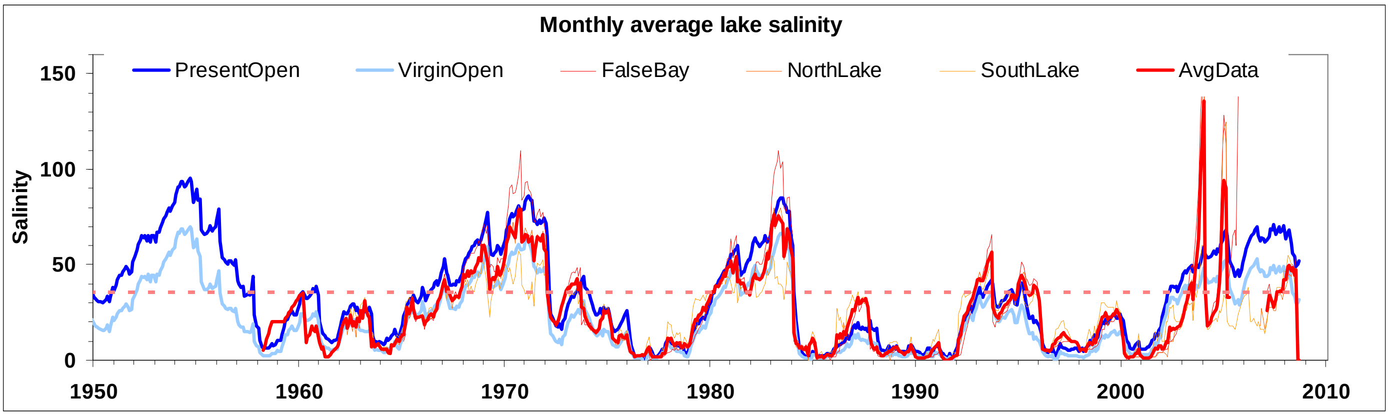


Figure 3.2 Simulated and measured monthly average lake salinities.

Figure 3.3 shows simulated versus measured monthly averaged lake salinities but without artificial manipulation of the mouth state i.e. the mouth state model was used to predict the natural state of the mouth as shown in Figure 3.3. Note how predicted salinities are generally significantly lower during dry periods when compared to the actual lake salinities that occurred with the mouth artificially maintained in a permanently open state.

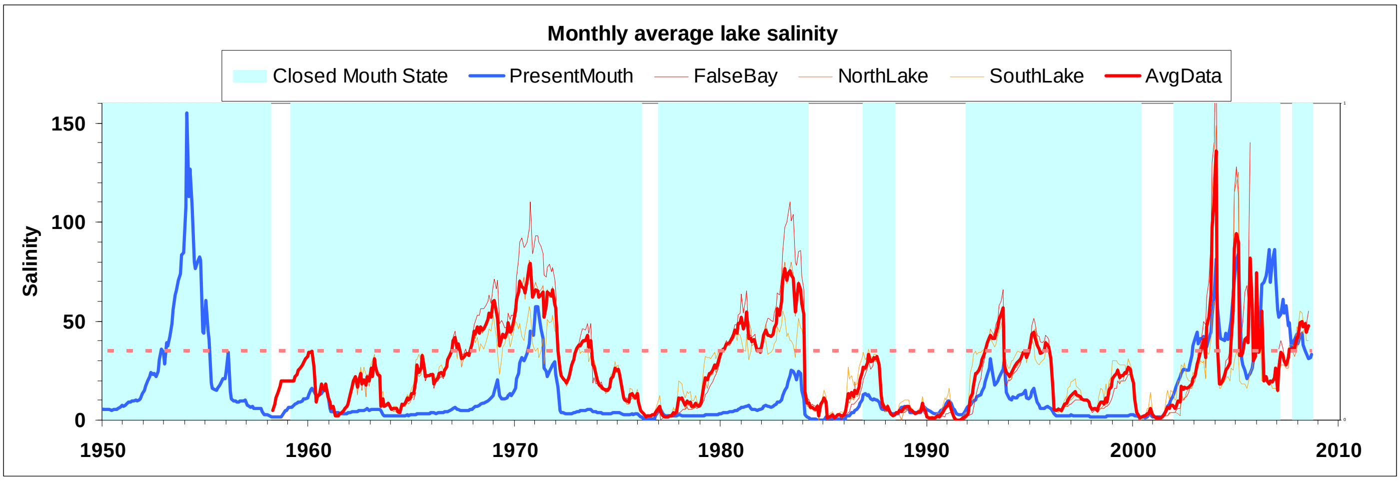


Figure 3.3 Measured versus simulated monthly average lake salinities with no artificial breaching.

3.2 Long Term Simulations

To illustrate the long-term behaviour of the system under different management strategies, water levels, salinities and mouth states were simulated for a 90-year period (1918 until present).

The following scenarios were modelled in order to address the objectives of this study:

- Scenario 1A : Separate Umfolozi mouth and no imported fresh water
- Scenario 2A : Reinstated combined mouth and no imported fresh water
- Scenario 1B : Separate Umfolozi mouth with imported fresh water

3.2.1 Scenario 1A: Separate Umfolozi mouth, no artificial breaching and no imported fresh water

With a mean annual runoff of 736 Mm^3 the Umfolozi was once an important source of fresh water to St Lucia when the combined system was closed. Water balance simulations indicate that the Umfolozi link provided an additional mean annual fresh water contribution of 150Mm^3 per year. Model simulations were run without the Umfolozi mouth link and with no imported fresh water. Figure 3.4 shows simulated annually averaged salinities, water levels and the mouth state for both *virgin* and *present* inflows. Note the significant increase in salinities, especially during hypersaline conditions, with *present* inflows. The grey shaded area in the mouth state figure represents mouth states under *virgin* conditions while the black shaded area represents mouth states under *present* conditions. The model indicates that without any artificial interference in the mouth state, St Lucia Lake would have been a predominantly closed system (about 88 % of the simulated period). At least a one in ten year flood would be required to “naturally” breach the mouth under these conditions, with the mouth subsequently staying open for only brief periods of about 18 months at a time. The lake is predicted to be a predominantly fresh system with highly variable water levels (refer to Figure 3.4 and Figure 3.5). Hypersaline conditions would generally occur during closed mouth phases and coincided with very low lake levels. Salinities tend to increase exponentially as water levels drop during dry cycles due to evaporation. Under severe drought conditions, the model predicts that the lake may be expected to dry up (as happened during the current drought in 2003). The salt loadings in the system depend on the inflows of sea water during open mouth periods. Since the model predicts these to be relatively rare and of short duration, the salt loadings are low.

In summary, the model results shown in Figure 3.4 predict the long-term implications of the current management policy with no artificial breaching of the mouth and with the Umfolozi separated from St Lucia.

It is important to note that the breaching of the St Lucia mouth in March 2007 was an extremely unusual event in the long-term context. The breaching occurred during a rare climatic event (with very high waves and tides) and during an extreme drought when lake water levels were very low. It should be noted that previous management strategies left the berm artificially narrow which added to the vulnerability of the system to wave breaching. The dredged sand trap at the mouth provided a sink for flood tide sediments, allowing the mouth to remain open for longer. This allowed a larger inflow of salt water, and hence higher salt loading, than is expected under natural circumstances.

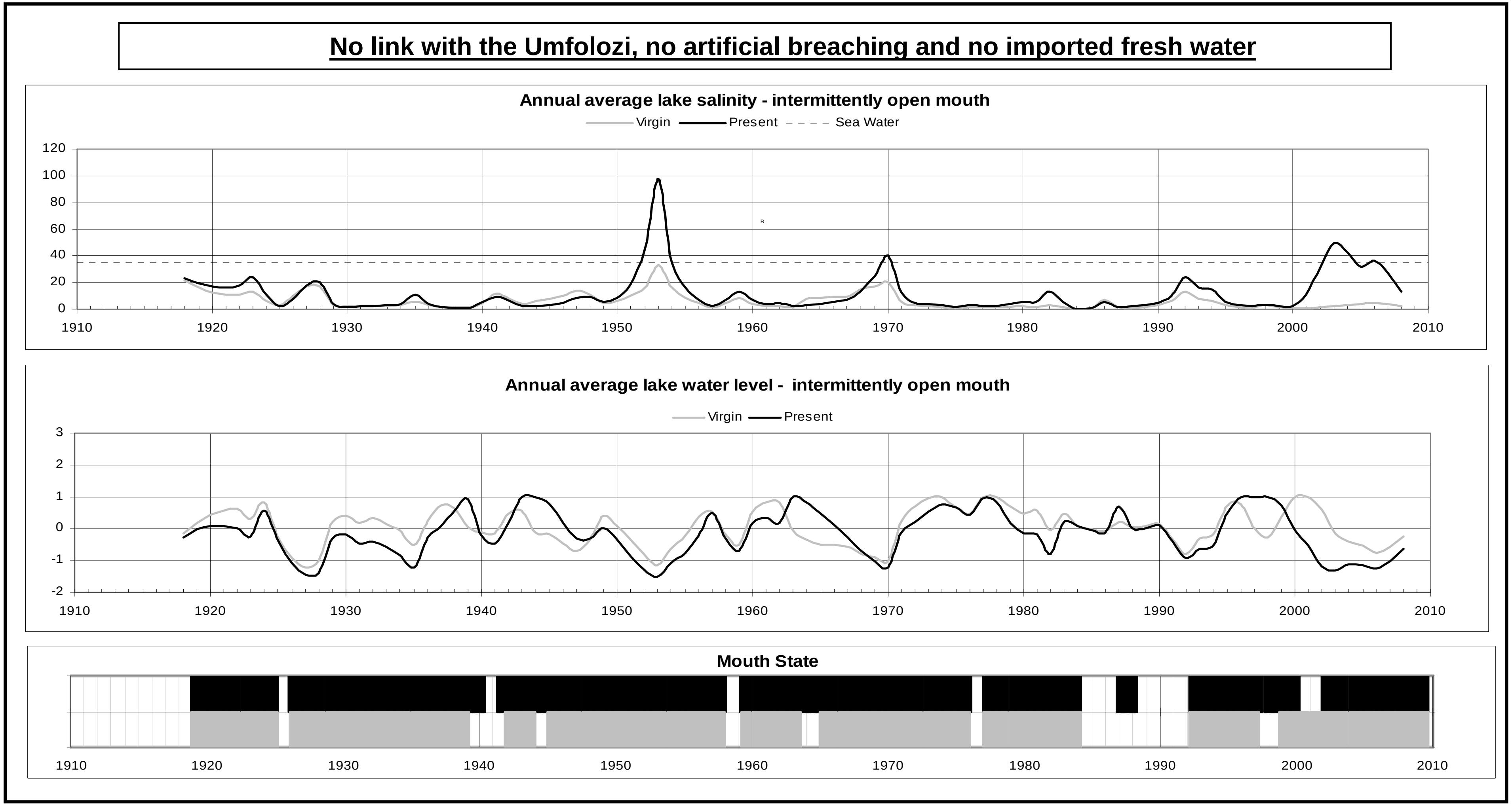


Figure 3.4 Simulations of Scenario 1A.

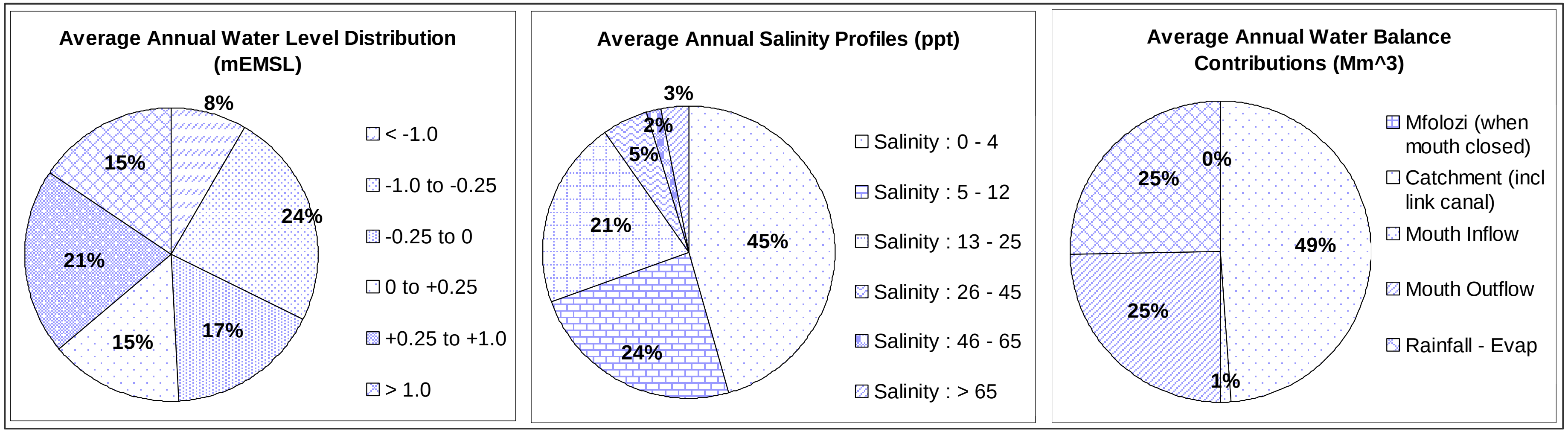


Figure 3.5 Average annual water level distribution, salinity profiles and water balance contributions for Scenario 1A.

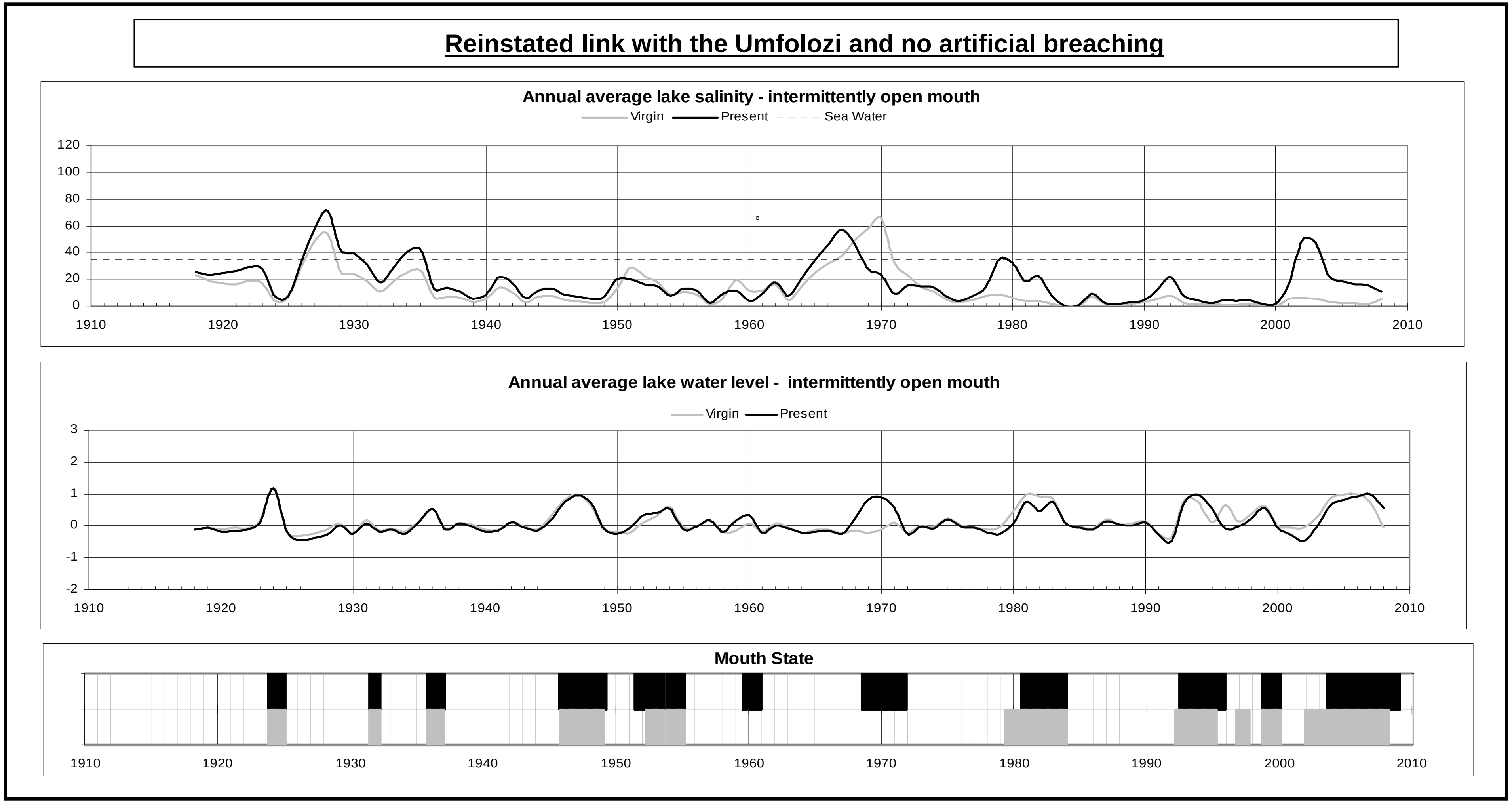
3.2.2 Scenario 2A: Reinstated combined mouth and no imported fresh water

Scenario 2A considers the effect of reinstating the Umfolozi mouth on the functioning of the system. With the Umfolozi mouth joined to St Lucia as it was in the past (pre 1952), the mouth is predicted to be predominantly open (about 80 % of the simulation period). Closure of the combined mouth would occur during severe drought periods. We have assumed that fresh water from the Umfolozi flows into the lake during these periods. The addition of this fresh water plays an important role during dry periods as it decreases lake salinities and increases water levels until the breaching level is reached. Breaching occurs about ten times in the ninety year period with the system remaining closed for about 2 – 3 years duration (refer to Figure 3.6). The system is predicted to be more saline than for Scenario 1A. Furthermore, in contrast to that case, hypersaline conditions occur mainly during open mouth phases, when salinities increase linearly due to the combination of tidal inflows of sea water, evaporation and low fresh water inflows. Taylor (2006) notes that experience (from the 70's) has shown that the combination of high water levels (about EMWL) and high salinities can have a detrimental effect on fringe vegetation of the lake. Salinities during closed mouth conditions are generally low due to dilution by fresh water inflows from the Umfolozi. With *virgin* inflows, salinities remain lower than for *present* inflows. Water levels are predicted to be stable at an average of 0.1 m EMWL, with increases occurring during closed mouth phases(refer to Figure 3.6 and Figure 3.8). A one in three year flood is sufficient to cause breaching of the estuary mouth under these conditions. By reinstating a combined Umfolozi/St Lucia mouth and allowing the mouth to function naturally, the additional fresh water supplied to the Lake from the Umfolozi is on average about 150 Mm^3 per year (approx 12 Mm^3/month). This contributes a significant amount, approximately 35% ,of fresh water to the overall water balance (see Figure 3.8). The large percentage of mouth outflows is due to the frequently open mouth.

Notice how reinstating the Umfolozi mouth changes the system from a predominantly closed, almost fresh water system with highly variable water levels, to a predominantly open system with more stable water levels but more variable salinity regime. Drought conditions impact differently in these two scenarios: salinities increase exponentially with dropping water levels during closed mouth conditions without the Umfolozi link. With the Umfolozi link, salinities increase approximately linearly during open mouth conditions with fairly constant water levels. However, during severe droughts the combined mouth closes and the diversion of fresh water from the Umfolozi reduces salinities and increases water levels. The results indicate the profound influence that the Umfolozi has on the functioning of the St Lucia mouth and thereby on the water balance. However, the issue is complicated by a perceived threat of siltation from the silt laden Umfolozi.

3.2.3 Scenario 1B: Separate Umfolozi mouth with fresh water addition via the back-channel.

With the threat of silt from the Umfolozi building up in the narrows, another method of obtaining freshwater was investigated. The simulations for scenario 1A were repeated but for a case where additional fresh water is imported into St Lucia e.g. via the back-channel or link canal – the results are shown in Figure 3.7 for *virgin* and *present* conditions. The monthly fresh water addition was assumed constant throughout the year. Recall that an inflow of about 5 Mm^3 per month of fresh water into St Lucia approximately restores *virgin* inflow levels. This is illustrated in Figure 3.7, where water levels and salinities for both *virgin* and *present* conditions were predicted to be similar. Introducing the additional fresh water into St Lucia, would maintain salinities below 35ppt, however water levels remained highly variable (see Figure 3.7 and Figure 3.9). The model indicates that this increase in fresh water does not influence the mouth state of the St Lucia Estuary as indicated by the continued prevalence of closed mouth conditions (about 85 % of the simulated period). This emphasizes the significant role that the Umfolozi plays in the functioning of the combined mouth. Figure 3.9 provides the average annual salinity, water level and water balance statistics for this scenario. Note that water levels and salinities follow the same trends as for Scenario 1A, but are less variable.

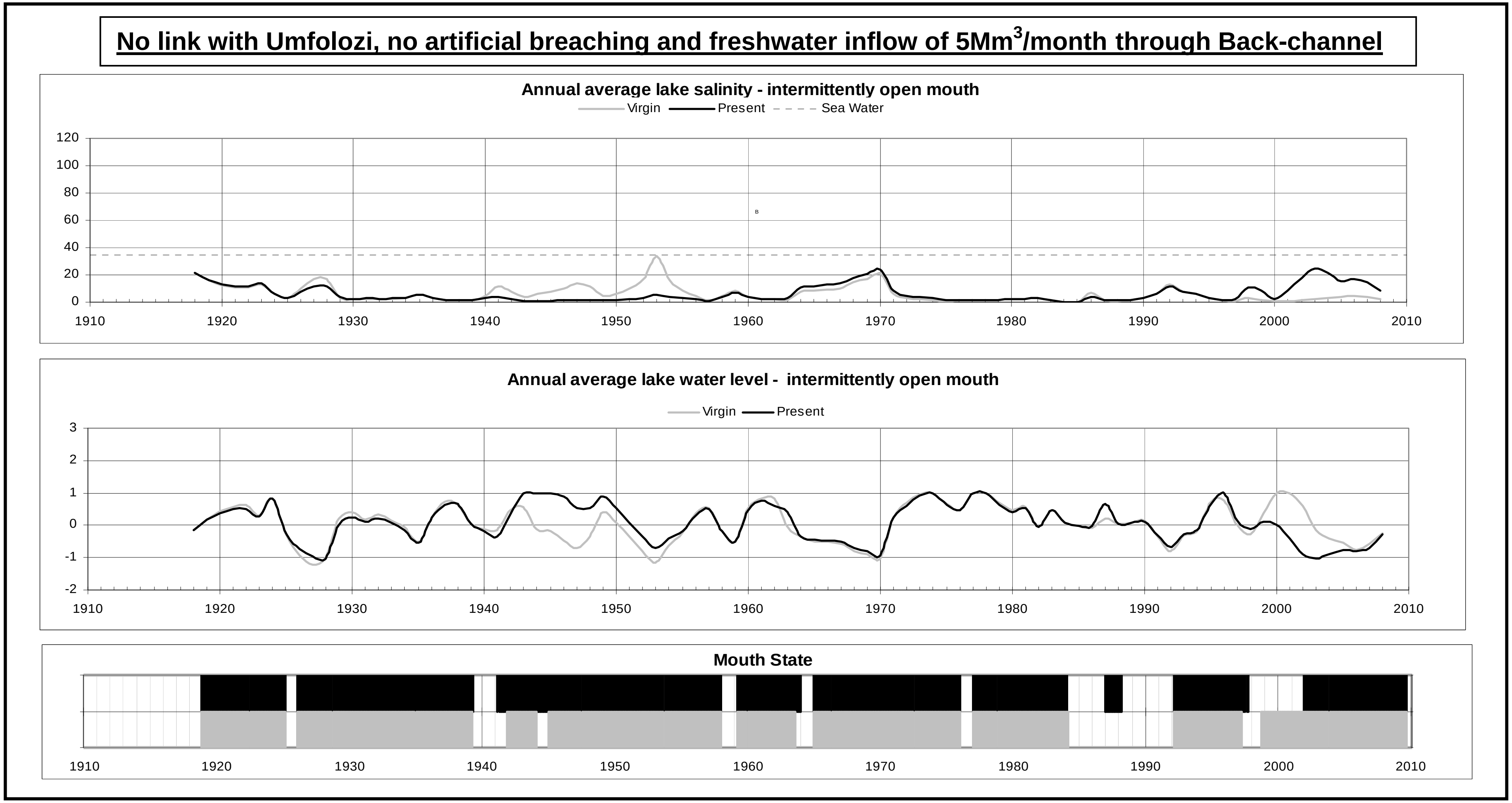

Reinstated link with the Umfolozi and no artificial breaching

Annual average lake salinity - intermittently open mouth

Annual average lake water level - intermittently open mouth

Mouth State

Figure 3.6 Simulations of Scenario 2A.



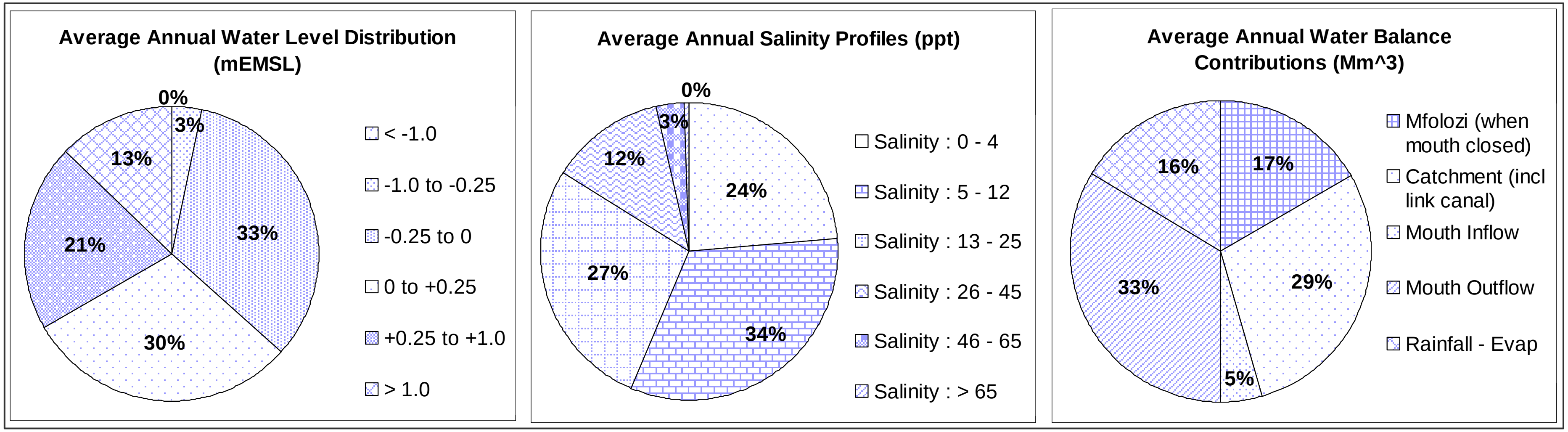
No link with Umfolozi, no artificial breaching and freshwater inflow of $5Mm^3$/month through Back-channel

Annual average lake salinity - intermittently open mouth

Annual average lake water level - intermittently open mouth

Mouth State

Figure 3.7 Simulations of Scenario 1B.

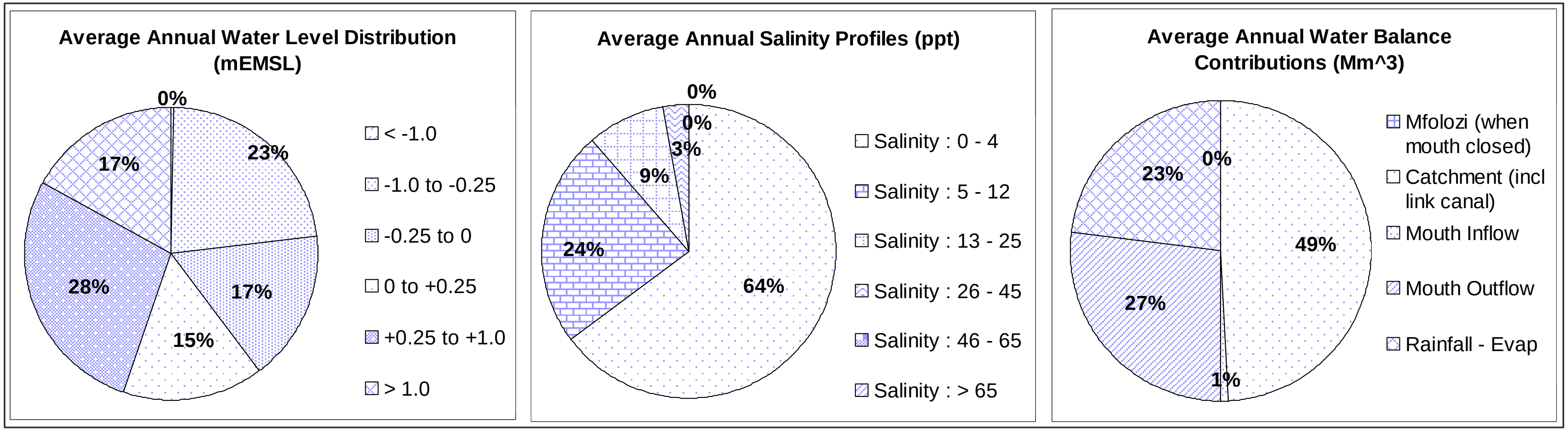


Average Annual Water Level Distribution (mEMSL)

Average Annual Salinity Profiles (ppt)

Average Annual Water Balance Contributions (Mm^3)

Figure 3.8 Average annual water level distribution, salinity profiles and water balance contributions for Scenario 2A.



Average Annual Water Level Distribution (mEMSL)

Average Annual Salinity Profiles (ppt)

Average Annual Water Balance Contributions (Mm^3)

Figure 3.9 Average annual water level distribution, salinity profiles and water balance contributions for Scenario1B.

3.2.4 Summary

In summary, the three scenarios simulated illustrate the key role that the Umfolozi mouth plays in the functioning of this system. The model predicts that a combined mouth would be predominantly open with stable water levels and variable salinity regime. During dry periods, if the mouth remains open, salinities would increase linearly due to the reduced fresh water inflows and the inflow of salt water from the sea. However, in more severe droughts the combined mouth would close - water levels would then increase and salinities decrease due to fresh water contributions from the Umfolozi. This leads to subsequent re-opening of the mouth by breaching the berm – a small flood with a return period of about 3 years would suffice to naturally re-open the system. On the other hand, separation of the Umfolozi results in a predominantly closed system with highly variable water levels and generally very low salinities. During drought periods the salinities rise exponentially due to falling water levels. In order for the mouth to breach naturally under these conditions requires a flood of at least a 10-year return period. The importing of additional of fresh water can restore the *virgin* water balance contributions, but the mouth of St Lucia would remain mostly closed if it is not allowed to re-combine with that of the Umfolozi.

3.2.5 Sensitivity analysis of the model

To analyze the sensitivity of the model to changes in the key parameters, the model was run using different pan factors, breaching levels and threshold Umfolozi flows. The average water levels, salinities and the percentage that the mouth was predicted to be closed over the simulation period was noted for each simulation. The results are presented in Table 2.

Varying the pan factor by one percent had no significant affect on the average salinity, and the percentage that the mouth is closed. Average water levels however increased by about 0.04m with a one percent decrease in pan factor. Hutchison (1976) provided different pan factors for the different parts of the lake, ranging from 96.5% in the south to 106% in the north.

As expected, altering the breaching level of the estuary had a significant effect on the average water level and mouth state. Varying the breaching level would change the scouring ability of the system at a breach. Scouring of the system at a breach is important as it inhibits the accumulation of sediment and salt. At a breaching level of 1m a peak discharge of roughly 117m^3/s was estimated to occur at a breaching event and at a breaching level of 3m a discharge of roughly 578m^3/s was estimated. A mouth discharge of approximately 325m^3/s was estimated at a breaching level of 2m EMWL. The decrease in salinity as the breaching level was raised was due to the dilution by freshwater and almost permanently closed mouth conditions.

The sensitivity of the model to the threshold Umfolozi flows was investigated with a reinstated Umfolozi link. The threshold Umfolozi flows required to keep the Umfolozi mouth open have been estimated to be about 1.5m^3/s. If the Umfolozi threshold flow was lower, for example 1.1m^3/s, salinities would increase due to more prolonged open connections to the sea. Increasing the threshold flow to 1.9m^3/s, the mouth stays closed for longer periods, thereby allowing water levels to build up and salinities to decrease due to river inflows.

Table 2 Sensitivity analysis of the model to certain key parameter changes

	Pan Factor		
Separate Umfolozi mouth	**101%**	**100%**	**90%**
Average salinity	13	13	13
Average water level (mEMSL)	-0.16	-0.13	-0.1
Percentage mouth closed (%)	87%	87%	87%
	Breaching level (mEMSL)		
Separate Umfolozi mouth	**1**	**2**	**3**
Average salinity	12	12	6
Average water level (mEMSL)	-0.41	-0.15	0.36
Percentage mouth closed (%)	81%	88%	94%
Approx mouth discharge at the breach (Mm^3/month)	117	325	578
	Threshold Umfolozi flow at closing (m^3/s)		
Link reinstated with the Umfolozi mouth	**1.1**	**1.5**	**1.9**
Average salinity	28	18	16
Average water level (mEMSL)	-0.05	0.11	0.13
Percentage mouth closed (%)	14%	32%	35%

3.2.6 The functioning of the back-channel

Water levels in the Umfolozi estuary must be higher than those in the St Lucia Narrows in order to provide a hydraulic gradient to drive a flow of fresh water into the lake. As indicated in Section 3.2.3, a fresh water addition of 5 Mm^3 per month into St Lucia would restore the *virgin* fresh water inflow conditions.

Hutchison (1976) performed simulations using a one-dimensional tidal propagation model to investigate the effects of introducing fresh water into St Lucia at different locations to dilute inflowing seawater (for open mouth conditions) and thereby to reduce lake salinities. The locations investigated include the Narrows south of the St Lucia Bridge, at the Mpate confluence, and at Makakatana Bay. The loss of freshwater during outgoing tides obviously increases as the inlet point is moved closer to the mouth. Therefore, it is important to note that the addition of freshwater via the back-channel would be influenced by tidal activity when the St Lucia and/or the Umfolozi mouth are open.

The following St Lucia and Umfolozi mouth state combinations were considered to understand the functioning of the back-channel fresh water link for the maintenance of the St Lucia ecosystem. Note that to accurately and quantitatively address these issues, a fully linked water balance model for both the Umfolozi and St Lucia basins is required. We currently do not have sufficient data for the Umfolozi basin to develop such a model.

Open Umfolozi mouth with the St Lucia mouth open

When both the Umfolozi and St Lucia mouths are open, both estuaries would be dominated by tidal exchange flows. Measurements at St Lucia indicate an average exchange flow of about 650 000m^3 per tidal cycle (Chrystal and Stretch, 2008). Measurements at the Umfolozi have shown an average flow of about 500,000m^3 per tidal cycle (Lindsay *et al.,* 1996). Average water levels in each estuary would be approximately the same. Under these conditions the back channel would cease to be effective in providing any significant fresh water flow between the Umfolozi and St Lucia estuaries.

Open Umfolozi mouth with the St Lucia mouth closed

An open Umfolozi mouth would be strongly influenced by tidal exchange flows (except under flood conditions). The functioning of the back channel in this scenario depends on the crest level of the weir that controls the outflow at the downstream end of the channel. If this level is below the mean water level in the Umfolozi, saline water from the tidally influenced Umfolozi could flow into the closed St Lucia system. Flow in the opposite direction could occur during ebb-tides if water levels in St Lucia are above the crest of the back channel weir. As noted previously accurate simulations of this scenario requires a linked water balance model for both basins. However, it is evident that the back channel would not be effective in providing significant fresh water flow into St Lucia in this scenario.

Closed Umfolozi mouth with the St Lucia mouth open
In this scenario the St Lucia estuary would be strongly influenced by tidal exchange flows. In order to maintain a fresh-water flow into St Lucia via the back-channel, the water level of the Umfolozi needs to be higher than that in the St Lucia Estuary. If it occurs, this fresh water could dilute the tidal inflow of seawater into St Lucia. However the tidal exchange simulations by Hutchison (1976) have shown that most of this water would simply be lost on the ebb tide. Nevertheless, with an average nett inflow into St Lucia of 5.5m^3/s (see Section 2.1.4) and incorporating 1.9m^3/s of fresh water from the back channel, a diluted salinity concentration of about 26ppt is theoretically possible for the mouth inflows into St Lucia. It is important to note that this scenario is highly improbable since the Umfolozi mouth remains open for most of the time and if the St Lucia estuary was breached naturally, it is likely that the Umfolozi would also be open.

Closed Umfolozi mouth with the St Lucia mouth closed
In the case of the Umfolozi mouth closed concurrently with the St Lucia mouth, water levels in both systems would be dependent on river flows. Provided that water levels in the Umfolozi are higher than in St Lucia, fresh water would flow into the lake increasing water levels and decreasing salinities. Scenario 1B provides a long-term simulation of a system with this configuration. However, as discussed in Section 3.4, the likelihood of the Umfolozi remaining closed for extended periods beyond the low flow season from June to September is very small.

In summary, the supply of water via the back-channel could dampen the effect of drought conditions in terms of lake salinities and water levels. However the configuration of the two mouths plays a major role in the functioning of this scenario. When both mouths are open, the back-channel will become ineffective. With the Umfolozi open and the St Lucia closed, sea water could flow into the system during high tide and flow out of St Lucia could occur during low tides. With the Umfolozi closed and the St Lucia open, the additional fresh water flow could dilute the salinity of the tidal inflows to about 26ppt as opposed to pure sea water (35ppt). In order for this strategy to work most effectively, both systems must be closed. The most suitable cross-sectional area of the back-channel is discussed in Section 3.5.2.

3.3 Short Term Simulations

The following scenarios were simulated for the next nine months both with and without the addition of fresh water via the Back-channel:

- Average rainfall scenario
- Above average rainfall scenario
- Below average rainfall scenario

The simulations were initialised using measured data at closure of the mouth in September 2007.

3.3.1 St Lucia water levels and salinity scenarios for the next nine months

Rainfall for the next nine months was forecast using statistical analysis of historical data. The median (50th percentile, average rainfall), 75th percentile (above average rainfall) and the 25th percentiles (below average rainfall) were estimated for each month and are presented in Table 3. This rainfall was used to simulate the next nine months of runoff into the lake and the Mfolozi catchment using the FDC method and the resulting water balance for the system was predicted.

Table 3 Forecasted rainfall using percentiles

	Forecasted Rainfall (mm)												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	MAP
75th	100	105	114	153	142	160	91	76	61	52	52	67	**1091**
50th	75	75	81	85	103	95	59	39	30	28	25	41	**863**
25th	40	60	50	53	61	63	42	22	14	16	12	20	**735**
10th	30	37	33	37	36	41	28	13	8	9	5	15	**624**

Rainfall forecasts for South Africa by Weather SA (2008) are provided in Appendix A1. Above and below "normal" rainfall for three consecutive months were compiled from a number of different weather models. The majority of the models predict that St Lucia will experience above normal rainfall for the next three months. Note that the darker colours (higher percentages) represent the number of models in agreement.

Figure 3.7 shows the nett annual rainfall/evaporation index from 2000 until 2010 for Lake St Lucia with the predicted average, below average and above average rainfall annual indices. Note the predicted negative nett rainfall index for both average and below average rainfall in 2008 and 2009.

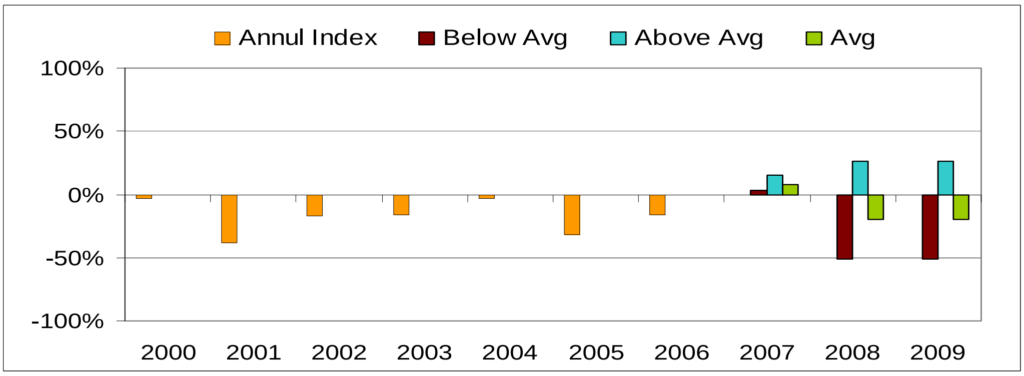


Figure 3.10 Nett Rainfall Index.

The monthly evaporation losses for the lake that were used in the water balance model are provided in Table 4 (Hutchison, 1976).

Table 4 Average Evaporation losses for Lake St Lucia

AVERAGE EVAPORATION (mm)												
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
140	155	175	175	145	150	105	85	65	70	90	115	1470

At average water levels the monthly losses to evaporation vary approximately in the range 20Mm^3 to 60Mm^3 (lowest during the period June to August). At low water levels (-1mEMWL) the evaporative losses are in the range 10Mm^3 to 30Mm^3

Average future rainfall scenario

Simulation results presented in Figure 3.8 illustrate monthly average salinities and water levels from September 2007 (when the mouth closed) and forecast (until 2010) with and without fresh water from the Umfolozi/Umsunduze via the back-channel. Forecast inputs were based on the median of the historical rainfall data. Note the overall increase in salinity, eventually reaching hypersaline conditions, and the overall drop in water levels from mouth closure in September 2007. The additional fresh water maintained salinities just above 35ppt, whereas without the additional fresh water, salinities continued to increase. Measured average lake salinities are also included in Figure 3.8 for comparison.

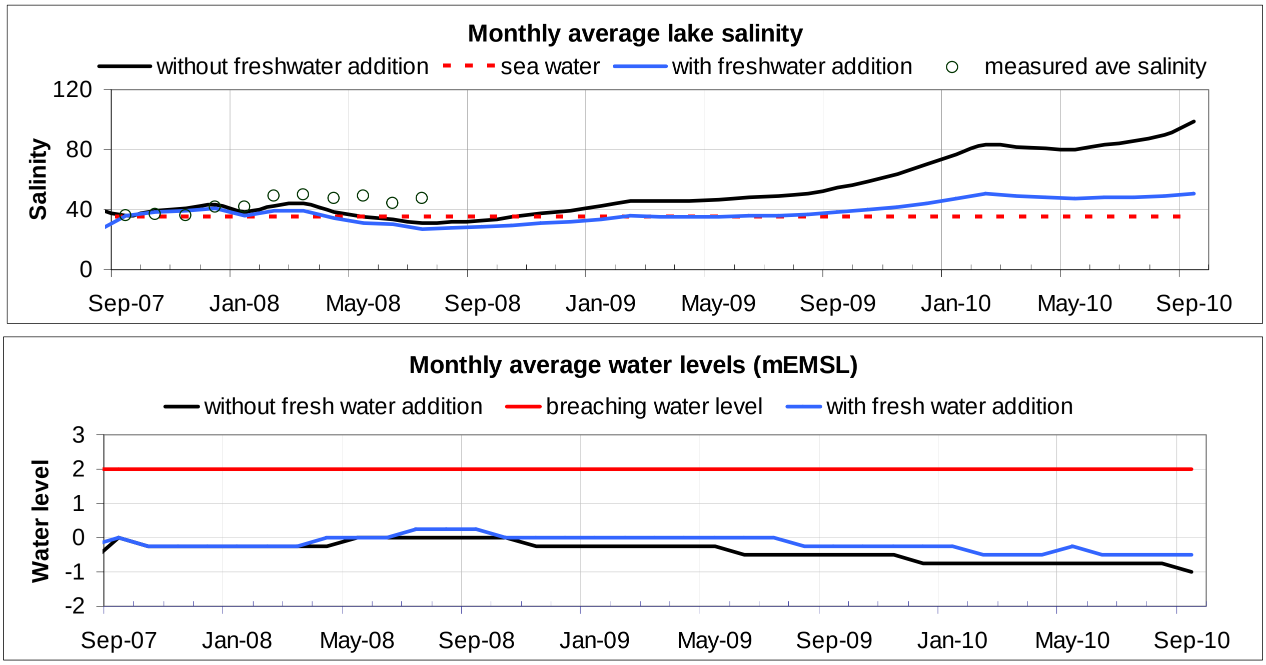


Figure 3.11 Simulations for average rainfall.

With the addition of fresh water from the Umfolozi/Umsunduze via the back-channel, the overall increase in salinity occurs at a much slower rate than without the link. Also, salinities tend to remain below 35 ppt in this case. The smaller decrease in water levels indicates the importance of the extra fresh water input for the prevention of desiccation. There is however still an upward trend in salinities and a downward trend in lake levels after mouth closure in September 2007. The probability that salinity levels will become intolerable is higher without the fresh water addition; however salinities continue to escalate in both cases. The mouth state is predicted to remain closed in both cases.

Above average future rainfall scenario

Simulation results presented in Figure 3.9 illustrate monthly average salinities and water levels with above average (75th percentile) monthly rainfall data. The system with and without a back-channel flow of $5Mm^3$/month is shown. In this case the system is unlikely to experience high salinity levels within the next year. Water levels rise until a water level of about 1m EMWL is reached. The additional $5Mm^3$/month of fresh water via the back-channel has no significant effect on the predicted salinities and water levels in this case. Obviously for this back-channel flow to occur, water levels on the Umfolozi side would have to exceed the levels on the St Lucia side.

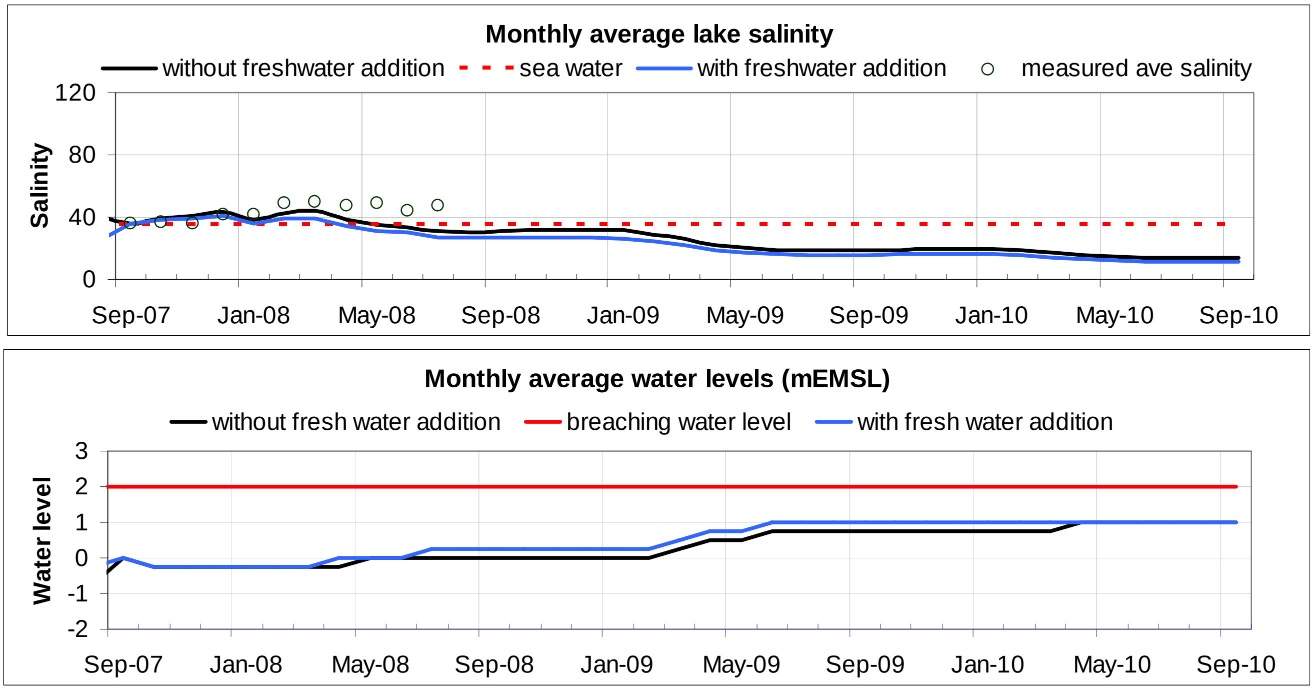


Figure 3.12 Simulations for above average rainfall.

Below average future rainfall scenario

Simulations assuming below average rainfall (25th percentile) until September 2010 are shown in Figure 3.10. In this case hypersaline conditions are predicted to occur both with and without the addition of fresh water. The additional fresh water delays the onset of hypersaline conditions by a few months. Water levels remain below EMWL with a slight increase during spring rains in 2008. With the significant increase in salinity and the drop in water levels, desiccation is likely to occur. The mouth is predicted to remain closed in both cases.

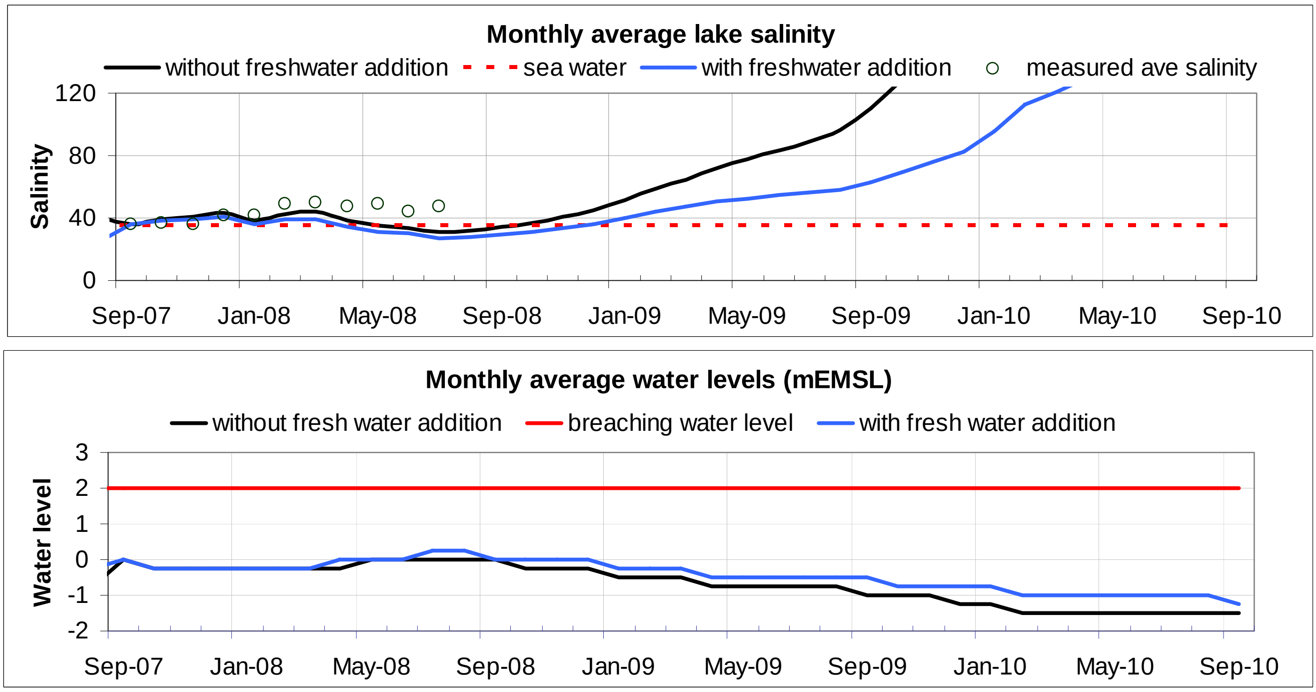


Figure 3.13 Simulations for below average rainfall.

In summary, the probability that intolerable salinities would be reached in the various scenarios discussed above is high if below average rainfall were to occur and low if above average rainfall were to occur. Hypersaline and even desiccation is likely if rainfall is below average. The addition of fresh water would however delay this by a few months. The addition of fresh water is valuable in dampening or delaying very high salinities and very low water levels.

3.4 Flow probabilities for the Umfolozi/Umsunduze

In order to investigate the probabilities attached to the flow of fresh water from the Umfolozi/Umsunduze for the next nine months, flow duration curves were plotted for each month (see Appendix B1) and a summary of the data is presented in Table 5.

Extremum analysis of the monthly Umfolozi flows indicate that a flow of 1183 Mm^3 has a 50-year return period, 604 Mm^3 has a 10-year return period, and 231 Mm^3 has a 3-year return period. The probabilities of these flows occurring in the next year are 2%, 10% and 33% respectively. The probability that flows will drop below 5Mm^3 is estimated to be 8% in any single month, 3% for two consecutive months and 1% for three consecutive months. Flows of below 5Mm^3 are emphasized in order to meet a minimum Back-channel flow of that amount. Note that monthly flows in the Umfolozi are lowest during the months June to September and are below 5Mm^3 for on average between 10% and 30% of the time during these four months (refer to Table 5).

Table 5 Umfolozi flow statistics

Umfolozi Flow Statistics (Mm^3/month)													
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	MAR
Mean	51	58	80	107	151	153	69	32	19	28	16	40	730
Standard deviation	108	71	79	150	201	378	139	33	19	66	28	111	
Flow exceedances….													
25%	28	64	117	120	142	115	53	35	20	15	12	13	843
50%	18	35	52	64	62	57	34	19	11	8	7	8	471
75%	10	18	26	41	36	32	22	12	9	6	5	4	327
90%	6	12	16	22	24	19	13	7	5	4	3	3	226
Probability that flows will be less than													
5Mm^3/month (%)	8	2	0	0	0	0	1	2	10	17	27	27	
10Mm^3/month (%)	22	3	2	2	1	0	6	16	39	61	67	63	

The expected change in water level for each month was estimated for the Umfolozi basin under closed mouth conditions and allowing for a 5Mm^3 monthly flow via the back-channel into St Lucia. We estimate that a flow between 5 Mm^3 and 6Mm^3 per month would open the Umfolozi mouth within that month. Therefore, the mouth would only be likely to remain closed during the months June to September. If above average rainfall (75th percentile) was to occur over the next nine months, simulations indicate that the mouth will breach and the back-channel will become ineffective (see Section 3.2.4). If however, average or below average rainfall were to occur, the Umfolozi may remain closed from June to September but could have insufficient flow to supply the full 5Mm^3 per month to the back-channel.

3.5 Back-channel Dimensions and Flow

In this section we discuss the deepening or widening of the back-channel (see Figure 3.11) to allow increased fresh water flow from the Umfolozi/Umsunduze into St Lucia, and making provision for the rapid closing of the back-channel in the event that the Umfolozi river comes down in flood.

Figure 3.14 Aerial view of the back-channel (Google Earth, 2008).

3.5.1 Back-channel flow

From long-term simulations, the estimated flow rate required to restore *virgin* flow contributions to the lake was found to be 5Mm^3 per month. This equates to a flow of approximately 1.9m^3/s. Broad-crested weir hydraulics (Equation 2.4) was used to estimate the critical depth and from that the maximum flow expected over the weir that controls the discharge from the back-channel. A critical depth of roughly 150mm with an extra 100mm for channel losses was found to be sufficient to provide a flow of 1.9m^3/s (5Mm^3 per month). Increasing the depth to 1m would provide a flow of about 36m^3/s (about 95Mm^3 per month), well above the required 1.9m^3/s.

Figure 3.12 illustrates the various water levels for the St Lucia Estuary, Umfolozi Estuary and the back-channel. The Estuary Mean Water Level is denoted as EMWL and is the mean water level of the estuary when open. The gauge plate refers to the St Lucia bridge gauge plate where EMWL is equal to +1.0m. In relation to geodetic mean sea level (GMSL), the actual mean sea level (MSL) is +0.20m and EMWL is +0.45m. A scale of GMSL is also provided in the sketch, but it should be noted that there remains a 200mm unresolved discrepancy in relating the GMSL datum to the St Lucia gauge plate. The levels shown are defined as follows :

- MFBL (the Umfolozi Breaching Level) - the minimum level required to meet hydraulic requirements for the back channel – its maximum value should be selected to prevent damage due to inundation of farmland
- SLBL (St Lucia Breaching Level) i.e. the natural berm levels for this location.
- BCWL (Back-Channel Weir Level) is the height of the weir crest at the discharge end of the back channel.
- HWS and LWS are the Spring High Tide Water Level (+1.05m MSL) and Spring Low Tide Water Level (-1.05m MSL) in the sea respectively. The neap high tide level is about +0.25m MSL and the neap low tide water level is -0.25m MSL.

- HWSE is the Spring High Tide Water Level in the Estuary when the mouth is open and is estimated to be between 1.6m and 2m on the gauge plate. Water level measurements, recorded by DWAF, at the St Lucia Bridge in 2007 indicated that the HWSE was about 1.6m.

The crest of the back-channel “weir” needs to be high enough to avoid the loss of water from St Lucia to the Umfolozi when water levels in the Umfolozi are lower than those in St Lucia and preferably high enough to avoid sea water from entering St Lucia during spring high tides when the Umfolozi mouth is open. Therefore we suggest BCWL must be larger or equal to HWSE (1.5 to 2m on the gauge plate). A water level of 0.25m above BCWL (1.75 to 2.25m on the gauge plate) is required to maintain a flow of 1.9m³/s. Therefore, the MFBL would have to be set from 1.8 to 2.3m (on the gauge plate) in order to allow for flow to occur through the back-channel. If MFBL is increased further, the flow via the back channel could be increased, but the MFBL level should be limited to prevent inundation of adjacent farmland. This does not leave much allowance for flow through the back-channel before a breaching event should occur in the Umfolozi. The SLBL level has been indicated as 2m above EMWL (3m on the gauge plate), which corresponds approximately to observed natural berm levels at this location.

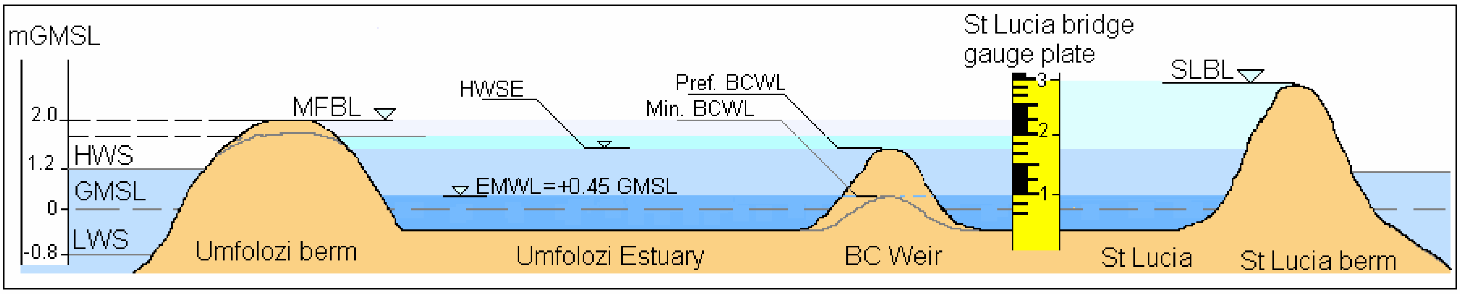


Figure 3.15 Schematic showing key levels required for the functioning of the back-channel (not drawn to scale). BCWL is the Back-Channel Weir Level and MFBL/STBL are the Umfolozi and St Lucia Breaching Levels respectively.

3.5.2 Back-channel dimensions

Flow is proportional to the cross sectional area of a channel, therefore an increase in channel area will result in an increase in flow and vice versa. Alternately, a larger channel will require less hydraulic head difference between the Umfolozi and St Lucia estuary to provide a specified flow rate.

A channel that is very large will in effect result in a joined mouth scenario. The larger channel, by allowing larger link flows into St Lucia, will reduce the build up of water levels in the Umfolozi and therefore reduce the likelihood of it breaching. However, in the event that the Umfolozi came down in flood, large silt loads could flow into the Narrows and providing a means for rapid closure of the back-channel would be difficult.

A small channel on the other hand would facilitate easier control of the flow rate and rapid closure if required. With a smaller channel, breaching of the Mfolozi will occur sooner in the event that the Umfolozi River comes down in flood, thus reducing the chance of high silt load entering the St Lucia system.

It is possible to generate linked water balance models for both the Umfolozi and the St Lucia basins that can simulate the functioning of the linked systems under various scenarios in more detail. This will however require a bathymetric survey to establish the water-level/surface area/volume relationships for the Umfolozi basin.

4 Conclusions

Due to the separation of the Umfolozi mouth, the system is functioning fundamentally differently to how it would naturally. Simulations suggest that with a combined mouth, the system would be predominantly open with stable water levels and salinities. During dry conditions, salinities increase linearly and reach hypersaline conditions during open mouth conditions until the mouth closure. During closed mouth conditions, water levels would rise and salinities would decrease due to the addition of fresh water from the Umfolozi. The rising water levels would cause the mouth to breach and the cycle would continue. Simulations indicate that a flood with a three-year return period would be sufficient to breach the system in this scenario.

The separation of the Umfolozi mouth results in a predominantly closed, fresh water system with highly variable water levels. The system would open briefly during floods. During drought conditions, the closed estuary would have salinities that would increase exponentially while water levels dropped. In order for the mouth to breach, this system would need approximately a ten-year return period flood. An additional 5Mm^3 per month of fresh water delivered via the back-channel would restore the 20 % reduction in fresh water inflows to the system due to anthropogenic activities (primarily abstractions from the Mkuze). The additional fresh water would dampen the effect of drought conditions in terms of lake salinities and water levels and the mouth state would remain open longer. This is however dependant on the configuration of the mouths. In order for this strategy to work most effectively, both systems would have to be closed.

It has been estimated that a minimum depth of 250mm above the crest of the back-channel “weir” is required to maintain a flow of 1.9m^3/s (5Mm^3 per month). Therefore it is recommended that the crest of the back-channel “weir” be at HWSE (+1.5 to 2.0m on the St Lucia bridge water level gauge) and the MFBL at 1.8 to 2.3m (on the gauge plate).

The probability that the Umfolozi mouth will close (and remain so) is significant only during the low flow months from July to September. Therefore a continuous supply of fresh water into St Lucia via the back channel would generally not be maintained outside of this period.

Historical rainfall was used to forecast rainfall for the next nine months. Simulations suggest that above average rainfall will provide a positive nett rainfall/evaporation index and average and below average rainfall a negative nett rainfall/evaporation index. The probability that intolerable salinities would be reached in the next nine months is high if average or below average rainfall were to occur and low if above average rainfall were to occur. Hypersaline and even desiccation is very likely to occur if below average rainfall persists. The addition of fresh water would however delay this by about 6 months. Forecasted rainfall predictions by Weather SA indicate that above “normal” rainfall is expected over the next three months.

The probability of flows in the Umfolozi being less than 5Mm^3/mth is in the range 10% to 30% during the months June to October, but is less than 2% during the remainder of the year. If above average rainfall is received over the next nine months, we predict that there should be sufficient water to supply 5Mm^3/mth into St Lucia. However if average or below average rainfall is received, we predict that there will be insufficient water to provide this supply into St Lucia.

5 Recommendations

Our model simulations suggest that the long-term implications of past management decisions have completely altered the natural functioning of the system and the system is now functioning fundamentally differently to how it did in the past. The key result of the simulations is the conclusion that the separation of the Umfolozi and St Lucia mouths is by far the most significant anthropogenic intervention in terms of long-term impacts on the functioning of the St Lucia system. Aside from providing an important source of fresh water inflow to the system when the combined mouths are closed, the Mfolozi also plays a key role in providing a more stable mouth state regime for the system.

The perceived threat of siltation to the lake due to the silt-laden Umfolozi is the fundamental driver for a strategy of artificially maintaining a separate Umfolozi mouth. However, the issue is poorly understood and there appears to be no scientific evidence linking the silt deposits in the St Lucia lake basin to the Umfolozi. This needs to be thoroughly and expeditiously investigated and the sediment origins for the St Lucia basin clarified. The mechanisms governing the mouth dynamics also need to be further researched to develop our understanding of this complex issue and improve our confidence in the modelling of mouth processes.

In summary our primary recommendations are that:

1. The back-channel link should be maintained essentially as it is, with some adjustment of the control point elevations if required. Overall the additional freshwater delivered via the back-channel is beneficial to the system in its current state. However these benefits are limited and are likely to be short-lived since there is a high probability that the Umfolozi will breach at the onset of spring rains.

2. The management strategy should move away from persistent intervention towards a new strategy of non-intervention, supplemented by detailed monitoring. This implies allowing the re-establishment of the historical configuration of a combined Umfolozi/St Lucia mouth. The monitoring program, together with on-going research, should focus on the uncertain issues concerning siltation and mouth dynamics. For example the recent high resolution bathymetric survey of the lower Narrows will be a useful baseline from which to monitor siltation effects.

Finally we note that while considerable scientific research has been undertaken on the biological component of the system, there has been limited research on the physical dynamics of the systems and on how the biology responds to changes in the physico-chemical environment and mouth dynamics. The development of an integrated biophysical model should help us understand how different management strategies affect the biological functioning of the system.

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APPENDICES

Appendix A: Forecasted rainfall of South Africa for the next three months

Appendix B: FDCs of the Umfolozi River for each month of the year

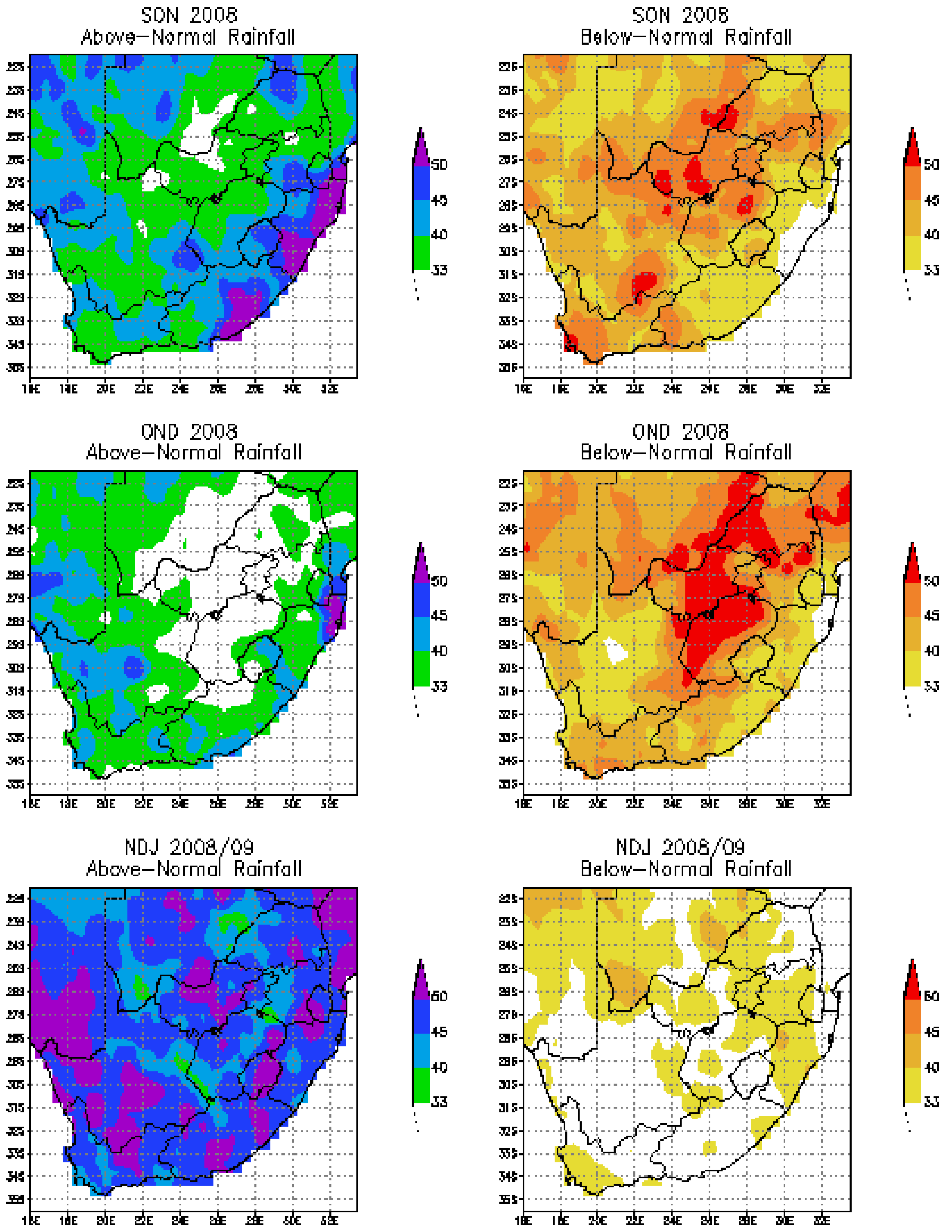

Figure A1 Three month above and below normal rainfall forecast for Southern Africa 2008 (Weather SA).

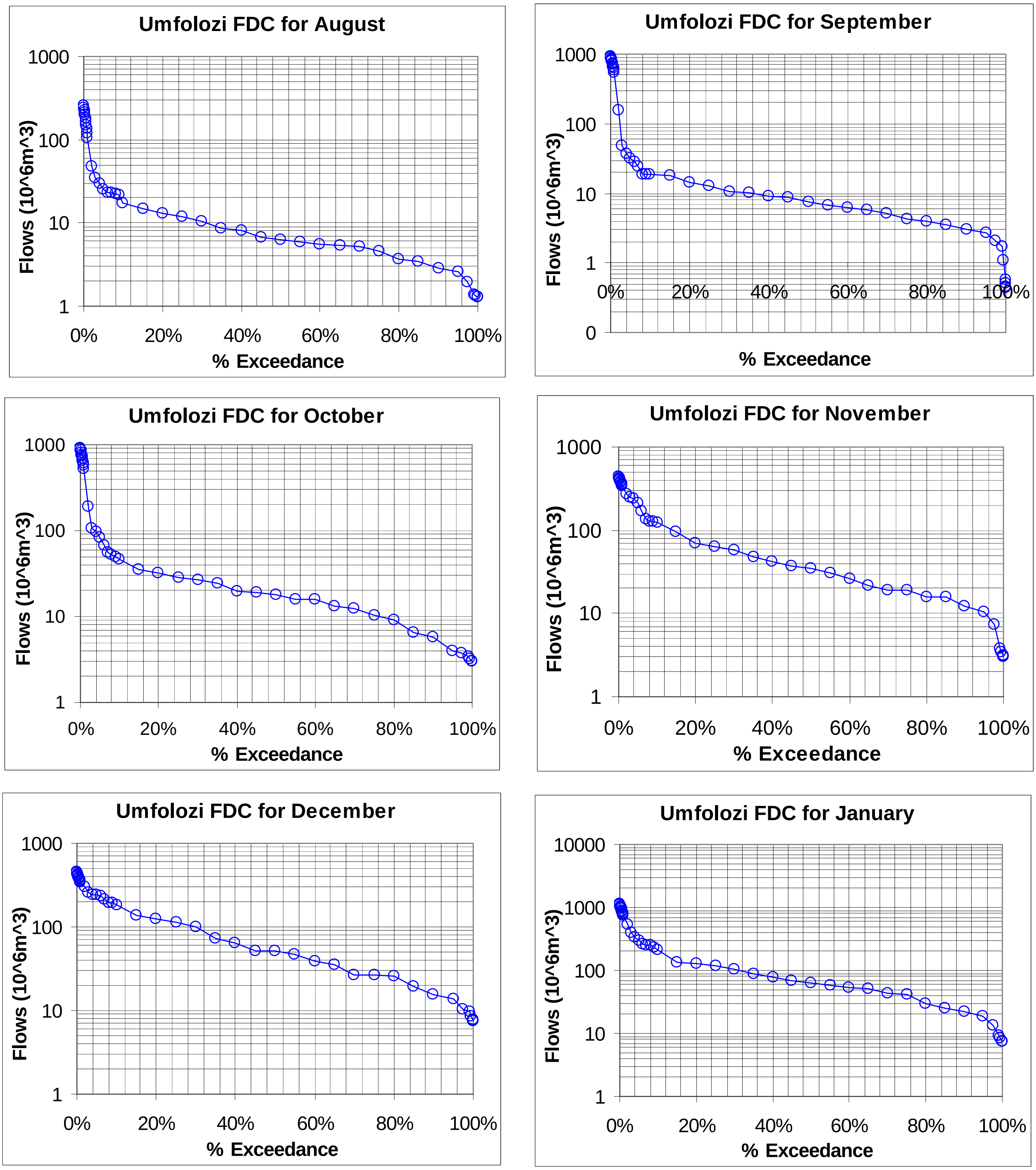

Figure B1: FDC of the Umfolozi from August to January

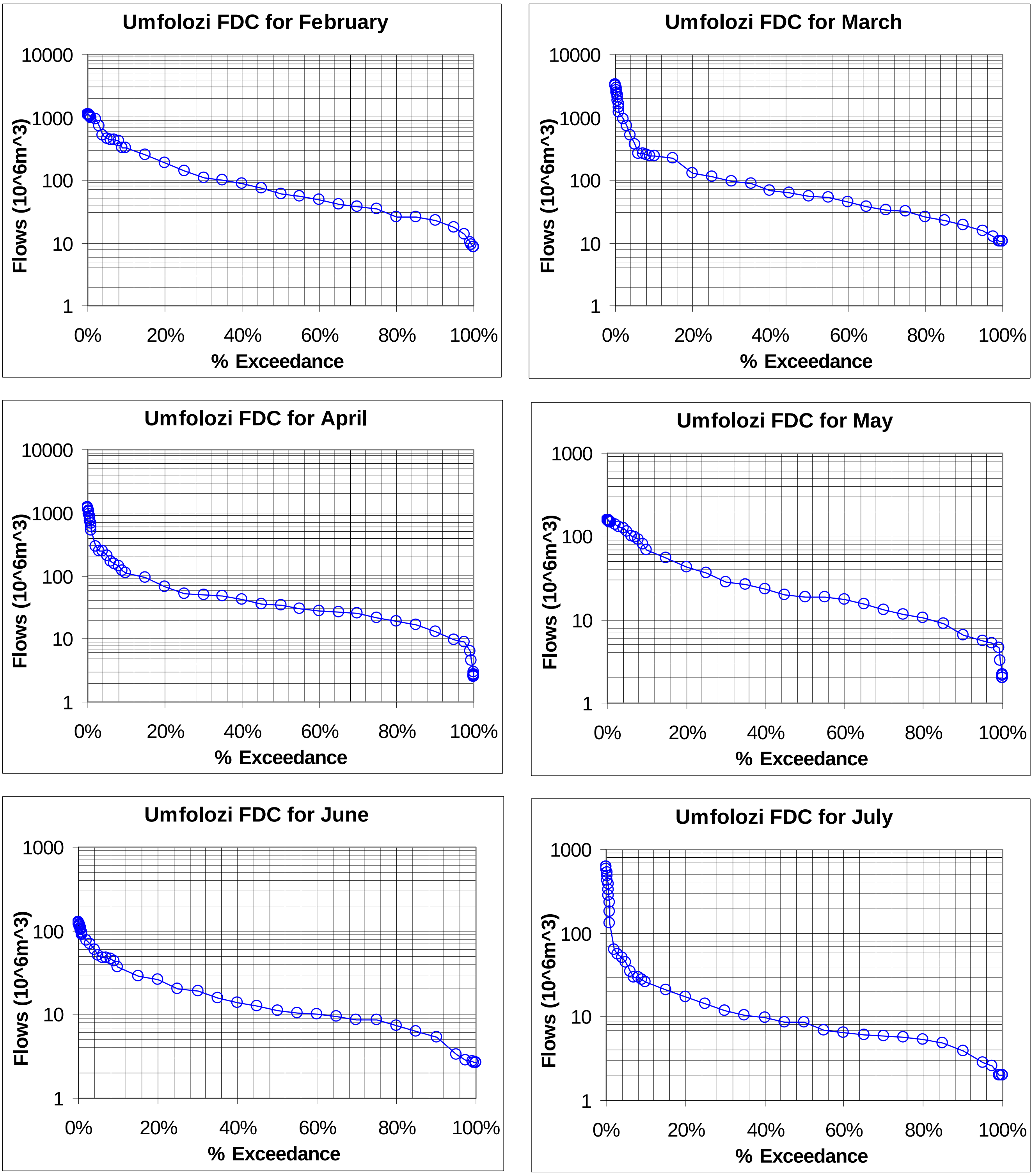

Figure B2: FDC of the Umfolozi from February to July