MLALAZI ESTUARY AND FLOODPLAIN: HYDROLOGY AND VEGETATION DYNAMICS

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Report to the

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EXECUTIVE SUMMARY

South Africa has 280 estuaries, of which about 75% are classed as Temporarily Open/Closed Estuaries (TOCEs). The ecology of TOCEs is very much dictated by mouth closure events, the frequency of closures, how long the mouth remains closed each time and how much backing up of water occurs behind the closed mouth.

This study focused on the Mlalazi Estuary. Its purpose was to understand and model the evolving relationship between fluvial and marine conditions that control the mouth dynamics and estuarine vegetation.

TOCEs are very much influenced by catchment inflows – both the frequency and magnitude of inflow events. These influence the mouth closing process and the natural beaching. A component of this study has focussed on the rainfall of the Mlalazi catchment area and the patterns of flows entering the Mlalazi estuary/floodplain basin to establish a reliable estimate of the depth-duration-frequency of flows and sediment into the estuary using a calibrated and validated hydrological model.

To understand the hydrodynamics of the estuary and its floodplain, a DEM was developed. This enabled the calculation of hypsometric curves that give the relationships between estuary and floodplain water levels, the volume of water held in the basin and the area of the estuary and floodplain that is inundated by floods of different magnitudes. From this the area flooded with different intensities of floods, and the velocity of the floodwaters are simulated using a calibrated numerical model.

The controlling hydrodynamic feature of the estuary is the mouth. Much of the study has considered the behaviour of the mouth in relation to changes in the estuary. Continuous water elevation fluctuations were recorded at various sites in the estuary. Satellite data were used to study the changes in mouth morphology, and sea tides data for Richards Bay were used as estimates of the fluctuations in the sea at Mlalazi. From these, water volumes passing through the mouth were calculated – based on the changes in estuary water level during flood and ebb tides.

The short monitoring record shows that the ebb tides have a period that is double that of the flood tide period, creating a higher inflow velocity though the mouth during the flood tides in the estuary that can be attributed to the interaction with the marine tides. This can create an imbalance in the estuary storage between flood and ebb tides during spring tides and the systematic accumulation of sediments at the mouth.

The monitoring data further indicates that there is an accumulation of sediments that progressively reduces the estuary-marine interaction leading to the partial closure of the mouth during periods of low runoff from the catchment. However, the data indicates that the stochastic runoff events of varying magnitude can interrupt the progressive mouth closure by changing the estuary water level (storage) that can induce sediment mobility and reduce the mouth elevation through scouring processes.

From the ecological perspective, Mlalazi Estuary, as a TOCE, is a special case. It closes naturally every few years. But, since the late 1890s, it has not been allowed to remain closed for long enough to allow the water level to rise behind the closed beach berm. Since then it has always been breached artificially when water levels threaten to flood crops and infrastructure for extended periods. This has had a profound effect on the ecological functioning of the estuary and it now has many characteristics of a Permanently Open Estuary.

This study accumulated historical records relating to the estuary management. The mouth breaching has enabled mangroves to colonise the estuary. They were absent from it until the 1930s and now there are 40 ha of mangrove habitat. If there is prolonged back-flooding it will kill-off these mangroves. Colonisation from adjacent estuaries is a process fraught with difficulties for the plants and hence the probability of successful recolonisation is low.

The submerged water plant *Zostera capensis* occurs in small quantities in the estuary, and only under specific conditions where there is strong marine connectivity and suitable salinities. This study considers the scenario where, in the absence of artificial breaching of the mouth, there is the potential for considerable growth of several species of submerged water plants as estuarine water backs-up behind a closed mouth. A rich growth of several species of submerged plants could be the result.

This study also considers the parameters that influence the vegetation of the estuarine floodplain. There are several different types of flooding – each having specific characteristics and impacts.

These include:

River floods, which may rise to almost 10 m, are high-energy events where sediment-laden freshwater flushes the estuary. These floods last for a few days. The velocity of the outflow can scour the estuary mouth.

Flooding caused by water backing up behind a closed mouth is a slow event that may raise water levels by 3 to 4 m. If the water is saline on closure, it is diluted by the inflowing river water – resulting in the flooded areas being inundated with low salinity or fresh water. The water has low turbidity and no sediment movement occurs. Breaching may be an event where outflows are rapid and would scour sediments from the mouth area if there is a sufficient head of water at the time of breaching.

Storms at sea may result in storm-surges. If these are associated with extreme high tides, the result will be flooding of the estuary with saline water. The salinity will kill vegetation.

In addition to the above, there are the twice-daily and two-weekly tidal cycles which flood the intertidal areas of the estuary. Under extreme tidal events these will flood the supratidal area of the estuary. This flooding may be with marine water near the mouth, and with estuary water upstream of the saline wedge that enters with each high tide.

Floodplain vegetation is shaped by these different flooding events, resulting in complex patterns. Adding to the variability is the effect of groundwater and small streams that wet parts of the floodplain with freshwater in a very consistent manner.

The mouth state is a transient condition that cannot be modelling using steady state or acyclic modelling methods applied to Bayesian models. It comprises both transient and stochastic events that determine the state at any point in time. Consequently, the attempts to statistically model the mouth state using probabilistic approach required a Dynamic Bayesian Modelling system. Two programs were examined with little success. An alternate approach using simplistic spreadsheet model showed sufficient potential to proposed further studies.

At present the main management intervention is to manipulate the mouth. The artificial breaching of the estuary mouth over the past century has had an overwhelming influence on the vegetation of the estuary. Care must be taken not to alter the present management regime without full cognisance of the implications of doing this.

CAPACITY DEVELOPMENT

MSc projects

- Rasifudi K J (2018). Simulation of catchment runoff, erosion and sediment transport using a transient numerical model for Mlalazi Catchment. MSc dissertation submitted to University of Zululand, Dept Hydrology 100pp.
- Mmako L V (in prep); Flow and sediment dynamics of Umlalazi Estuary in KwaZulu-Natal of South Africa.

Honours projects

Table I: Honours projects done as part of this study.

Student name and Number	Year	Project Title
Msweli, M. P. 201063413	2016	A description of the sediments at the river-estuary and the estuary-sea interfaces of the Umlalazi Estuary
Ndwandwe L. 201079710	2016	A description of the basin sediments in the Umlalazi Estuary
Nsibande L. L. 201055278	2016	A description of beach profiles, sediments and vegetation in the vicinity of the Umlalazi Estuary, Mouth.
Dlamini K. N. 201230063	2016	Description and mapping of sediment patterns and Processes of the floodplain of the Umlalazi Estuary – backwaters.
Mabaso M. P. 200957811	2016	Description and mapping of sediment patterns and Processes of the floodplain of the Umlalazi Estuary – flow channels
Mkhungo B N 201334505	2016	To estimate the hydrological attributes for each category of land use derived from land cover images
Mtshali R N 201224629	2016	To estimate the sediment transport along the Mlalazi River from a study of the river geomorphology
Sigabundu S N 201255886	2016	Determine the sediment loads and historical flows for the Ntuze River
Mpungose M S 201304956	2016	The temporal and spatial patterns of rainfall and pan evaporation affecting the Mlalazi Catchment
Mbatsane M S 201000411	2016	The hydro-geomorphic features of the Mlalazi Estuary floodplain
Mpungose MPB 201329572	2017	Surveying Mlalazi floodplain transect using a Differential Geographic Positioning System to assist with the creating a Digital Elevation Model
Mkhize B C 201088536	2017	Mapping the changes in the Mlalazi Mouth Configuration
Hlabisa, SM 201315221	2017	An Investigation of Soil and Groundwater Characteristics in Ncema (*Juncus kraussii*) And Reed (*Phragmites australis*) Plants at Mlalazi Estuary Floodplain, KwaZulu-Natal.
Mtshali, ZP 201309587	2017	The Investigation of The Effects of Groundwater on Salt Marsh Vegetation at Mlalazi Estuary
Nkosi, M 201441629	2017	The Influence of Crab Burrows on Groundwater in Mangroves at Mlalazi Estuary, KZN
Zondo, PS, 201316104	2017	Investigation of Groundwater Effects on The Distribution of Plants in the Malazi Estuary
Zulu, SG 201435337	2017	An Investigation of groundwater in vegetation At Mlalazi Estuary
Tembe SS 201320053	2018	Floodplain mapping to upgrade the DEM
Hlatshwayo S 201251219	2018	Measurement of the flow rates through the Mlalazi estuary mouth during a flood tide.
Buthelezi, ML 201243323	2018	Modelling population dynamics of the black mangrove (Bruguiera gymnorrhiza) in the Mlalazi Estuary*

Student name and Number	Year	Project Title
Dzanibe, S 201534755	2018	The effects of flooding on sediment transport and distribution at the Mlalazi estuarine floodplain.
Mbuyazi, XSM 201453661	2018	The relationship between soil salinity and groundwater salinity and flooding frequency in the Mlalazi floodplain.
Msomi, S J 201452361	2018	Vegetation responses to flooding frequency along the Mlalazi estuarine floodplain, KwaZulu-Natal

**Project ongoing*

Lecture course

- Taylor R.H. (2018). Mangroves. A six-lecture module, including a field excursion to the Mlalazi mangroves, presented to the Zoology Honours students.

Papers

- Taylor, R.H. (in prep). Mangrove colonisation of the Mlalazi Estuary in response to artificial breaching: an ecological history. *In*: Janine Adams and Alan Whitfield (Editors) Special issue of African Journal of Aquatic Science entitled: Perspectives on protecting African estuarine ecosystems in the Anthropocene.

Species guides

Two iNaturalist guides were developed to assist students to identify species. These are:
In the mangroves of Mlalazi Estuary: https://www.inaturalist.org/guides/8154
Mlalazi estuarine floodplain: https://www.inaturalist.org/guides/7739

Presentations

- Rasafudi, K.J., B.E. Kelbe and B.K. Rawlins (2019). Simulation of catchment runoff, erosion and sediment transport using a transient numerical model for Mlalazi Catchment. *Presentation at International Water Association Young Professional Conference, Canada.25/6/2019.*
- Taylor, R.H. (2017). What we know about the Mlalazi Estuary and what we would like to know. *South African Marine Science Symposium, Port Elizabeth. 4-7 July 2017.*
- Taylor, R.H. (2017). Historical ecology: Insights into past conditions and future trajectories of change in the Mlalazi Estuary. *Contemporary Conservation Symposium, Ferncliff, Pietermaritzburg, 6 to 10 November 2017.*
- Taylor, R.H. (2019). The Mlalazi Project. WRC 101 Youth roadshow programme for water researchers. *UniZulu 22 May 2019.*

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- Frans le Roux and the DWS hydrographic survey team from Potchefstroom for their bathymetric mapping in the estuary downstream of the Railway Bridge.
- Much of the historical understanding of the system is from CJ "Roddy" Ward, Dr Burke Hill, and Prof William MacNae whose scientific works and historical notes from the 1960s provide insights to conditions at that time. Dr John Ward who provided access to the photos by CJ Ward.
- Prof Albert van Jaarsveld who provided historical details.
- One of the models described in this paper were created using the GeNIe Modeler, available free of charge for academic research and teaching use from BayesFusion, LLC, http://www.bayesfusion.com/
- Students at the University of Zululand – Hydrology and Zoology Departments – who assisted with field work (see the list of student projects for names of the students).

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TABLE OF CONTENTS

EXECUTIVE SUMMARY i
CAPACITY DEVELOPMENT iii
ACKNOWLEDGEMENTS v
LIST OF FIGURES x
LIST OF TABLES xv
PHOTOGRAPHS xv
ABBREVIATIONS AND ACRONYMS xvi
PLACE NAMES xvii

1. INTRODUCTION 1

2. STUDY AREA 2

2.1 Geological evolution of the Mlalazi Estuary 3
2.2 Human influences 5
2.3 Climate 6
2.4 Digital Elevation and Bathymetric Model of the Estuary. 9
2.5 Mouth characteristics 12
2.5.1 Beach Berm 13
2.5.2 Mouth Channel 14
2.5.3 Mouth Delta 15
2.6 Fluvial contributions to the Estuary dynamics 15
2.7 Estuary Water Levels (stage) 19
2.8 Estuary Simulated Hydrodynamics 21

3. ESTUARY DYNAMICS 26

3.1 Floodplain 26
3.2 Estuary channel 27
3.3 Estuary mouth 28
3.4 Estuary tidal characteristics. 29
3.4.1 Tidal period 30
3.4.2 Tidal range 30
3.4.3 Low Tide Predictions 31
3.5 Mouth Hydraulic Characteristics 32
3.5.1 Lag time during Flood and Ebb Tides 32
3.5.2 Flux rates through the mouth 33
3.5.3 Groundwater fluxes 33
3.5.4 Estimation of Mouth Elevation under Tidal influence. 35
3.5.5 Mouth Elevation after Fluvial/Breach Scour events 36
3.5.6 Mouth Elevation during Mouth Closure Conditions 37
3.5.7 Summary of Mouth Control Features/Indicators 38

4. EXAMPLES OF MOUTH CHANGES 39

4.1 CASE STUDY 1: MOUTH CLOSURE – June 2015 39
4.2 CASE STUDY 2: MOUTH CLOSURE – November 2017. 41
4.3 CASE STUDY 3: MOUTH BREACH – May 2018 42
4.4 CASE STUDY 4: STORM BREACH 43

5. MANGROVES 44

5.1 Introduction 44
5.2 Present and historical mangrove patterns. 44
5.2.1 Mangroves during the geological evolution of the Mlalazi Estuary 44
5.2.2 Historical conditions – Mlalazi as an estuary with no mangroves. 45
5.2.3 The colonisation of the estuary by mangroves and present mangrove abundance and distribution. 45
5.2.3.1 Historical evidence of mangrove colonisation 45
5.2.3.2 Anthropogenic changes and interventions that have facilitated mangrove colonisation 49
5.2.3.3 Present distribution of mangroves 51
5.2.3.4 Mangrove population growth – spatial expansion 52
5.2.3.5 The spread of mangroves from adjacent estuaries 55
5.3 Drivers and concepts needed to develop a conceptual model of mangrove growth in the Mlalazi Estuary 56
5.4 Conceptual modelling 58
5.4.1.1 Purpose of the models? 58
5.4.1.2 Conceptual model 1: A die-off model 58
5.4.1.3 Conceptual model 2: Transport and recolonisation of mangroves from another estuary. 59
5.4.1.4 Conceptual model 3: Establishment phase 59
5.4.1.5 Conceptual model 4: Population spread once established – the exponential growth phase 60
5.4.1.6 Conceptual model 5: Density dependence phase 60
5.4.1.7 Conceptual model 6: Succession of species and ageing of the population 60
5.5 Discussion 61

6. SUBMERGED MACROPHYTE PLANTS IN THE MLALAZI ESTUARY AND FLOODPLAIN 63

6.1 Introduction 63
6.2 Approach and methods 63
6.3 Study area 63
6.3.1 Water levels, areas and volumes 64
6.3.2 Estuary zones 64
6.3.3 Salinity in the Mlalazi Estuary 67
6.4 Historical and present distribution of submerged macrophytes 70
6.5 Zostera capensis: 70
6.5.1 Recovery of Zostera after a die-off 74
6.5.2 Submerged macrophytes other than *Zostera* 75
6.5.3 Future possible scenarios for submerged macrophytes. 76
6.6 Ecological drivers 77
6.6.1 A conceptual model for *Zostera* in the estuary 77

6.6.2 Conceptual model for water plants, other than *Zostera*, in the estuary 78
6.6.3 A conceptual model for submerged macrophytes in an inundated floodplain. 79
6.7 Modelling 80
6.8 Discussion 81

7. FLOODPLAIN VEGETATION 82

7.1 Approach 82
7.2 Descriptive ecology 82
7.2.1 The nature of floods and the floodplain 82
7.2.2 Flood inundation classes 84
7.2.3 Characteristics and effects of different types of flooding 86
7.2.3.1 Marine tides 86
7.2.3.2 Extreme marine tides and storm-surge flooding 86
7.2.3.3 Backing up of water during a closed-mouth event. 87
7.2.3.4 River floods and areas affected by them 88
7.2.3.5 Wetlands in the floodplain caused by freshwater seeps and streams 88
7.2.4 Groundwater effects 88
7.2.5 Geomorphological units 90
7.2.6 Vegetation in the full floodplain 91
7.2.7 Vegetation in the detailed study site 92
7.3 Towards a synthesis and conceptual model 95
7.4 Discussion 99

8. STATISTICAL MODELS OF MOUTH DYNAMICS 100

8.1 Conceptual Model of the Mouth Dynamics 100
8.2 NUMERICAL MODELS 101
8.2.1 Graphical Models 101
8.2.2 NETICA 101
8.2.3 GeNIe by BayesFusion, LLC 102
8.2.4 SPREADSHEET MODEL 105

9. SUMMARY AND CONCLUSION 109

10. REFERENCES 113

LIST OF FIGURES

Figure 2-1. The location of the Mlalazi study site comprising the runoff catchment represented by the black polygons and river network that discharge directly into the estuary. The Digital Elevation Model (DEM) of the estuary and floodplain is shown by the coloured contours. Also included is a Google Earth image of the mouth illustrating the mobile sandy berm that has a controlling influence on the estuary hydrodynamics. 2

Figure 2-2: Schematic depiction of the geological formation of the Mlalazi Estuary 4

Figure 2-3: Geomorphological units of the Mlalazi Estuary and Floodplain 5

Figure 2-4: Probability Density Function for storm Areas defined by three radar reflectivity levels (Kelbe, 1984) 6

Figure 2-5: The mean correlations over 5 km intervals for various accumulated rainfall series for summer month. Dashed lines represent the best fit power functions (Kelbe, 1987). 7

Figure 2-6: Storm isohyetal map of the five-day rainfall between 25 and 30 September 1987 (from Kovacs, 1988). 8

Figure 2-7: The selected catchment daily rainfall record for catchment and estuary hydrological studies 8

Figure 2-8: The probability distribution of rainfall accumulation over 1-, 2-, 3- and 6-month periods. .. 9

Figure 2-9: Water level and cross-sectional profile at the old N2 road bridge survey during several major flood events by Badenhorst *et al.* (1989). 9

Figure 2-10: The derived Digital Elevation Model (DEM) of the Mlalazi Floodplain with selected infrastructures. The Estuary floodplain has been divided into four regions where the hypsometric conditions are significantly different. The red triangles show the location of stage monitoring sites. 10

Figure 2-11: The Hypsometric curve for the entire floodplain and estuary channel 11

Figure 2-12: The hypsometric curves for surface area and volume for the channel below the 2 m contour. 11

Figure 2-13: The measured tidal range (red graph) before and after the mouth closure in December 2017 used to calculate the flow rate (m^3/hr) through the mouth (blue graph). 13

Figure 2-14: Sub-catchments network generated in HEC-GeoHMS 16

Figure 2-15: Observed (red) and simulated (blue) hydrographs for two storm events. 16

Figure 2-16: Calibration period cumulative observed (red) and simulated (blue) flows 17

Figure 2-17: Validation period cumulative observed (red) and simulated (blue) flows 17

Figure 2-18: Daily simulated flows (m3/s) and sediment yield (tonnes/day) from Mlalazi Catchment (after Rasifudi, 2018). 18

Figure 2-19: Simulated sediment yield grainsize distribution (tonne/day) 19

Figure 2-20: The combined logger water level series for all the available logger downstream of the Railway Bridge. Also shown in the lower plot are the rainfall series the lower sections of the catchment. 20

Figure 2-21: The HEC-RAS model covering the Mlalazi Estuary configured, calibrated, validated and applied by Mmako (2019). 21

Figure 2-22: The simulated water table profile along the estuary channel downstream of the confluence of the Mlalazi and Ntuze tributaries at the peak of the 1987 storm events shown by the blue shading.. 22

Figure 2-23. The spatial extent of the flooding along the Mlalazi Estuary under average flood conditions (1:2 year events) from Mmako (2019) 23

Figure 2-24: The simulated spatial extent of the flooding along the Mlalazi Estuary during a 1:10 year events (from Mmako (2019)........ 24

Figure 2-25: The simulated spatial extent of the flooding along the Mlalazi Estuary during a 1:50 year events (from Mmako (2019)........ 24

Figure 2-26: The cross-section profile at the Railway bridge for the 1987, 1932 and 1969 storm events (after Badenhorst et al., 1989). The water level almost reached 6 mMSL during the 1987 event with minimal scour between the 1932 and 1987 surveys........ 25

Figure 3-1: A Google Image of the floodplain shown by the white contour and the channel........ 26

Figure 3-2: The rainfall (lower graph) and the simultaneous measurements of the water level (upper graph) at the confluence of the two tributaries in the upper estuary (red line) and near the mouth (blue line) near the discharge point........ 27

Figure 3-3: The water level measurement near the mouth (red line) and at the confluence of the tributaries (Blue line) illustrating the magnitude of the lag and attenuation during the wave propagation from the mouth to the top of the estuary. 27

Figure 3-4: Water level measurements of the marine and estuary tides over a complete lunar cycle showing the lag and attenuation of the marine wave through the mouth........ 28

Figure 3-5: The level of attenuation of the marine tide entering the estuary for the observation period from 2014-2016. Some of the extreme values were due to fluvial events. 28

Figure 3-6: An example of the simultaneous marine and estuary tidal variation across the mouth. The lower arrows show the lag for the corresponding water level elevation in the marine and estuary tide across the mouth. The estuary tide would be expected to turn when the elevations were the same. 29

Figure 3-7: The marine and estuary tidal cycle showing the flood and ebb tide features in relation to the marine tide. 29

Figure 3-8: The duration of the flood and ebb tide at the mouth taken from the W1T001 logger series. 30

Figure 3-9: The high (red) and low (blue) tide series for W1T001 gauge during Apr-Jul 2014........ 30

Figure 3-10: Scatter plot of the high and low diurnal tidal elevation for W1T001. The grouping of points at the low tide elevation of1.6 m correspond to the period the mouth was closed........ 31

Figure 3-11: W1T001 logger series showing the diurnal Minimum (Low tide) and the modified low tide estimated from a direct proportion of the High Tide (H-H/5)........ 32

Figure 3-12: The calculated hourly flux (m^3/hr) through the mouth channel from May 2017........ 33

Figure 3-13: The model configuration for estimating the groundwater fluxes through the mouth with varying tidal action. 34

Figure 3-14: (A) The simulated groundwater fluxes out of the estuary (to the south) and the corresponding groundwater inflow during the marine high tides (blue). (B) The lower graph shows the estuary water level tides (red) and their high and low sequence in relation to the marine tides (grey series). 35

Figure 3-15: Example of the tidal pattern associated with the rainfall in the estuary catchment. 36

Figure 3-16: The water level measurements for the Mlalazi Estuary. The blue line shows the low tide. The grey lines show the hourly tidal range. The early period represents “drought” conditions when there were few large fluvial events. From 2017 there was a significant increase in rainfall and the occurrence of extreme storm events........ 37

Figure 3-17: The marine tides and estuary water level (Upper graph), the smoothed wind direction (middle graph) and the hourly wind speeds during the period leading up to the mouth closure in Nov 2017. 38

Figure 4-1: An example of the Mlalazi Mouth Closure in 2015. The two Google images show the state of the mouth on two dates in May and June during which the mouth became closed. The upper graph shows the tidal range in the estuary between the two dates shown and indicates that the mouth closed during the neap tide on 27 June 2015 when the tidal interaction ceased. The lower graphs show the wind direction and speed for the same period. 40

Figure 4-2: Conditions associated with the mouth closure during Nov 2017........ 41

Figure 4-3: Conditions during and after the mouth breaching event in the southern extent of the beach berm to protect anthropogenic activities in the estuary. 42

Figure 4-4: Conditions during and after the mouth breaching event in the southern extent of the beach berm to protect anthropogenic activities in the estuary. 43

Figure 5-1: The area marked with arrows is the Dunn's Pool area. These mangroves would be in the 'establishment' phase – as discussed in Figure 5-9. Photo from the Mtunzini Public Library. Photographer unknown and the date are unknown. The photo was possibly taken in the mid-1940s. 46

Figure 5-2: Early colonisation of a mud flat by Avicennia marina mangroves. This is the 'recruitment or establishment phase' stage in colonisation of an intertidal bank. The young trees have many lateral branches and a well-developed shallow rooting system as shown by aerial breathing roots around each plant. (Photo: Ward, 1960) 46

Figure 5-3: Rapid growth of a single-age cohort of Avicennia. These are closely spaced, straight-trunked and with little lateral branching. These mangroves would be reaching the end of their 'exponential growth'-phase (see Figure 5-10). (Photo: Ward, 1960) 47

Figure 5-4: Mangrove growth in Dunn's Pool area (beyond the present-day Estuary Car Park). Bruguiera gymnorrhiza are the dark 'conical' trees to left, central background and also to right (along the estuary margin). Avicennia is the primary colonising species which, to a large degree, facilitates the recruitment of Bruguiera. (Photo: Ward, 1960) 47

Figure 5-5: Mangrove development in the Dunn's Pool area (the Anchorage to the right, and the Estuary Car Park in the foreground) showing colonisation of the area with Avicennia and Bruguiera mangroves. (Composite of photos by Ward, 1962)........ 47

Figure 5-6: Mangrove distribution in the Mlalazi Estuary in 1963 (Hill, 1966) 48

Figure 5-7: Expansion over time of the mangroves in the Mlalazi Estuary 49

Figure 5-8: Vegetation map of the Mlalazi estuarine system (Taylor, 2015). Based on 2013 aerial photos. 51

Figure 5-9: The expansion of the mangroves at the Estuary Car Park since 1960. The data were used to estimate the logistic rate of growth of mangroves in Mlalazi, using the technique described by Neal (2004). 52

Figure 5-10: The three phases of growth of the mangrove population in the stand at the Estuary Car Park. The dotted line in the recruitment phase is theoretical, based on the fact that there were no mangroves in Mlalazi in 1935. This initial phase, when colonisation and establishment occurs, can be very slow and spread over a long time. 53

Figure 5-11: The study area in the Estuary Car Park mangroves in which the sampling sites were located. (Photo from Google Earth) 54

Figure 5-12: Location of the 25 m^2 sampling quadrates relative to the boardwalk. The histograms show the size classes of the trees on the x-axis (1 m class intervals) and the number of trees along the y-axis. (Photo: Google Earth)........ 54

Figure 5-13: The white plastic 'nurdles' washed up in the Mlalazi Estuary after having spilt in Durban Bay 16 days previously ... 56

Figure 6-1: The weir on the Ntuze Stream that separates the Upper Estuary from the Tributary portion of the estuary. Here the wall is a barrier to upstream flows and biotic movements. There is no longer a gradient in physical changes, but an abrupt change. ... 66

Figure 6-2: The road-crossing in the upper portion of the Mlalazi Estuary. High tides rise above the rocks to flood the tributary area upstream of this causeway. (Photo R Taylor, 28 August 2012). 67

Figure 6-3: Salinity measurement sites within the estuary. ... 68

Figure 6-4: Salinity at the 11 salinity sampling stations (shown in Figure 6-3) for the period from January 2013 to mid-2018. Each box shows the distribution of the data for that site in quartiles. The mid-line is the mean of the data. The 'whiskers' indicate the range of the data. Note that the two sampling stations in the Tributary section of the estuary are downstream of the weir/causeway... 69

Figure 6-5: The graphs calculated using salinity dilution at different estuary volumes – using different mean salinity values at the time of mouth closure. The assumption is made that water level is at MSL on closure. Also shown on the graph are upper tolerance limits for Ceratophyllum and Stuckenia. This graph assumes complete mixing of the water, a situation that is unlikely to occur... 70

Figure 6-6: Submerged macrophytes, likely to be Zostera capensis, in the 1937 aerial photograph. This is the section of the estuary that is bounded by the current-day salinity sampling sites 2 and 3... 71

Figure 6-7: Map showing the distribution of Zostera in 1963 from Hill (1966). At this stage its distribution was much more widespread than its present distribution. It occurred in both the Mouth Zone and the Mid-estuary Zone of the estuary. ... 72

Figure 6-8: A small clump of Zostera growing in Mlalazi Estuary, 15 Nov 2014 (Photo: Ricky Taylor)... 73

Figure 6-9: Salinity measured in the lower portion of the estuary (mean of salinity stations 2 and 3). The red box is the preference window for Zostera (above 25 ppt). The green arrow shows the period when Zostera was recorded in the estuary. (Salinity data from EKZNW). ... 74

Figure 6-10: Zostera has a preferred salinity tolerance range of 25 to 45 ppt. The red box shows this range superimposed on the salinity ranges measured in the 2013 to 2018 period. This indicates that suitable conditions for its growth are mainly in the lower-estuary, but occasionally in the mid-estuary. This supports the distribution pattern shown by Hill (1966) shown in Figure 6-7) ... 75

Figure 6-11: Given the individual salinity tolerances for each plant species (left column), this figure summarises which parts of the estuary (the salinity sampling stations 1 to 11 in the top row) have had salinity conditions in the 6-year period since January 2013 that could have supported each plant The red shading indicates sites that are at times within the salinity tolerance ranges for each plant... 78

Figure 6-12: Area of habitat suitable for the growth of water plants (<60 cm deep) in Mlalazi at different water levels. Although <60 cm has been used, this is for illustrative purposes. The different plants have different tolerances to low light penetration. Water clarity is likely to increase as plant biomass increases, reducing waves and currents. The responses of the plants will also be affected by the rate of change in water level and whether the water is rising or dropping. Of interest is that the amount of available area is similar at all levels. ... 80

Figure 7-1: The floodplain width relative to distance from the mouth. ... 84

Figure 7-2: Schematic depiction of the extreme water levels associated with the different types of flooding of the floodplain. In addition to the flooding depicted, there can be perennial or seasonally waterlogged sites where groundwater seepage enters the floodplain. The source of this water is beyond the boundary of the floodplain. ... 85

Figure 7-3: The upper ranges of recorded berm crest elevations of selected South African TOCEs (from: Booysen, 2017) 87

Figure 7-4: Relationship between vegetation and depths to groundwater – (Hlabisa, 2017)........ 89

Figure 7-5: Relationship between vegetation and groundwater salinity. (Hlabisa, 2017). 89

Figure 7-6: Groundwater salinity. The number is salinity measured in ppt. The dark blue colour is fresh or minimally saline water. The raised salinity is in the supratidal areas 90

Figure 7-7: Geomorphological units – based on topography, geomorphological processes and resultant expression of the vegetation. (See description of the units in the text above). 91

Figure 7-8: Present day vegetation of the Mlalazi Estuary and Floodplain, mapped from 2009 images (Taylor, 2015). The red circle demarcates the detailed study site. 92

Figure 7-9: Detailed study area. The red dashed lines show the coverage of the oblique aerial photo shown in Figures 7-11 and 7-12. The locality of the detailed study site is shown in Figure 7-8. 93

Figure 7-10: Map of the vegetation categories in the sample study site. (see table 7-2 for the categories) 94

Figure 7-11: Conceptual model of the dominant drivers of the floodplain 95

Figure 7-12: A photograph of the part of the floodplain shown in Figure 7-12. 98

Figure 7-13: The classification of the floodplain ecological units 98

Figure 8-1: Simplistic graphical representation (using Netica) of joint probabilistic model of the main conceptualised factors controlling the mouth state. Arrows indicate the joint probabilities. 101

Figure 8-2: A simplistic model of the changing mouth conditions in incremental time steps in Netica. 102

Figure 8-3: The model configuration in GeNIe for the state of the mouth during the 28 step sequence starting with initial conditions of tidal range and storm event. 104

Figure 8-4: The DBN in GeNIe showing the attempt to include a stochastic storm sequence linked to the mouth state. Also shown is the conditional probability table for the time steps in the storm node. 105

Figure 8-5: A model simulation of the marine tide (grey) and estuary tide (blue) assuming the indicated level of storage within the estuary between flood and ebb tides leading to the systematic reduction in the tidal range associated with the rising mouth elevation without fluvial interruptions. 106

Figure 8-6: Observations of the marine (blue) and Estuary (red) tidal interaction during 2014 showing the trends in estuary storage resulting in rising levels of the minimum low tide that is assumed to be associated with the mouth elevation. The rising trend in storage (mouth elevation) is interrupted by fluvial events shown by the rainfall record in the lower graph. 107

Figure 8-7: The simulated marine-estuary tidal interaction with random occurrences of fluvial events (Red graphs). 108

LIST OF TABLES

Table I: Honours projects done as part of this study. iii

Table II: Abbreviations and acronyms used in this report....... xvi

Table III: Place names referred to in this report. xvii

Table 2-1: Minimum Mouth width from Google Earth Images. 12

Table 2-2: The predicted and measured water levels at selected estuary cross-sections for various flood events (from Mmako, 2019). 22

Table 6-1: Description of the main features of each estuary zone 65

Table 6-2: Aerial photos inspected for the presence of submerged macrophytes in the Mlalazi Estuary. 70

Table 6-3: Herbarium records of Zostera collected in the Mlalazi Estuary 71

Table 6-4: Recovery of Zostera after flood events 74

Table 6-5: Salinity ranges of these plants used in this report 78

Table 7-1: Inundation classes for mangroves as described by Watson (1928) 85

Table 7-2: The features and main species of the floodplain habitats recognised in the detailed study area. 94

Table 7-3: Summary of characteristics and features of the different flood zones 96

PHOTOGRAPHS

Photograph 2-1: Google image of the beach berm within the constricting dune formations comprising a channel and basin sand banks that establish the hydraulic controls at the mouth. 12

Photograph 2-2: An example of supercritical flow through the mouth following mouth breaching (Photo by RH Taylor) 13

Photograph 2-3: Google image of the mouth closed by sediment accumulation along the shoreline but it is speculated in the text that this is not the cause of the closure. 14

Photograph 2-4: The mouth delta region showing the large accumulation of sediments forming very shallow sand banks that may be highly restrictive to the tidal interaction due to a through the mouth channel that is clearly open. 15

Photograph 2-5: Photograph of the old N2 Road Bridge several hours after the main flood peak had receded following an approximate 1:100 year rainfall event in September 1987. (Photo Kelbe) 19

Photograph 3-1: The monitoring pipe near the mouth that was installed below the water level before the extreme event was exposed by nearly 05 m after the event. 36

ABBREVIATIONS AND ACRONYMS

Table II: Abbreviations and acronyms used in this report.

AMSL	above MSL
CCWR	Computing Centre for Water Research
Dbz	Decibel relative to Z. It is a logarithmic dimensionless technical unit used in radar, mostly in weather radar
DWS	Department of Water and Sanitation
EFZ	Estuary Functional Zone
EHWT	Extreme high-water tide
EKZNW	Ezemvelo KZN Wildlife. This is the provincial conservation agency. It has the mandate to care for the Mlalazi Nature Reserve.
HRU	Hydrological Research Unit, University of Zululand
mMSL	metres above Mean Sea Level
POE	Permanently Open Estuary
ppt	Parts per thousand. Some people prefer to use this Figure as a dimensionless number. This takes into account the ions formed. However, for the purposes of this study ppt is used as some of the calculations involve masses of salt that are diluted. Salinity is typically measured as a concentration of grams of salt per kilogram of water (g/kg). PSU (practical salinity units is often used – as this is the measure of salts in sea water – when measured using electrical conductivity
PSU	(Practical Salinity Unit), is a unit based on the properties of sea water conductivity.
TOCE	Temporarily Open/Closed Estuary
UKZN	University of KwaZulu-Natal
UNIZULU	University of Zululand

PLACE NAMES

Table III: Place names referred to in this report.

Place name	Latitude (degrees E)	Longitude (Degrees E)
Amatikulu-Nyoni Estuary	-29.102444°	31.623285°
Anchorage	-28.954736°	31.775895°
Balcombe's Rocks	-28.936314°	31.764711°
Bishop's Trees	-28.946276°	31.804768°
Café	-28.955379°	31.775620°
Confluence	-28.919278°	31.749845°
Dredged Basin	-28.954170°	31.773853°
Dunn's Pool	-28.954809°	31.774947°
Estuary Car Park	-28.955114°	31.775260°
Fish Farm (Prawn Farm)	-28.950289°	31.767893°
Islands	-28.948737°	31.779303°
Lake Nhlabane	-28.630041°	32.275410°
Mhlathuze Estuary	-28.842805°	32.027451°
Mlalazi Estuary (Umlalazi)	-28.947306°	31.799036°
Mlalazi Estuary Mouth	-28.945375°	31.816167°
Mlalazi River	-28.918518°	31.734244°
Mouth	-28.945375°	31.816167°
N2 Road Bridge	-28.932446°	31.756983°
Nel's Pool	-28.948793°	31.795295°
Ntuze Tributary	-28.917988°	31.750396°
Ntuze Weir	-28.917589°	31.755721°
Old Road bridge (R102 road)	-28.929851°	31.755182°
Picnic Site	-28.948659°	31.776318°
Powell's Landing	-28.932131°	31.769433°
Railway Bridge	-28.935806°	31.780394°
Railway embankment	-28.942171°	31.772678°
Riprap wall	-28.943458°	31.810832°
Road causeway across the upper reach of the estuary	-28.919175°	31.743363°
Siyaya Estuary	-28.965727°	31.762023°
Slipway for boats	-28.949955°	31.775000°
St Lucia Estuary	-28.386942°	32.417684°
Richards Bay	-28.802634°	32.057424°
Durban Bay	-29.872720°	31.025267°
Beachwood	-29.804590°	31.040647°
Zini Estates	-28.942582°	31.767004°
Locations of water level recorders		
Mouth (Sandbag wall) (DWS logger)	-28.943417°	31.812129°
Rail Bridge	-28.935973°	31.780007°
Mangrove trail bridge	-28.952178°	31.773139°
Confluence	-28.920524°	31.750887°

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1. INTRODUCTION

The main aim of this study was to develop a model of the hydrodynamic characteristics of the Mlalazi mouth to support management of the estuary and mouth to protect anthropogenic activities and ecological functions of the estuary. The Mlalazi Estuary is a typical small estuary found along the South African and other coastlines around the world (Slinger, 2016). These estuaries are productive habitats. They are well known for their biodiversity and fish nurseries. These estuaries have important social, economic and environment functions (Turpie *et al.*, 2002). The future health of these estuaries is dependent on two main factors: their direct management and the quantity and quality of their water (Turpie *et al.*, 2002). Consequently, there is a need to understand the hydrodynamics of these systems to support their effective management. The Mlalazi is ranked in the top 20 (of 250) most important estuaries in South Africa in terms of its conservation status (Turpie *et al.*, 2002).

The Mlalazi Estuary is on the east coast of South Africa between Durban and Richards Bay. It is at the southern extent of the Zululand Coastal plain that also includes a further four of the top twenty most important estuaries in South Africa (Kosi Bay, St Lucia, Mfolozi, Mhlathuze). The estuary has been classified as a "Temporarily Open/Closed Estuary" (TOCE) (DWS, 2015). Its current ecological status is a Category "B" as classified by DWS (2015); given its present artificial management of the open and closed state of the mouth. The assessment is that there has been an 80% reduction of the natural conditions that are derived mainly from the apparent reduction in fluvial inflows, anthropogenic activities, historical and current sediment management programmes.

More recent information on the fluvial inflow into the estuary has been determined as part of this project by Rasifudi, 2018 and Rasifudi *et al.,* 2019. Current, hydrodynamic model simulation of the estuary by Mmako (2019 – in prep) is included in sections of this report.

The exchange of water in this estuary across a bar-built beach (mouth berm) is dominated by fluvial and marine processes that control the mouth basin and channel dynamics. To understand the controlling nature of the fluvial and marine processes it is necessary to establish the nature and characteristics of these two processes and how they may influence the dynamics of the mouth channel.

For the vegetation, the aim has been to describe the present and historical vegetation patterns within the Mlalazi Estuary and its floodplain established during the past hydrodynamic nature of the system. Then, using this information, to describe the physical environment that controls these patterns. This is the information needed to develop conceptual models which are used to interpret how the vegetation would respond to physical conditions in the estuary which we have not experienced and for which we have no records.

2. STUDY AREA

The Mlalazi River catchment feeding the Mlalazi estuary rises in the Ngoye Hills at elevations of over 500 mMSL. The catchment has a drainage area of 397 km^2 (Rasifudi, 2018).

In this study the Mlalazi Estuary, as defined by the expected maximum level of inundation of the surrounding floodplain is considered to be the area below the 10 mMSL contour after the 1987 extreme rainfall event (1:100 year) that reached a height of 9 m in the upper estuary. This is above the default 5 m used to define the Estuary Functional Zone (EFZ) in South Africa (Veldkornet *et al.*, 2015).

The main hydrological and hydrodynamic features of the Mlalazi Estuary and catchment are shown in Figure 2-1. The sub-catchment delineation and river network was taken from Rasifudi (2018) based on a Digital Elevation Model from 5 m contour and spot height data provided by National Geo-spatial Information (NGI) section in the Department of Rural Development and Land Reform. The extent and profile of the Estuary DEM is described further in the text and shown in Figure 2-1 by the coloured elevation zones.

The estuary mouth is a highly dynamic feature comprising a beach berm forming a natural barrier between the sea and estuary channel. Generally, there is a well-defined open channel through the beach berm that forms a hydraulic control feature of the exchange of marine and estuary flows. Behind the beach berm (Figure 2-1 inset), the mouth basin comprises dynamic sand banks that also effect the hydraulic exchange of marine and estuary flows.

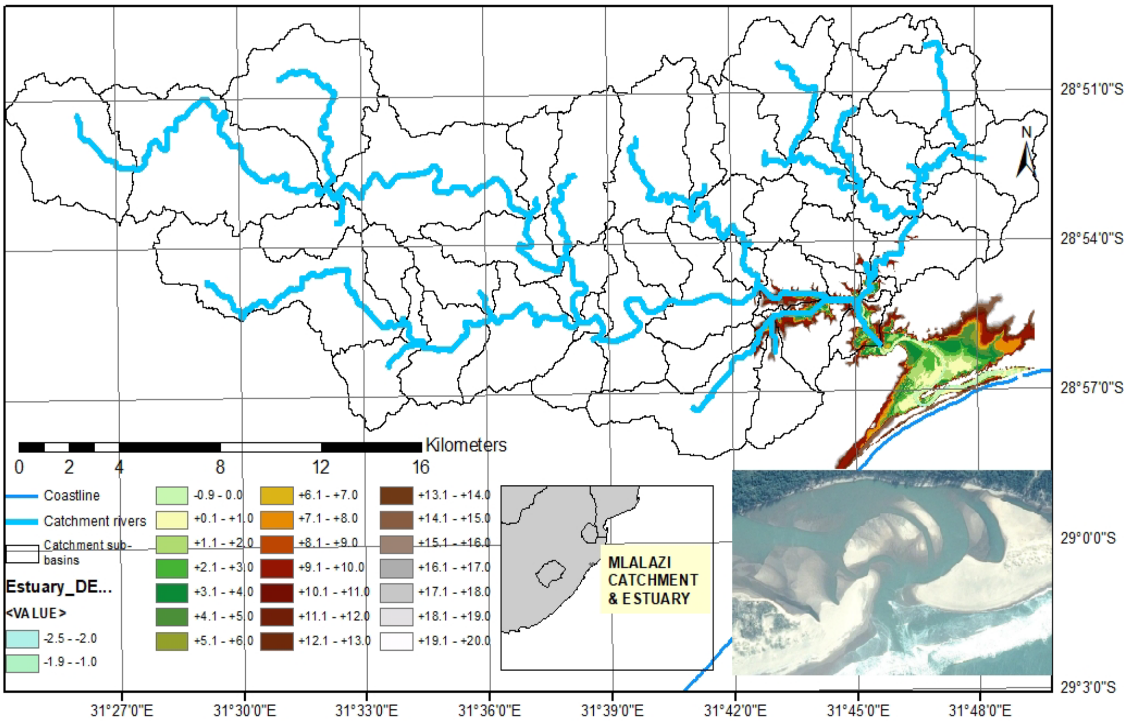


Figure 2-1. The location of the Mlalazi study site comprising the runoff catchment represented by the black polygons and river network that discharge directly into the estuary. The Digital Elevation Model (DEM) of the estuary and floodplain is shown by the coloured contours. Also included is a Google Earth image of the mouth illustrating the mobile sandy berm that has a controlling influence on the estuary hydrodynamics.

2.1 Geological evolution of the Mlalazi Estuary

Estuaries are dynamic systems. Dynamic at a variety of temporal scales. Most estuarine research in South Africa has focussed on changes due to tides, seasons and decadal-length wet-dry cycles. Where there is a paucity of knowledge is in the longer-term scale which takes into account the geomorphological trend of a deep system accumulating sediments, and in the process of shallowing up it goes through a series of different hydrological and ecological states. This is a scale where knowledge is needed as current regional land-use practices and global changes will alter the rates of this trajectory change of the estuaries geomorphology. This is the scale of dynamics at which long-term management will need to focus.

To understand the functioning and dynamics of the Mlalazi Estuary we need to consider its evolutionary trajectory. There has been a rapid (in geological time) evolution of the estuary since the last Glacial Maximum. At its peak (~18000 years ago), sea level was about 130 m below that of the present day (Cooper *et al.*, 2018). This has taken the system from a deep-water bay to a shallow and narrow estuary set in a wide floodplain. This has not been a linear process – but has been a trend over time that still continues and as more sediments accumulate.

Initially, a deep and wide basin was scoured during the low sea level. Since then sea level has risen to close that of the present, flooding the scoured basin. As sea level was rising there was an accumulation of sediments. These were initially mainly marine and later mainly riverine in origin. The sea level reached present levels 6000 to 3000 years BP. It then 'overshot' to between 2 and 4 m above present-day sea level before receding to what it currently is (Cooper *et al.*, 2018).

The bay filled to the extent that the estuary became a small channel within a large floodplain. Wave-wash ridges were deposited along the northern margin of the bay – at a sea level slightly higher than present. During this period the dune barrier formed. This had the effect of constricting the mouth of the bay creating a low-energy environment landward of the barrier dune. The bay then became more river-dominated – with fluctuating salinity and it accumulated river-borne sediments. This trajectory is depicted in Figure 2-2.

Mlalazi has a prograding coastline. There is an abundance of sediments from the Tugela River and these accumulate along the seashore. The shoreline extends seawards at an average of 2 metres per annum (Weisser *et al.*, 1982; Van der Elst *et al.*, 1999) The longshore drift – which is predominantly from the south – has pushed the mouth of the Mlalazi northwards at the same time as it has been moving seaward. The result is the 4 km long narrow estuary channel that links the ancestral estuarine bay with the sea.

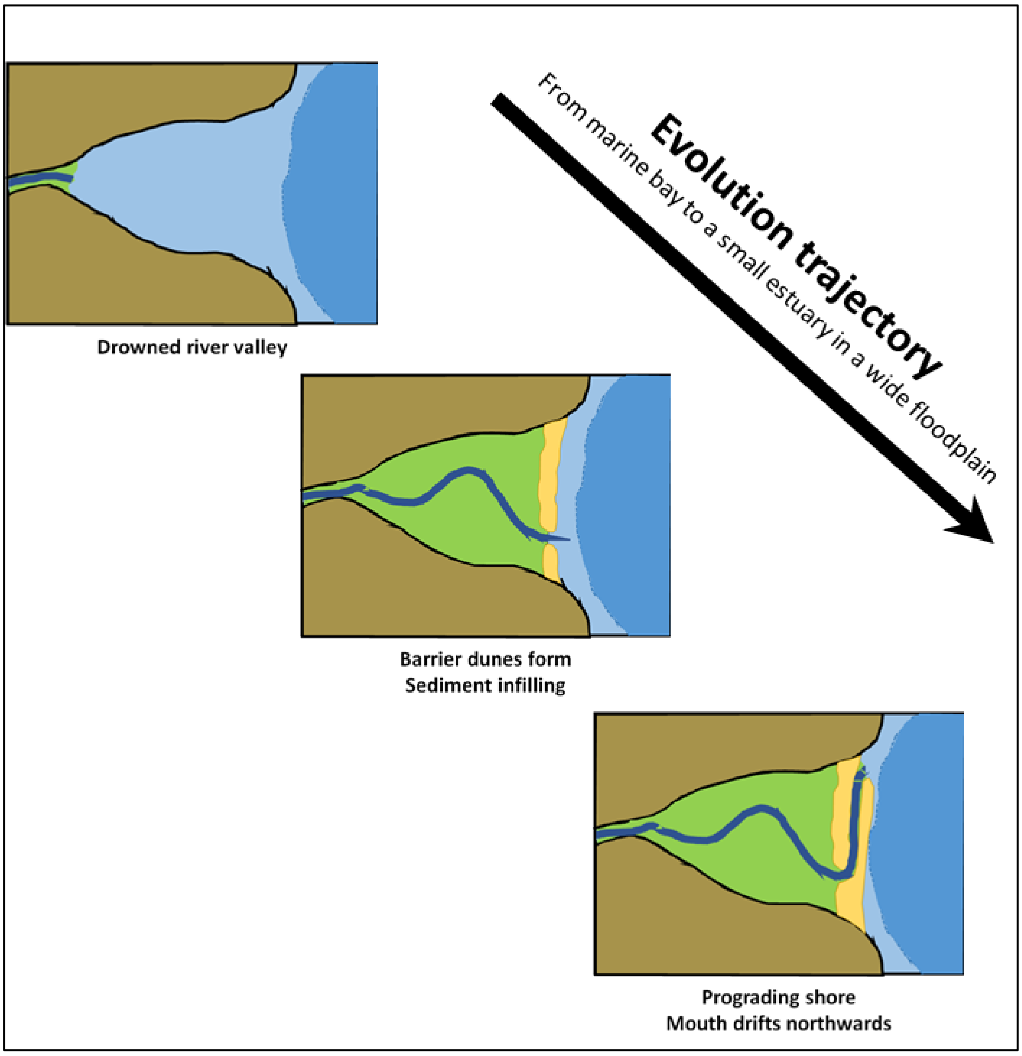


Figure 2-2: Schematic depiction of the geological formation of the Mlalazi Estuary

The ancestral bay was a relatively stable environment. The water level, salinity, turbidity, wave action and water temperature were those of the sea. However, with time the connectivity with the sea was reduced and there was less tidal water exchange. At the same time the influence of the inflowing river increased. The system became more variable – having larger ranges in water levels (associated with river floods and mouth closures), salinity as sea water was diluted with fresh water, turbidity as catchment clay and silt particles were introduced by the river, wave energy was reduced by the barrier formation between the estuary and the sea and temperature fluctuated in the enclosed shallow basin. The biota responded to these changes – becoming much more estuarine and less marine in nature.

The estuary is in the state where it has progressed from the stage when the mouth was permanently open (a POE) to the state where the mouth closes at times (a TOCE). To open naturally after closure, either backing up water must rise to breach the mouth by overtopping of the beach berm, or there needs to be a large storm event that erodes the beach berm. (Figure 2-3).

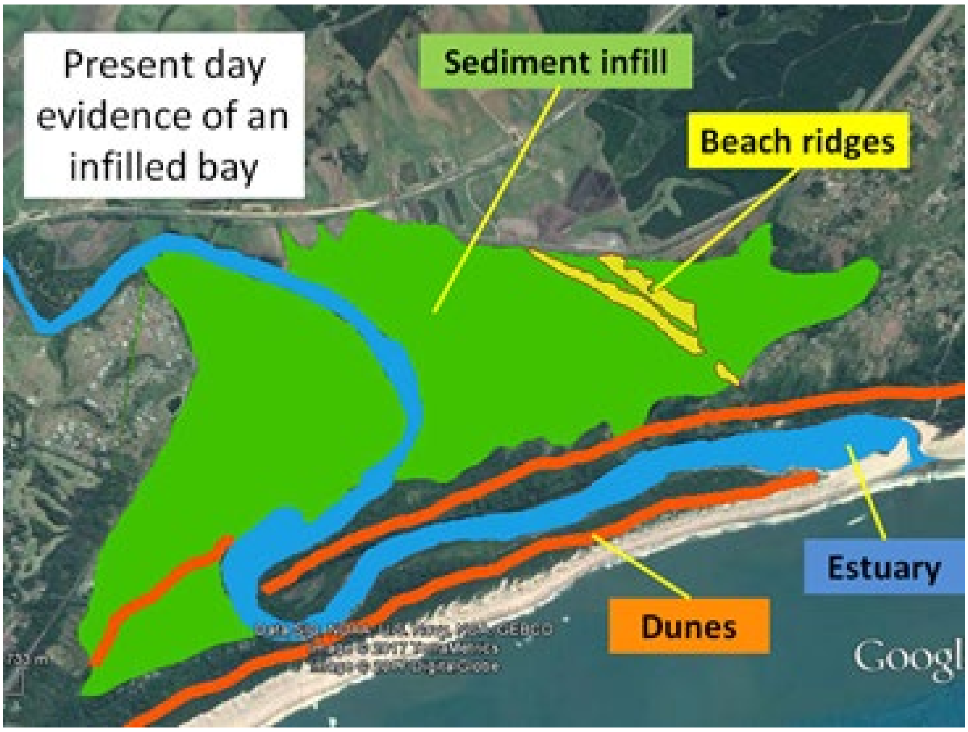


Figure 2-3: Geomorphological units of the Mlalazi Estuary and Floodplain

The change from a POE to a TOCE is a 'tipping point' event which has a profound influence on the vegetation of the estuary. For instance, a prolonged mouth closure will kill mangroves in the system. This is due to the backing up of water which then floods the floodplain. At present the mouth is closed for 4% of the time (EKZNW records) – usually closing every few years, and the mouth is then breached artificially within a few weeks of closure.

Since the 1890s the mouth has always been breached within weeks of it closing. This has, to some extent, reversed the changes that occurred when it changed from a POE to a TOCE. There are still some TOCE ecosystem characteristics – such as the loss of fiddler crabs from the system after a closure period of several weeks (Taylor pers. obs.) but the system does behave to a large extent as a permanently open estuary.

2.2 Human influences

Since the early 1800s the catchment and estuary have been affected to an increasing degree by human impacts. The salient change has been the breaching of the mouth within a few weeks after closure (the first record of this is in the late 1890s).

Also, in the 1890s the Zululand railway was constructed. A long embankment leading to a bridge over the estuary was constructed. These structures may have constricted the river floods.

For the past 100 years or so, parts of the floodplain have been used for the cultivation of cane. In places this has subsequently been allowed to revert to natural (due to saline soils?).

Land transformations in the catchment have been severe. Much of the catchment was grassland until it was partitioned into farms in 1904 and sugar farming activities started in 1906 (Van Jaarsveld, 1998).

Farm establishment is associated with drains to dry out wet areas and with the planting on the floodplain.

There are parts of the catchment that are forestry plantations, parts still under traditional land use (but containing much higher densities of people than ever in the past) and there has been significant wooding up of non-cultivated areas – due to bush encroachment as well as forest formation.

In the mid-1960s, large portions of the estuary downstream of the Railway Bridge were dredged which increased the volume of water exchanged in each tidal cycle. This has possibly helped to reduce the frequency of mouth closure events. This effectively reduced the intertidal habitat.

When considering the ecological state of Mlalazi we do need to recognise that the human imprint has been large – and there are several layers of cumulative impacts.

2.3 Climate

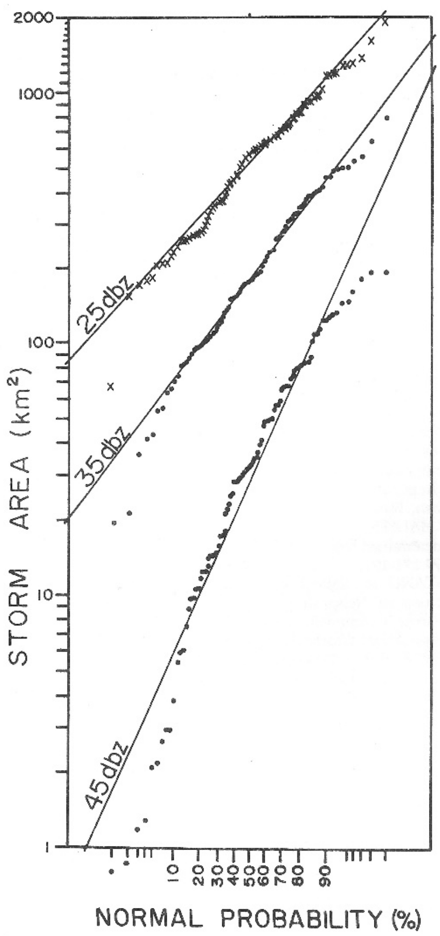


Figure 2-4: Probability Density Function for storm Areas defined by three radar reflectivity levels (Kelbe, 1984)

There are numerous rainfall records for the region, most of which were obtained from the local farmers and civic organisation for periods during the past 50-100 years by the Computing Centre for Water Research (CCWR @ UKZN). Unfortunately, these local records suffer from various sources of inaccuracies. Most civic organisation did not record daily rainfall over weekend, and many of the farm records had varying lengths and periods with missing records over the past 100 years. The total monitoring rain gauge area of the catchment is over 1000 km^2. This is an order of magnitude greater than the characteristic single cell convective storm cell size for the north-eastern region of South Africa (Figure 2-4). Equivalent rainfall rates of 5 mm/hr and 20 mm/hr for the 35dbz and 45 dbz respectively in Figure 2-4 were derived from studies by Mason (1971). Consequently, it would require many storm cells to provide a uniform rainfall distribution over the monitoring catchment. There is also a sharp decline in rainfall intensity away from the storm cell centre (Figure 2-5) so there is unlikely to be a high correlation between daily gauge readings even from nearby station for the summer rainfall region of South. The station more distant than 10 km show low correlation between rainfall series. Consequently, it would require a dense network of rain gauges for a complete spatial coverage of the catchment for convective systems.

However, for the extreme rainfall event that generally last several days and move over a very large area, the cumulative rainfall for the region should show much higher correlation between nearly all stations. The regional accumulated 5-day rainfall map for the extreme storm event in September 1987 (Figure 2-6) was described by Kovacs (1988). The Mlalazi catchment lies within the 600 mm isohyetal contour. The highest 5-day rainfall during this event was 928 mm in Richards Bay which is similar to the 5-day rainfall recorded during cyclone Domoina in 1984 near Empangeni. (Note, “the 5-day point rainfall depths during Domoina and 1987 events were at many places considerably higher than the corresponding 200-year values obtained by Adamson (1983)” quote from Kovacs (1988). There were no records of the flow in the Mlalazi for the 1987 extreme event but the peak flow rate in the Matigulu at Dunn's Reserve was 3,100 m^3/s in a catchment of 583 km^2, an event that was classified by Kovacs (1988) as a 1:150-year event. The previous maximum peaks for the Mhlatuze in 1984 were considerably lower than the 1987 peaks (Kovacs, 1988).

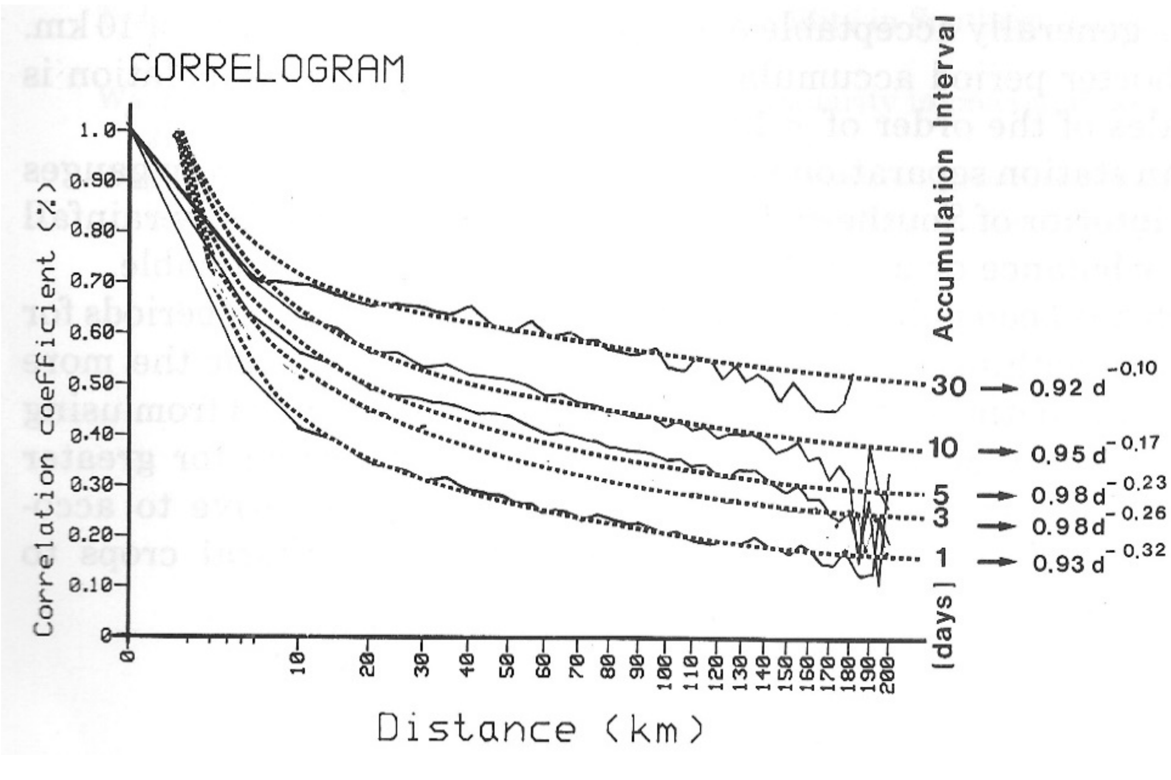


Figure 2-5: The mean correlations over 5 km intervals for various accumulated rainfall series for summer month. Dashed lines represent the best fit power functions (Kelbe, 1987).

The lack of consistent spatial and temporal coverage by all the available rainfall stations create difficulties in deriving the required catchment discharge into the estuary so only selected stations were used in the study by Rasifudi (2018). The Port Durnford weather station with >100-year record for the eastern portion of the catchment was selected for this study because there was close agreement with it and most of the surrounding station that were available during the selected 100-year period. Similarly, the northwestern catchment used the WE011 station at Goedertrouw dam that showed good agreement with available local records (Rasifudi, 2018). For the central catchment area with no rainfall records the regional derived daily rainfall (W113A Quaternary Record, van Heerden and Walker, 2016) was selected. All three station daily values are shown in Figure 2-7 for the period from 1950 to 2018.

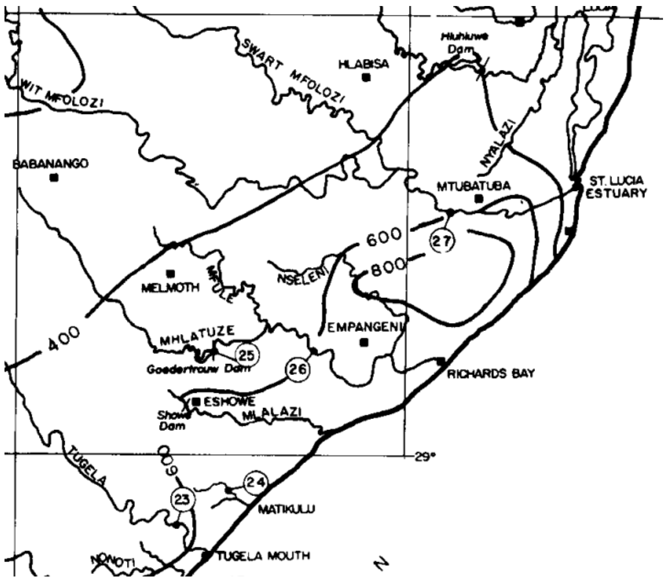


Figure 2-6: Storm isohyetal map of the five-day rainfall between 25 and 30 September 1987 (from Kovacs, 1988).

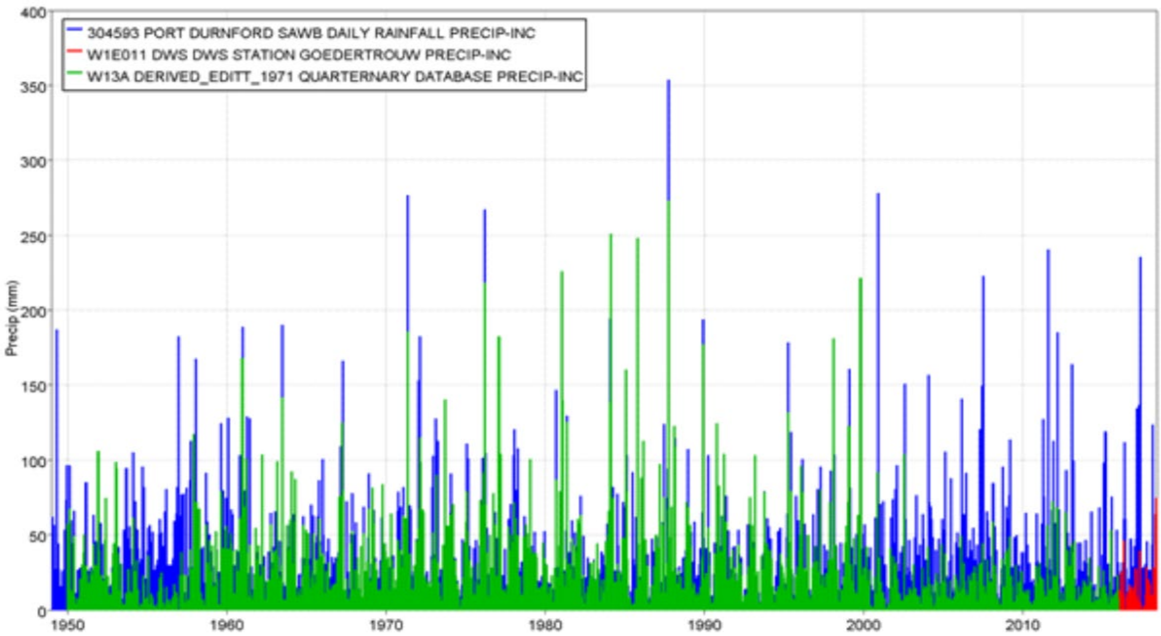


Figure 2-7: The selected catchment daily rainfall record for catchment and estuary hydrological studies

The catchment and estuary are prone to periods of drought and flooding that will have a significant impact on the estuary and mouth. There are significant cyclic patterns in the annual rainfall for the east coast region (Tyson *et al.,* 1975; Kelbe *et al.,* 1983) that indicate short (~2½ year) and medium (18 year) annual cycles that create periods of above and below average rainfall. Sangweni (2017) presented a frequency plot of the rainfall extreme for extended periods of up to a year (Figure 2-8) based on 60 years of monthly rainfall. There have been periods of 6 month with less than 300 mm of rainfall (10% of the record) and periods with >1000 mm (6% of the record). These extreme events would significantly impact the Mlalazi Estuary and mouth dynamics.

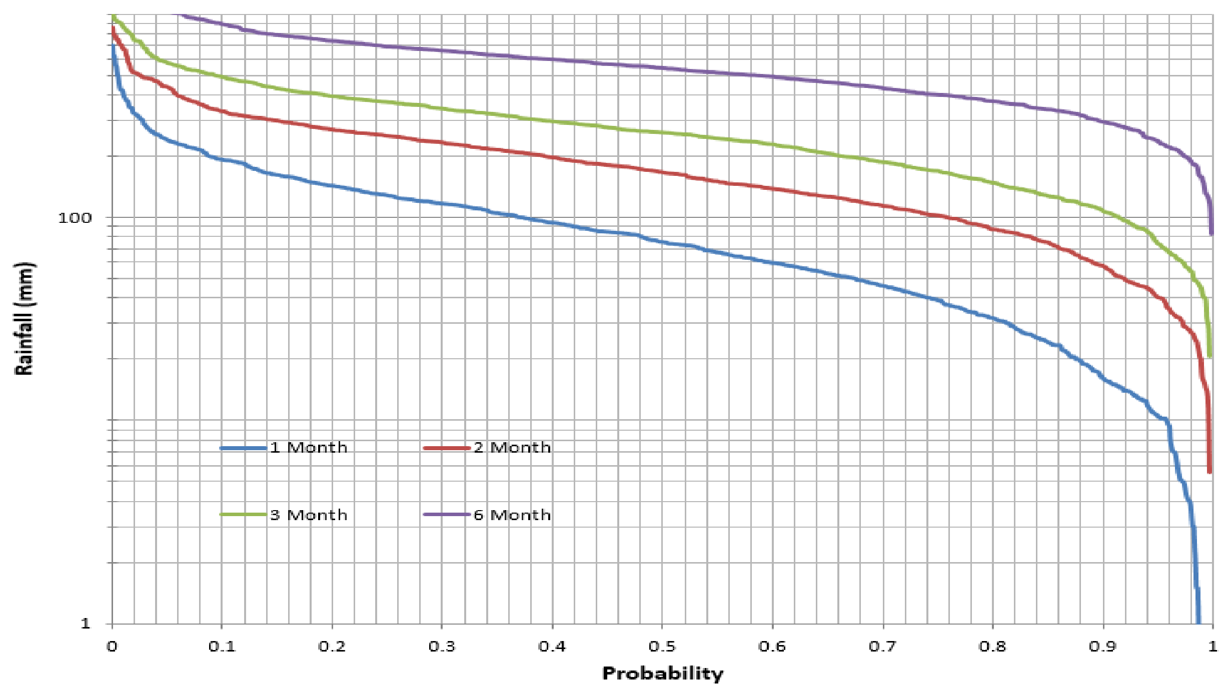


Figure 2-8: The probability distribution of rainfall accumulation over 1-, 2-, 3- and 6-month periods.

2.4 Digital Elevation and Bathymetric Model of the Estuary.

Estuary floodplains have traditionally been classified as the area below the 5 mMSL contours. However, during the 1987 flood event the water level in the Mlalazi Estuary rose to over 8 mMSL at the R102 (old N2) road bridge in the upper estuary (Figure 2-9). This corresponds closely with the 8.95 mMSL stage recorded at the W1H012 gauging weir located several kilometres upstream of the estuary (HRU, 1988). Consequently, it is necessary to establish the topographical profile of the floodplain up to an elevation of at least 10 mMSL.

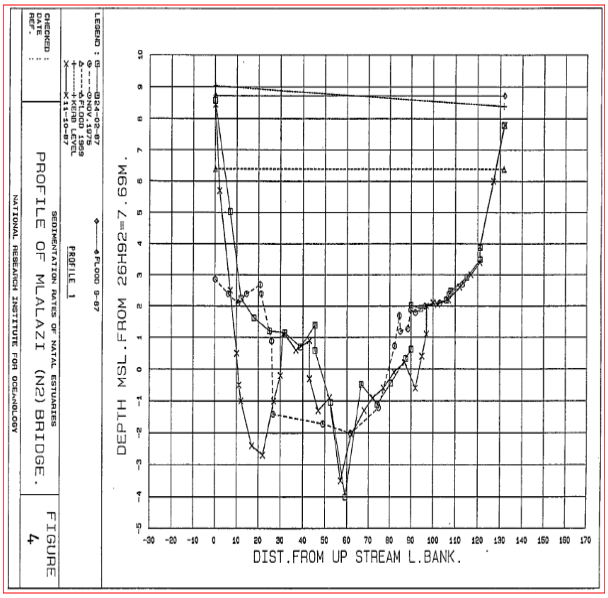


Figure 2-9: Water level and cross-sectional profile at the old N2 road bridge survey during several major flood events by Badenhorst *et al.* (1989).

The only available elevation data from the region are 5 m contours and spot heights that have been made available by the National Geo-spatial Information (NGI) section in the Department of Rural Development and Land Reform. SRTM data and variants of it are freely available at 30x30 m grids but there are serious errors with this data for areas with high vegetation as the Radar signal does not penetrate to ground level (Farr *et al.,* 2007). However, this data set has been combined with the available elevation data to create an initial Digital Elevation Model (DEM) of the estuary Floodplain.

Apparently, there is Lidar Data available for section of the floodplain but this has not been made available to the project. Consequently, intensive field surveys by the project team and students coupled with aerial imagery were used to create an initial DEM for the entire floodplain up to an elevation of 10 mMSL (Figure 2-10).

No historical hydrographic data exists for the Mlalazi Estuary channel except for several cross-sectional profiles at strategic location between the mouth and upper estuary that were surveyed by Badenhorst *et al.* (2989) following major storm events (Figure 2-9). The estuary channel bathymetry was subsequently surveyed by Taylor and Bathos in 2016 (*per. comm*) and the lower sections of the estuary below the railway bridge have recently been surveyed by DWS (2017). These bathymetric surveys were incorporated with the floodplain data to create the final DEM shown in Figure 2-10 that has subsequently been used in this study. The estuary floodplain and channel are conceived to comprise four separate features that may have different hydraulic responses to fluvial events. The four sub-catchments are shown by the dotted ellipses in Figure 2-10 and labelled as Mouth; Middle; Upper and Tributary floodplains. The DEM has been used to extract the hypsometric curves for the entire floodplain (Figure 2-11) and the Channel (Figure 2-12) separately assuming that the mouth berm completely separated the estuary from the marine topology (*i.e.* mouth closed). It is important to note that these hypsometric curves cannot be used for flood events where there is a strong evolving hydraulic gradient along the length of the estuary during the passage of the storm hydrograph.

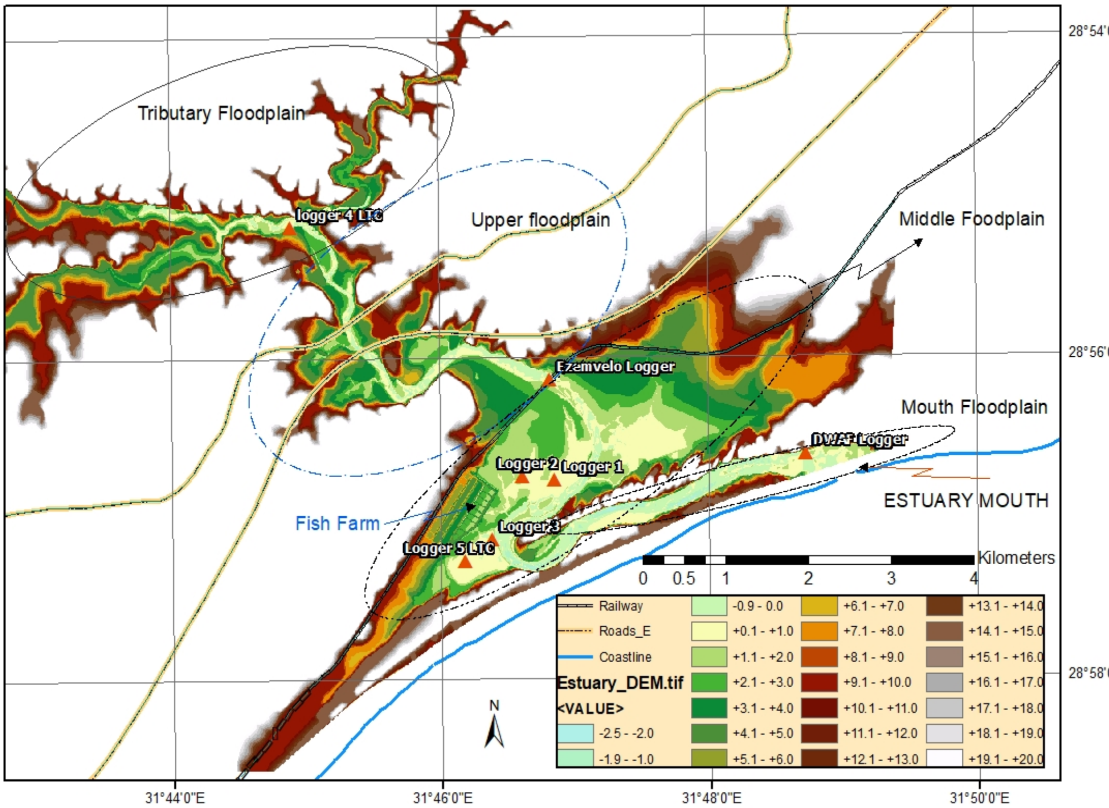


Figure 2-10: The derived Digital Elevation Model (DEM) of the Mlalazi Floodplain with selected infrastructures. The Estuary floodplain has been divided into four regions where the hypsometric conditions are significantly different. The red triangles show the location of stage monitoring sites.

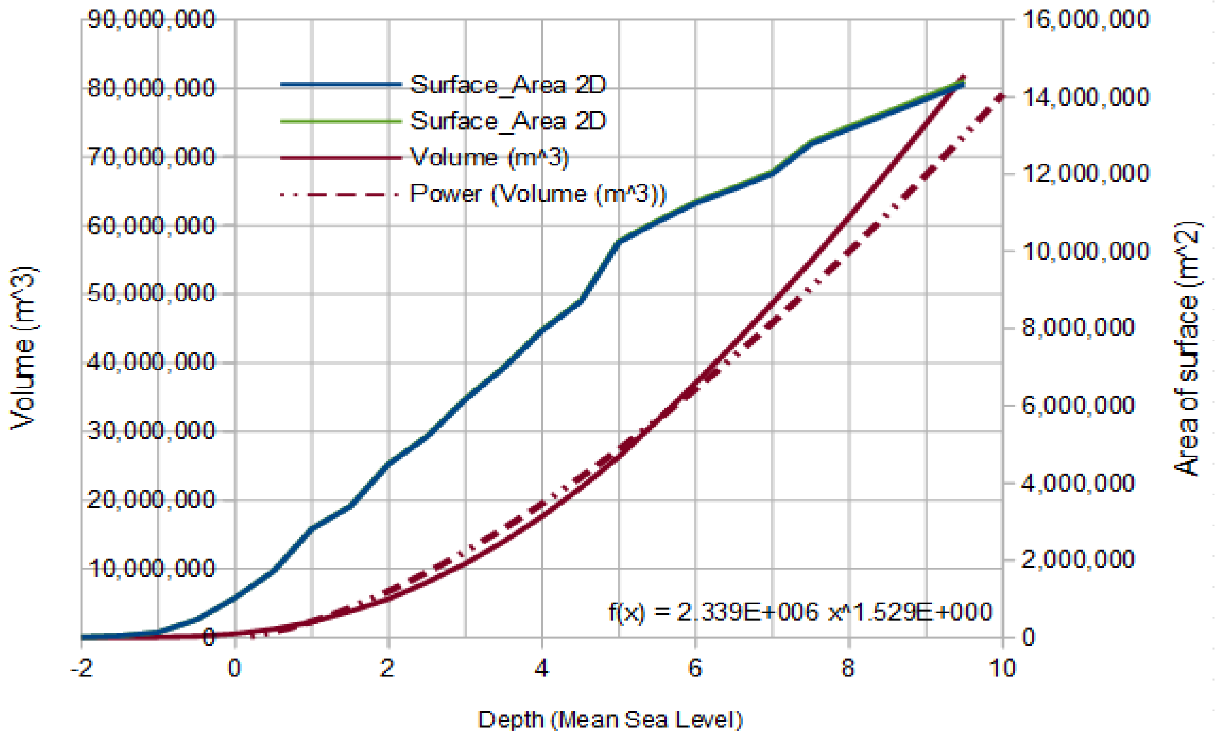


Figure 2-11: The Hypsometric curve for the entire floodplain and estuary channel

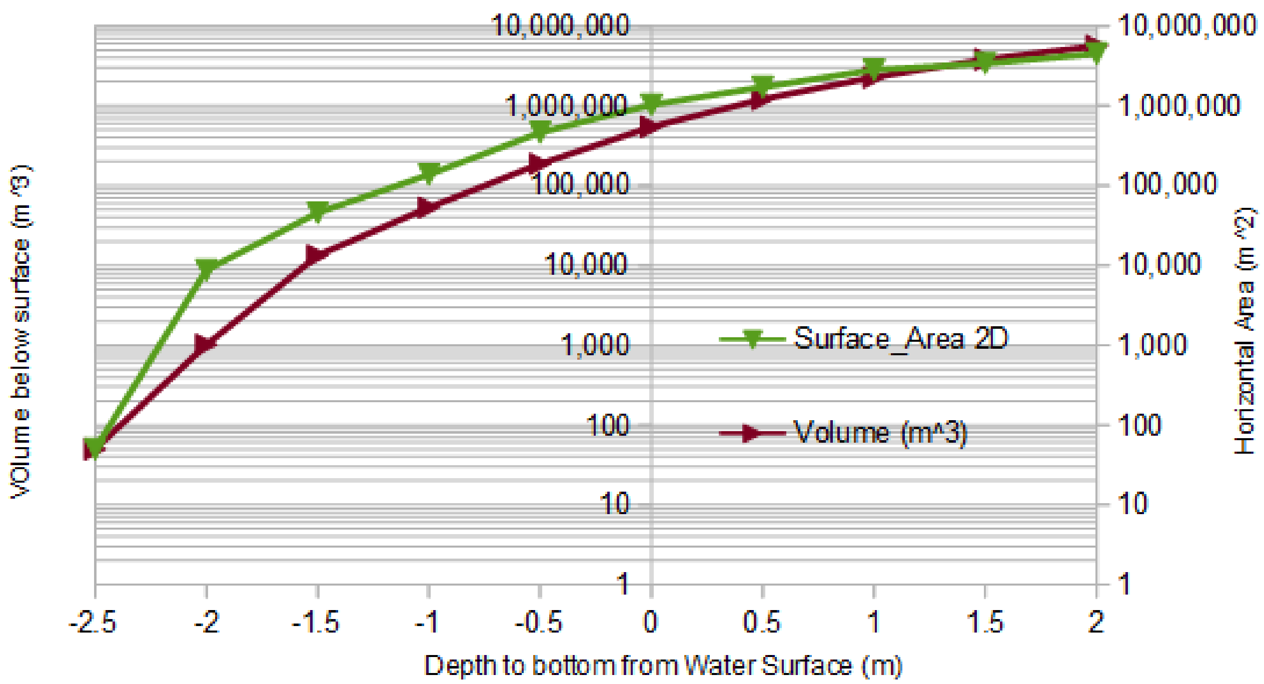


Figure 2-12: The hypsometric curves for surface area and volume for the channel below the 2 m contour.

2.5 Mouth characteristics

The concept of mouth closure is not well defined as it involves both;

- The often mobile and narrow channel through the beach berm remnants, foreshore and surf zone, and
- The estuary mouth basin just upstream of the channel with mobile sand bars that also has a controlling influence on the flow of water between the marine and the estuary.

Photograph 2-1: Google image of the beach berm within the constricting dune formations comprising a channel and basin sand banks that establish the hydraulic controls at the mouth.

The "narrow channel" (Photograph 2-1) is highly mobile and moderated by relatively high flow velocities and wave action causing scour and deposition of the sediments between the sea and estuary through a relatively narrow section (Table 2-1) that will generally maintain a constant hydraulic radius during flood and ebb tides. It tends to migrate northwards under the influence of the prevailing near shore currents to a northern limit because it has been blocked from further migration by anthropogenic actions. If the mouth channel is left to natural long-term processes it is likely to continue moving northwards in a similar manner to the Siyaya estuary. However, it is currently constrained within the extent of the dune gap.

Table 2-1: Minimum Mouth width from Google Earth Images.

DATE	width	DATE	width	DATE	width	DATE	width
9/25/2018	50	7/5/2016	45	7/9/2015	22	5/3/2014	52
5/6/2018	80	7/3/2016	70	7/16/2015	closed	3/26/2014	55
11/18/2017	closed	5/12/2016	70	7/10/2015	closed	9/17//2013	37
11/04/2017	35	2/19/2016	50	6/21/2015	closed	8/29/2013	60
8/2/2017	40	10/31/2015	72	6/10/2015	closed	7/27/2013	45
6/10/2017	35	10/25/2015	35	6/4/2015	closed	1/24/2013	57
5/30/2017	45	10/18/2015	45	5/19/2015	30	7/22/2010	14
5/21/2017	88	9/10/2015	30	5/5/2015	40	6/2/2006	45
5/3/2017	53	8/17/2015	45	4/13/2015	40	4/27/2006	32
2/18/2017	64	8/4/2015	45	1/23/2015	53	2/24/2005	56
8/10/2016	39						

The estuary mouth basin has a general width that is ten times that of the channel filled with mobile sands. These sand bars, berms and banks are often exposed to various depth during the tidal cycles that will have a changing hydraulic radius during the tidal cycle.

The changing hydraulic radius of the channel and basin will generally create very different velocity regimes and associated sediment transport through these features and consequently they need to be considered separately. The mouth channel sediments are continually being moved (deposited and eroded) while the basin sediments are not reworked rapidly because the velocity profile is low except in the channel.

It is assumed that the fluxes into and out of the estuary mouth during tidal exchange can be used to estimate the maximum velocity though the mouth channel if the dimension of the mouth are sufficiently well known at its narrowest point. If the velocities through the mouth can be estimated from the discharge rates (Figure 2-13), then the sediment transport can also be estimated using various models (Slinger, 2015). Slinger (2015) has indicated that the flood tide is unlikely to reach critical velocities. However, there are instances during the ebb tide that will exceed critical velocity through the mouth during specific events such as mouth breaching (Photograph 2-2).

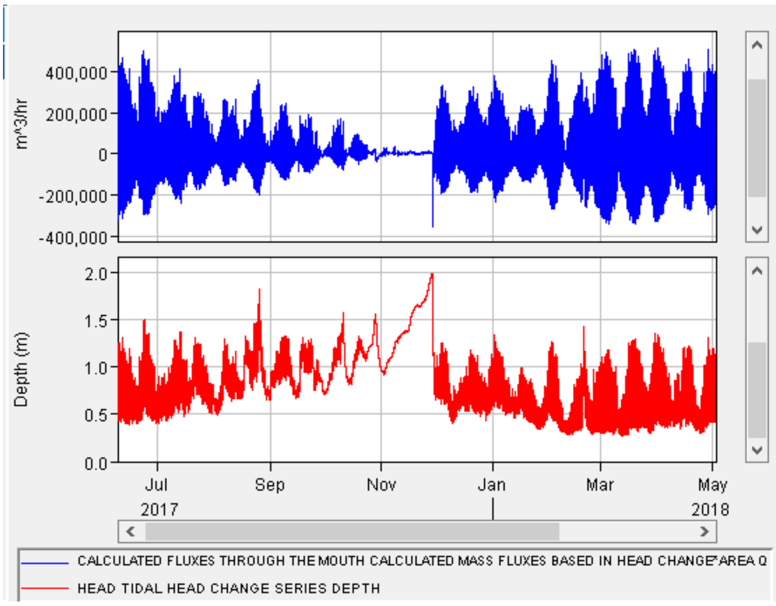


Figure 2-13: The measured tidal range (red graph) before and after the mouth closure in December 2017 used to calculate the flow rate (m^3/hr) through the mouth (blue graph).

2.5.1 Beach Berm

During regular semi-diurnal and 14-day tides, the beach berm is generally assumed to play no role in the mouth dynamics when the mouth is open or partially open although it may be a source of aeolian sediments into the delta during suitable wind regime. However, when the mouth is closed the beach berm could continue to rise in response to aeolian processes until it is naturally or artificially breached. Any accumulation / erosion of sand will be altered when a major fluvial event or artificial breaching occur. The artificial breaching generally occurs in the southern extremity of the berm and the channel generally migrates northwards impacting the size of the berm between these events. If there are no natural or artificial breaches in the south then the beach berm can become more stable and evolve with vegetative

Photograph 2-2: An example of supercritical flow through the mouth following mouth breaching (Photo by RH Taylor)

stabilisation causing long term changes in the estuary. However, for this study, the natural and artificial breach occurs sufficiently regularly to assume this is unlikely to happen unless the management strategy changes. Consequently, it is assumed that the beach berm is not a major contributor to the mouth hydrodynamics in this study of near real-time changes.

2.5.2 Mouth Channel

The mouth channel varies in location, length, width and depth over a season and possibly over a 14-day cycle but is assumed to be stationary and invariant over a diurnal cycle. The water level in the estuary is directly influenced by the width (Table 2-1) and depth (sill elevation) of the mouth channel. From an examination of the logger series (Figure 2-13) several features that relate to the mouth conditions are apparent.

- During the slack periods when high and low tide are at the same elevation (*i.e.* the tidal range is near zero), it can be assumed that there is little or no tidal exchange through the mouth. In these circumstances, it could be assumed that when this happens, the logger values would indicate the elevation of the mouth channel sill. Examination of the logger series would suggest that the mouth channel sill elevation would be constantly changing (increasing) over a diurnal and 14-day cycle until it could be classified in the traditional sense as "closed" as shown at the end of November 2017 in Figure 2-13.
- When the mouth has no tidal interaction there can still be a change in the water level in the estuary (Figure 2-13). Since there is no apparent tidal signal during the period of mouth "closure" in Figure 2-13, it is assumed that there is insignificant tidal exchange through the groundwater as discussed in Section 3.5.3 below. Consequently, it is assumed this increase in estuary volume is due to fluvial inflow from the catchment.
- Following natural or artificial mouth breaching the tidal range would immediately increase and the low tide slack period would show a significantly lower elevation (Figure 2-13). This suggests that the sill elevation in the mouth channel has been scoured to a lower elevation during the mouth breaching. The subsequent rise in the low tide observations indicate that the mouth is progressively "closing" when the tidal range is significantly reduced during tidal cycles. However, it is not clear if this is due to sediment deposition in the channel or further up in the mouth delta. The Google image of 08 Nov 2017 shows the mouth channel was blocked by sediment along the ocean shoreline (Photograph 2-3). An earlier image (02 Aug 2017) shows very shallow section in the upper channel delta section while the shoreline region had a relative deep channel. This can be seen in the submerged section of

Photograph 2-3: Google image of the mouth closed by sediment accumulation along the shoreline but it is speculated in the text that this is not the cause of the closure.

Photograph 2-3 highlighted by the circle. Consequently, it is suggested that the tidal interaction may have ceased when the section between the channel and mouth delta accumulated sufficient sediment to restrict the flow rather than the sedimentary blockage in the mouth channel. This may be in conflict with more traditional conceptual models that suggest the marine sediment are the primary cause of the mouth closure.

2.5.3 Mouth Delta

If we restrict the mouth delta zone to within a distance of 1 km from the outlet, the sedimentary deposits (sand banks) in this zone may be fairly constant during semi-diurnal tides but generally vary in both spatial distribution and height over spring and neap tides. In Photograph 2-4, showing the Google image of the mouth channel and delta region, the white sands represent the beach berm areas above the high tide that play no role in the mouth hydrodynamics. The blue-green zone shows the water surface during the ebb tide indicated by the turbulent outflow from the channel to the ocean representing the mouth channel. The grey zones indicate the area of the delta that was inundated during high tide. In Photograph 2-4, the very shallow sand banks are almost entirely exposed in the upper reaches of the delta where it is probably that tidal interaction is severely restricted rather than through the mouth channel. Without more data of the extent of the delta sand banks in controlling the flood and ebb tidal action, it is difficult to ascertain the extent of the hydraulic controls on the tidal exchange though the mouth. Consequently, the hydraulic characteristics in the estuary upstream of the mouth have been used to ascertain upstream conditions that reflect the hydraulic exchange for the development of the mouth dynamic models.

Photograph 2-4: The mouth delta region showing the large accumulation of sediments forming very shallow sand banks that may be highly restrictive to the tidal interaction due to a through the mouth channel that is clearly open.

2.6 Fluvial contributions to the Estuary dynamics

There is no observed runoff or sediment data available for the Mlalazi Estuary. The fluvial contribution to the Mlalazi Estuary has been derived from a separate study by Rasifudi (2018) using hydrological models of the catchment. Rasifudi (2018) used the HEC-HMS model to simulate the flows and sediment load from the catchment into the upper reaches of the estuary. The simulation was based on a configured network of discrete sub-catchments (shown in Figure 2-14) derived using the DEM and river networks obtained from Google Earth. HEC-HMS, as a semi-distributed model has allowed for sub-catchments to be divided based on similar land use or location of flow gauges and for input parameters to be lumped to a large degree.

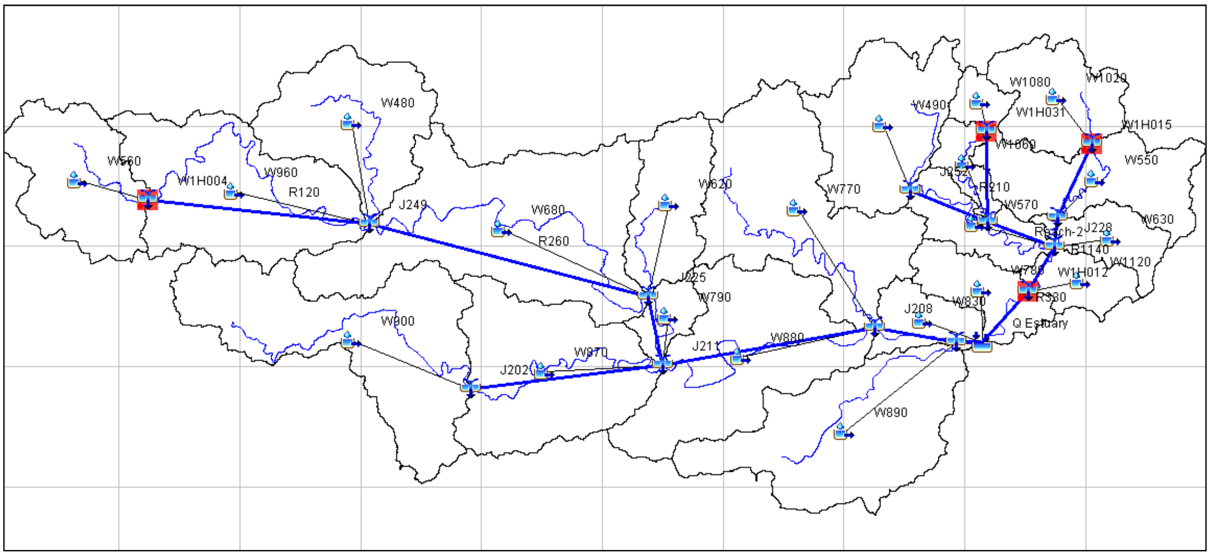


Figure 2-14: Sub-catchments network generated in HEC-GeoHMS

The drainage network and physical components of the model were configured in HEC-GeoHMS using the DEM created from 5 m contour and point height data, and all the available soil, vegetation and other available information described in Rasifudi (2018). The exogenous rainfall record from various point sources was patched and corrected to generate the runoff and sediment discharge from the catchment that was calibrated against available information using both an event based approach for extreme runoff conditions (Figure 2-15) and for the continuous based approach incorporating all storm events (Figure 2-16) using split samples to calibrate and validate the model predictions. The simulated series for both the event-based method and the continuous base approach for corresponding eight-year period was used to validate the calibrated model parameters (Figure 2-17).

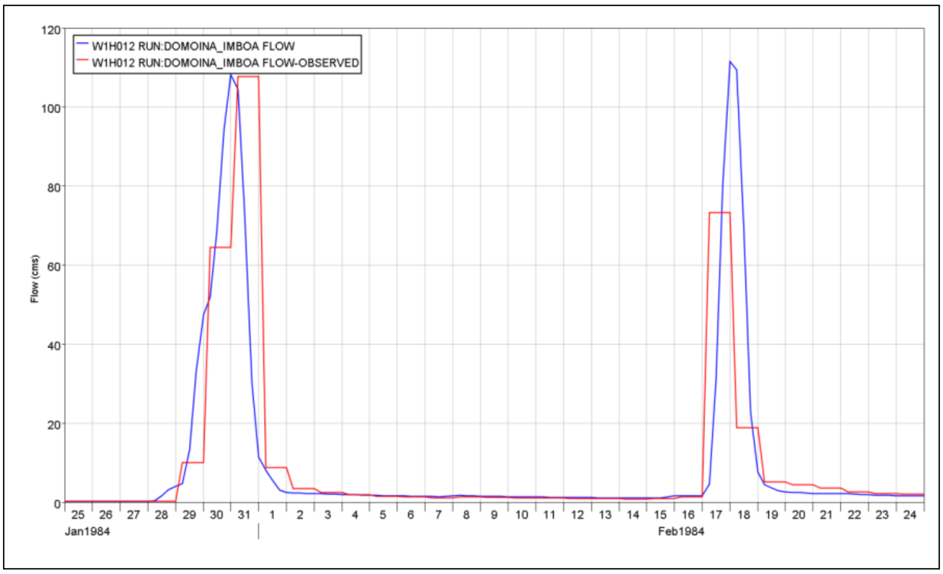


Figure 2-15: Observed (red) and simulated (blue) hydrographs for two storm events

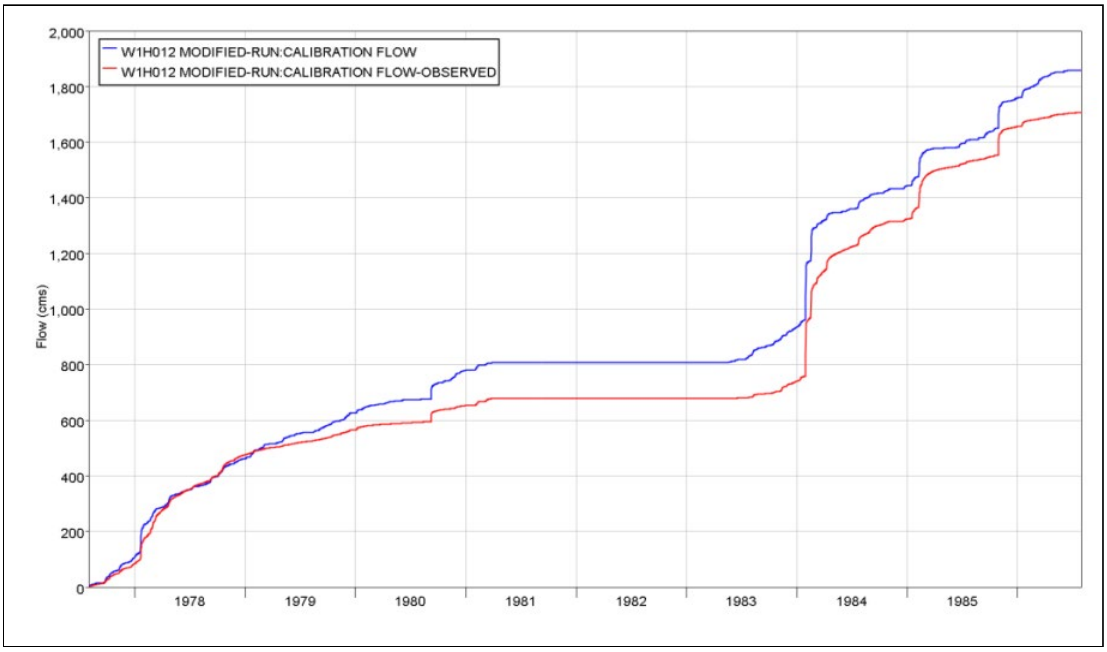


Figure 2-16: Calibration period cumulative observed (red) and simulated (blue) flows

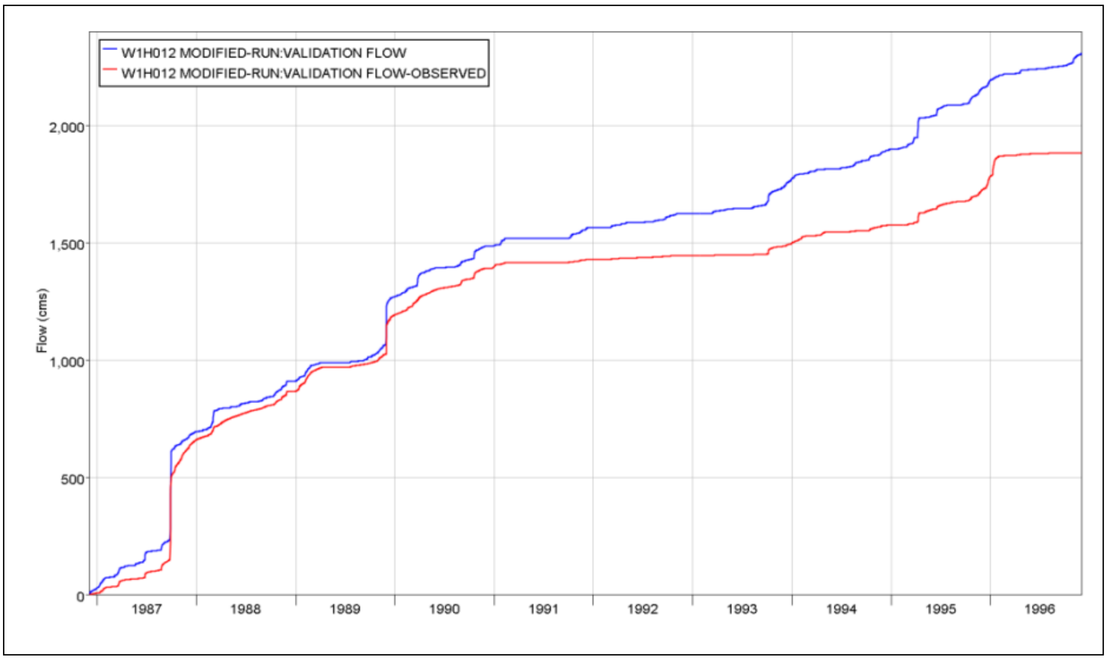


Figure 2-17: Validation period cumulative observed (red) and simulated (blue) flows

The simulated daily runoff and sediment yield from the catchment from 1950 to 2018 is shown in Figure 2-18. The MUSLE sediment model used to simulate sediment yield was not calibrated but was setup based on input parameters taken from data already available from other studies in the area.

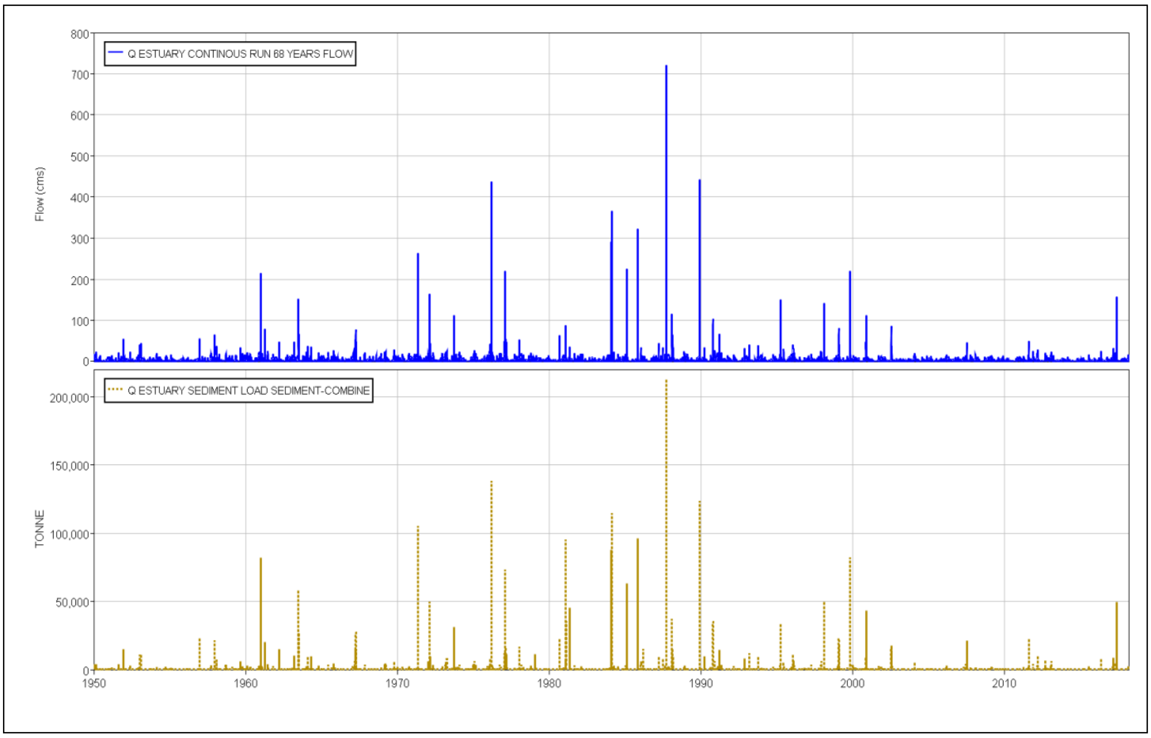


Figure 2-18: Daily simulated flows (m3/s) and sediment yield (tonnes/day) from Mlalazi Catchment (after Rasifudi, 2018).

Figure 2-19 shows the grain size distribution that is deposited into the top of the estuary, mainly during storm events with a discharge exceeding (50 m^3/s). The bulk of the material comprises silts and fine clay that would have been carried through the estuary and probably washed out to sea.

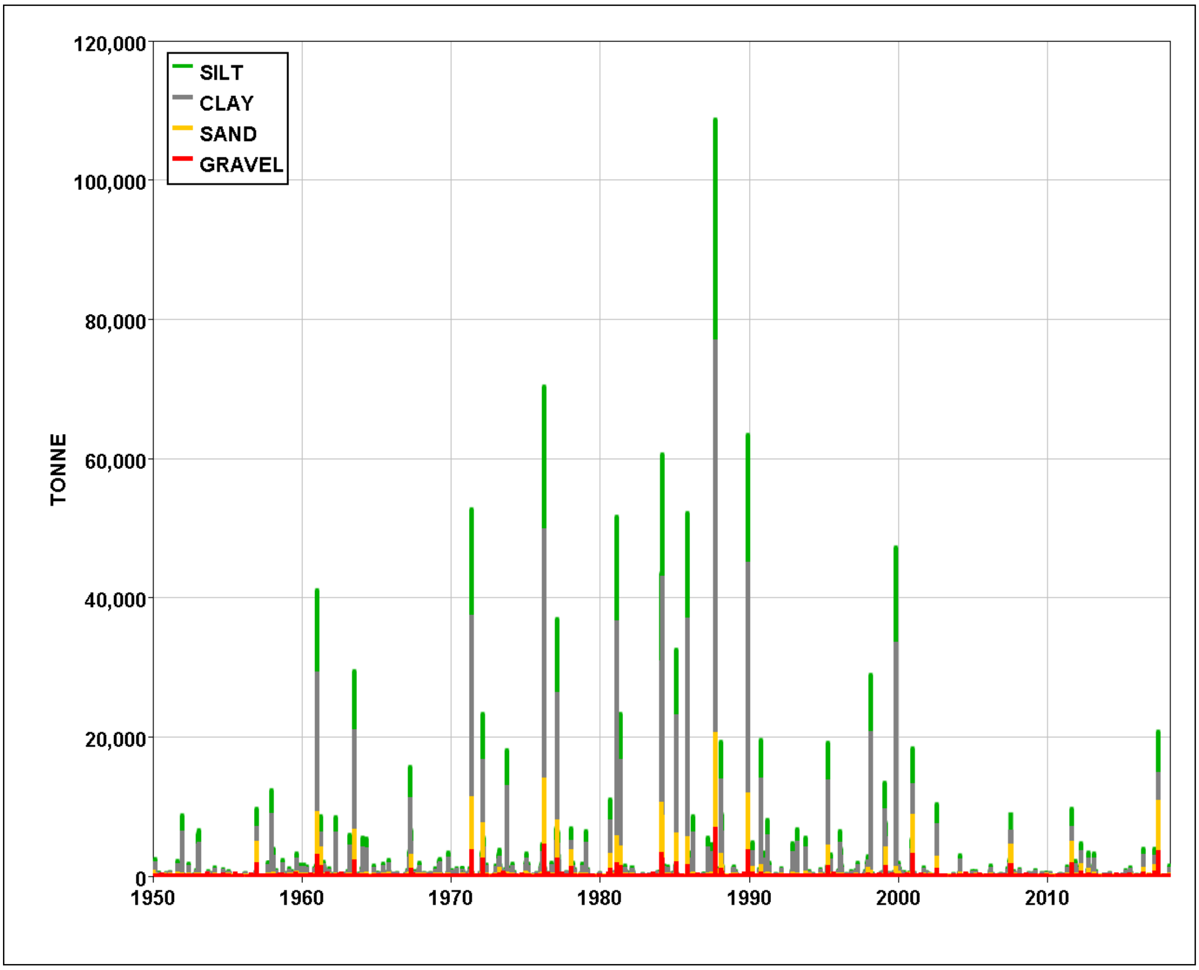


Figure 2-19: Simulated sediment yield grainsize distribution (tonne/day)

2.7 Estuary Water Levels (stage)

The floods levels for the Mlalazi have been obtained from a survey by Badenhorst *et al.* (1989) for the main bridges across the estuary for four major flood events, including the 1984 cyclonic events and the 1987 cut off low. The water level almost reached 9 and 6 mMSL at the R102 road and railway bridges respectively during the 1987 floods. This storm event has been classified as a possible 1:200-year (Kovacs, 1988) events and has provided a possible upper limit for the HEC-RAS model calibrations. A photograph of the water level at the old N2 Road Bridge after it had receded from a peak stage of ~9 m

Photograph 2-5: Photograph of the old N2 Road Bridge several hours after the main flood peak had receded following an approximate 1:100 year rainfall event in September 1987. (Photo Kelbe)

above the bridge is shown in Photograph 2-5.

The water level in the estuary has been monitored by various agencies over the past four years. In 2015, the National Department of Water and Sanitation (DWS) installed a monitoring station within 300 m of the mouth. Unfortunately, this logger was damaged in 2016 when the mouth closed and the vented logger was flooded. The logger was replaced on 16/May/2018.

Ezemvelo KZN Wildlife (Bachoo and Taylor, *pers comm*) installed an unventilated logger at the railway bridge on 17 September, 2015 and the pressure rectified data series has been made available up to 26, Aug, 2016.

The HRU, in Department of Hydrology at the University of Zululand, installed several unventilated loggers along the estuary channel bed from Aug 2016 for various studies that have also been used in this study to supplement the water level series.

The complete merged data series available for this study have been compensated for pressure variations and are plotted in Figure 2-20 (upper graph) from 25 Mar 2015 to June 2018.

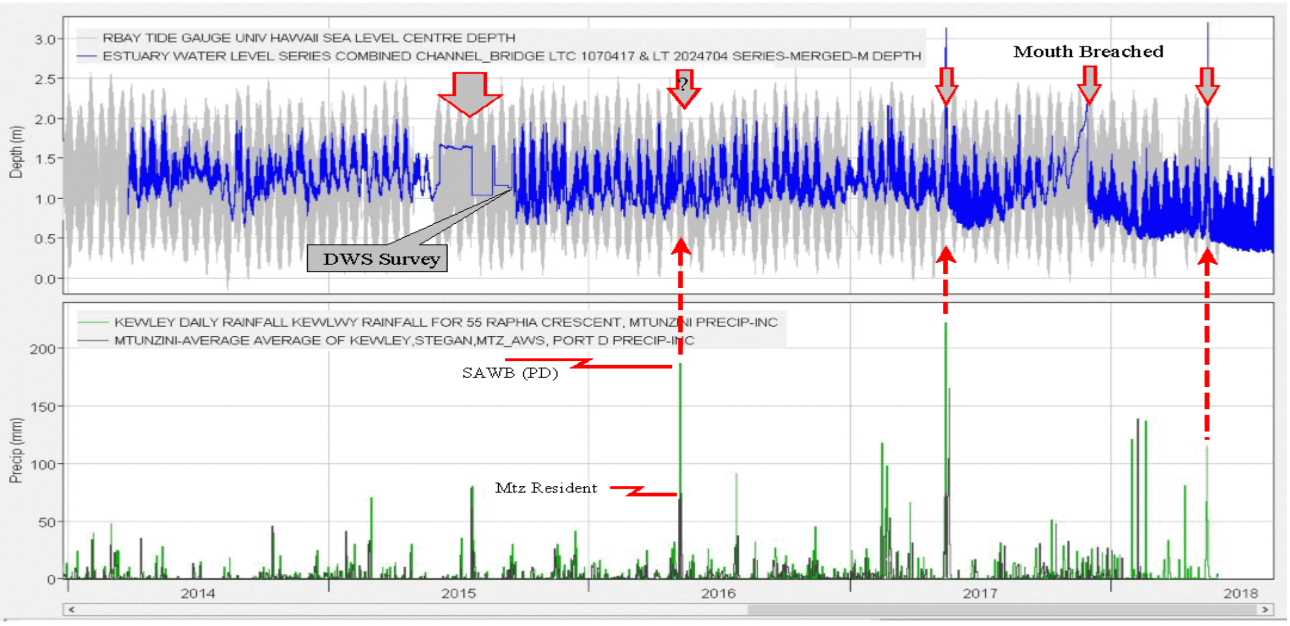


Figure 2-20: The combined logger water level series for all the available logger downstream of the Railway Bridge. Also shown in the lower plot are the rainfall series the lower sections of the catchment.

There is a very short period without observation between the failure of the DWS logger and the start of the Ezemvelo logger series. The most recent logger series for 2018 from DWS has not been included because it shows a cut-off for the low tide that needs further investigation. Some of the extreme natural and anthropogenic events are show by the red arrows in Figure 2-20.

The DWS and Ezemvelo logger sites were survey and used to estimate the datum for the HRU loggers using the period of overlapping measurements. These data have been used to establish an understanding of the estuary channel dynamics in the subsequent sections of this report.

2.8 Estuary Simulated Hydrodynamics

The main hydrodynamic characteristics of the Mlalazi Estuary have been derived by Mmako (2019) using the HEC-RAS model (2017) to study the estuary response to a range of storm events. His model configuration is shown in Figure 2-21 and was calibrated for both storm events and for continuous runoff over an extended period of 37 years (1980-2017). Mmako (2019) used both storm and continuous flow simulation techniques to examine the extent of flooding during various fluvial events (2 to 100-year recurrence intervals) using the catchment runoff studies by Rasifudi (2018) described above.

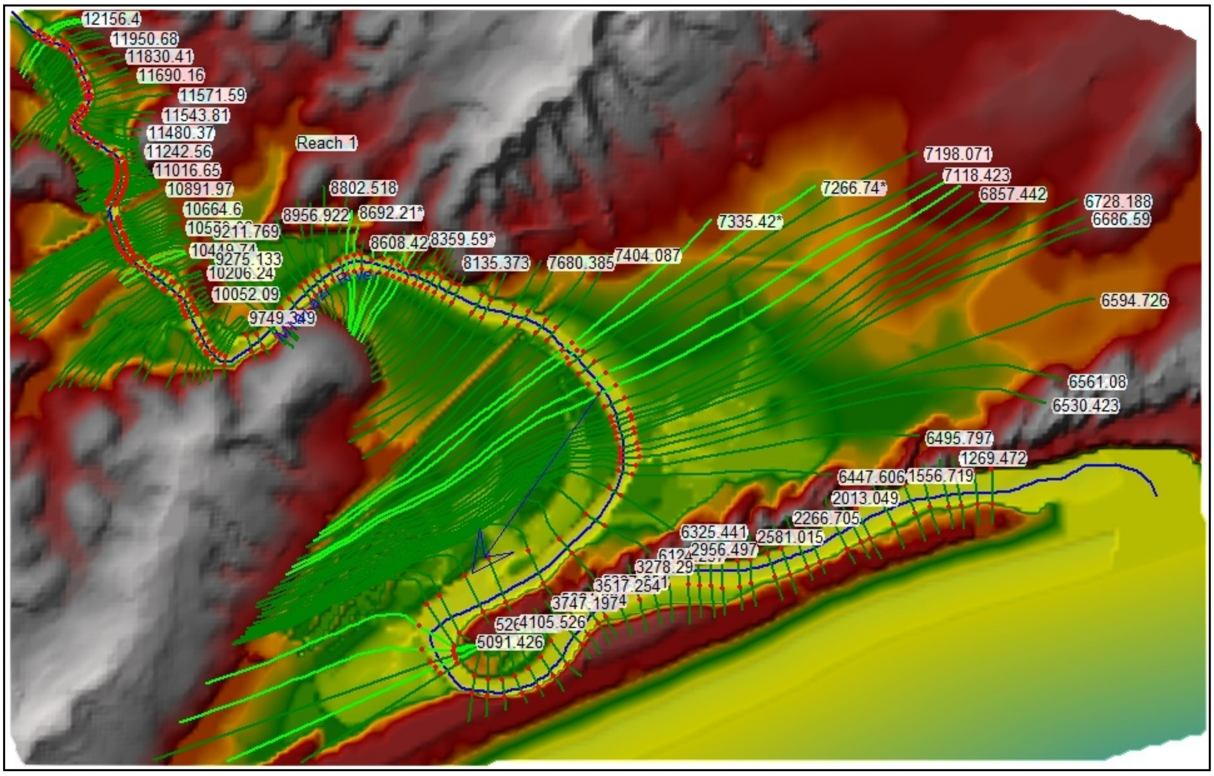


Figure 2-21: The HEC-RAS model covering the Mlalazi Estuary configured, calibrated, validated and applied by Mmako (2019)

The tentative results of the model predictions for a range of extreme storm events between 1980 and 2017 showed varying levels of agreement between the predicted levels of inundation along the estuary channel and historical measurements (Table 2-2). The predicted and observed level of inundation in the estuary floodplain for the 1987 extreme storm event (~1:100 year) is shown in Figure 2-22. The simulated heads were generally within 1 m of the observed values at the control structures along the estuary with the exception of the upper estuary where the boundary conditions are not well defined. The simulated stage along the estuary for the full range of events is generally within an acceptable range for the purpose of this study.

Table 2-2: The predicted and measured water levels at selected estuary cross-sections for various flood events (from Mmako, 2019).

Measured Sites	Distance (km)	Flood Events	Observed (m)	Simulated (m)	Model error m (%)
Confluence (*12156.4)	0.00	1:10	3.88	4.10	0.22 (5.7)
		1:50	7.28	7.10	-0.18 (-2.5)
N2 Bridge (*10449.74)	2.00	1:100	8.70	7.39	-1.31 (-15.1)
D/S of N2 Bridge (*8439.04)	2.00		6.10	5.99	-0.11 (-1.8)
Railway Bridge (*7595.656)	1.30	1:2	1.15	0.78	-0.36 (-32.2)
		1:100	5.95	5.73	-0.22 (-3.7)
D/S of Railway Bridge (*7118.423)	0.75	1:100	6.05	5.67	-0.38 (-6.3)
Lower Estuary (*5015.724)	1.87		4.95	5.55	0.6 (12.6)
Lower Estuary at the bend (*4767.722)	1.37	1:2	0.78	0.58	-0.2 (-25.5)
		1:20	2.73	2.93	0.2 (7.3)
Mouth (*1448.347)	2.71	1:2	1.27	0.81	-0.46 (-36.7)

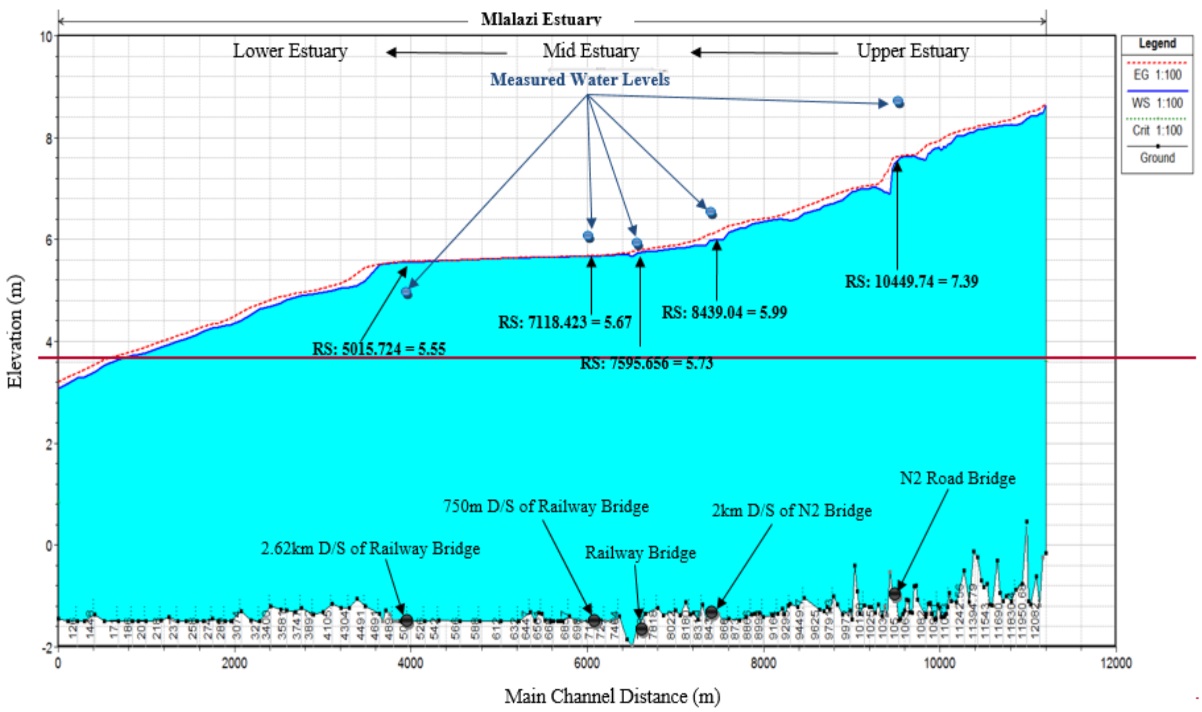


Figure 2-22: The simulated water table profile along the estuary channel downstream of the confluence of the Mlalazi and Ntuze tributaries at the peak of the 1987 storm events shown by the blue shading..

The 1:2 year runoff event (i.e. average conditions) extent of floodplain inundation is shown in Figure 2-23. The flow velocity seldom exceeds 0.2 m/s except in some of the constricted areas upstream of the railway bridge.

The extent of the floodplain inundation for the 1:10 and 1:50 year events are shown in Figure 2-24 and 2-25. The spatial extent of flooding could not be calibrated due to lack of information. However, it was known that the prawn farm and parklands downstream of the railway bridge were only partially flooded during these events. Subsequent survey of this section of the floodplain has been completed by Tembe (2018) and needs to be incorporated into the model DEM.

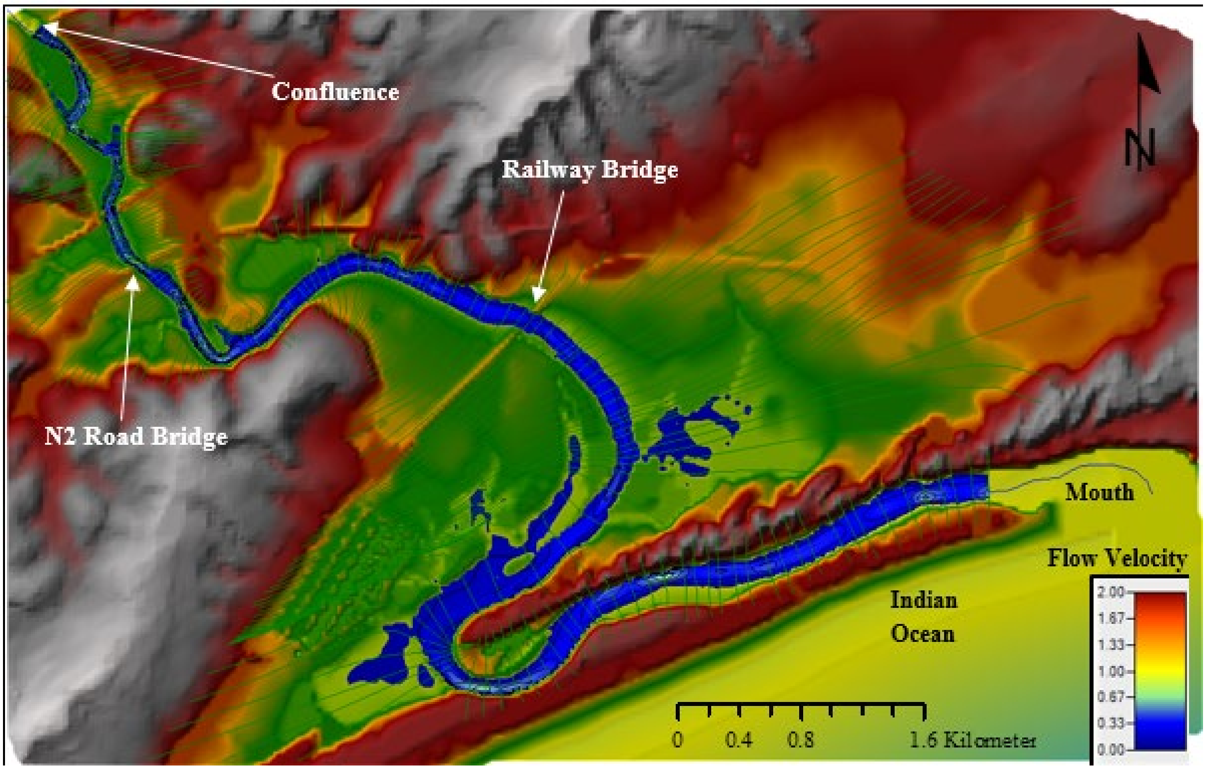


Figure 2-23. The spatial extent of the flooding along the Mlalazi Estuary under average flood conditions (1:2 year events) from Mmako (2019)

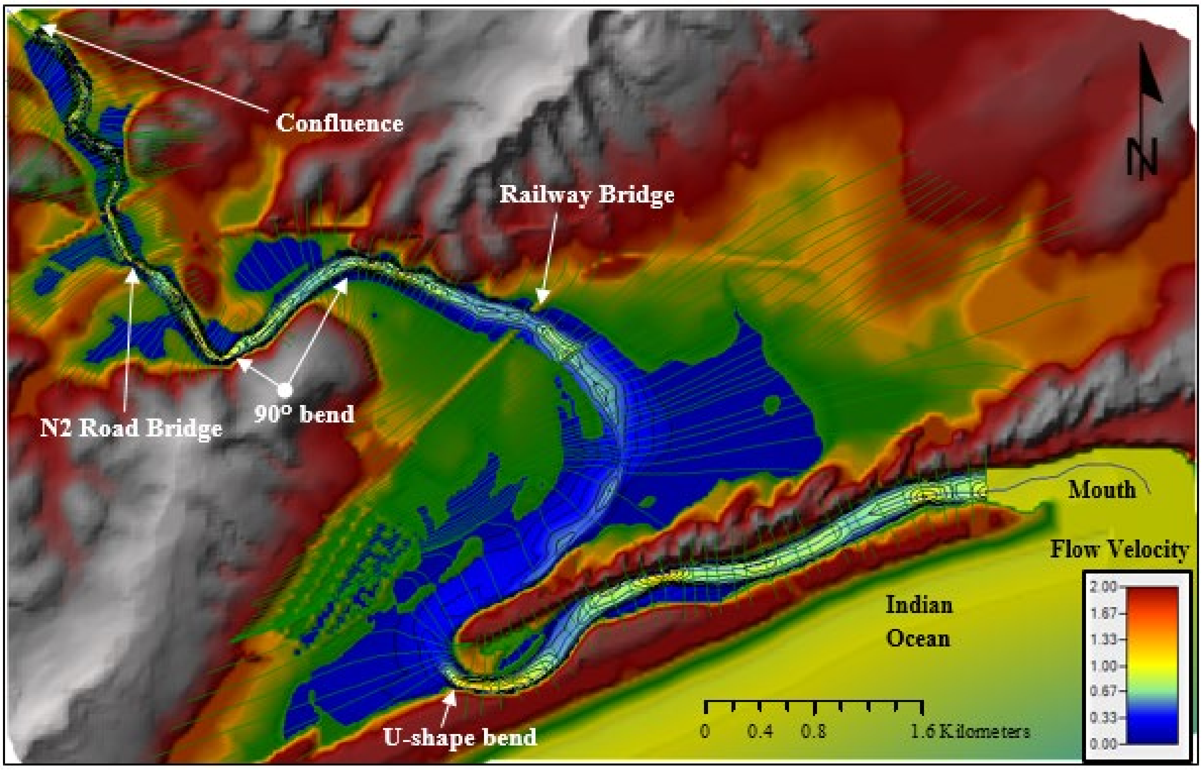


Figure 2-24: The simulated spatial extent of the flooding along the Mlalazi Estuary during a 1:10 year events (from Mmako (2019).

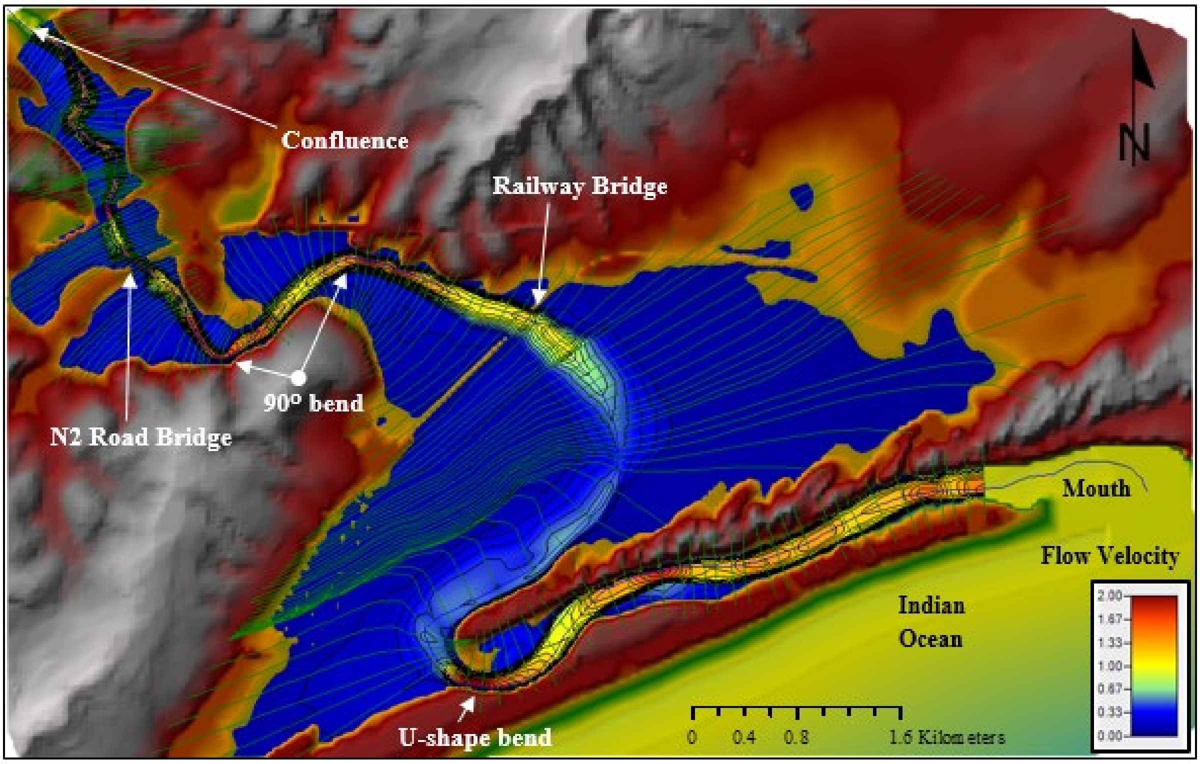


Figure 2-25: The simulated spatial extent of the flooding along the Mlalazi Estuary during a 1:50 year events (from Mmako, 2019).

The model predicts a rapid increase in velocity through the main hydraulic restriction along the channel and in the lower estuary causing backup storage that is clearly illustrated in Figure 2-25. However, there was little erosion at these structures based on the survey by Badenhorst *et al.* (1989). The cross-section profile across the railway bridge (RS505724 in Figure 2-26) was surveyed after the three major flood in 1932, 1969 and 1987 and does show some erosion at the railway bridge after the 1987 (1:100 year) flood event in the upper reaches but little scour in the lower reaches where the extensive floodplain would have reduced the flow velocities for scouring and sediment carrying capacity There is no observation or other data on the extent of the scouring in the estuary mouth during these extreme events.

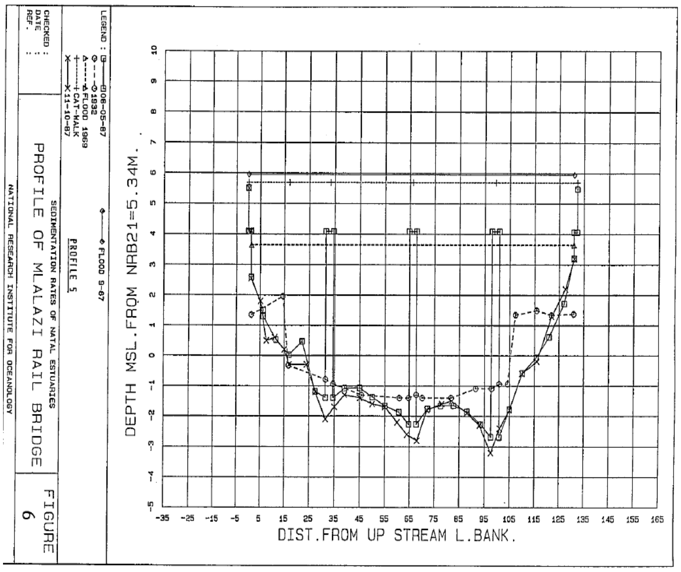


Figure 2-26: The cross-section profile at the Railway bridge for the 1987, 1932 and 1969 storm events (after Badenhorst et al., 1989). The water level almost reached 6 mMSL during the 1987 event with minimal scour between the 1932 and 1987 surveys.

3. ESTUARY DYNAMICS

There is very little open source hydrodynamic information of the Mlalazi Estuary currently available. Consequently, it was necessary for this study to expand the water level monitoring at strategic locations along the estuary channel using continuous loggers. These were located during various stages of the study at the sites shown in Figure 3-1.

The hydrodynamics of the estuary system is controlled by several main physical features; the estuary channel; the surrounding flood plain and the marine interface.

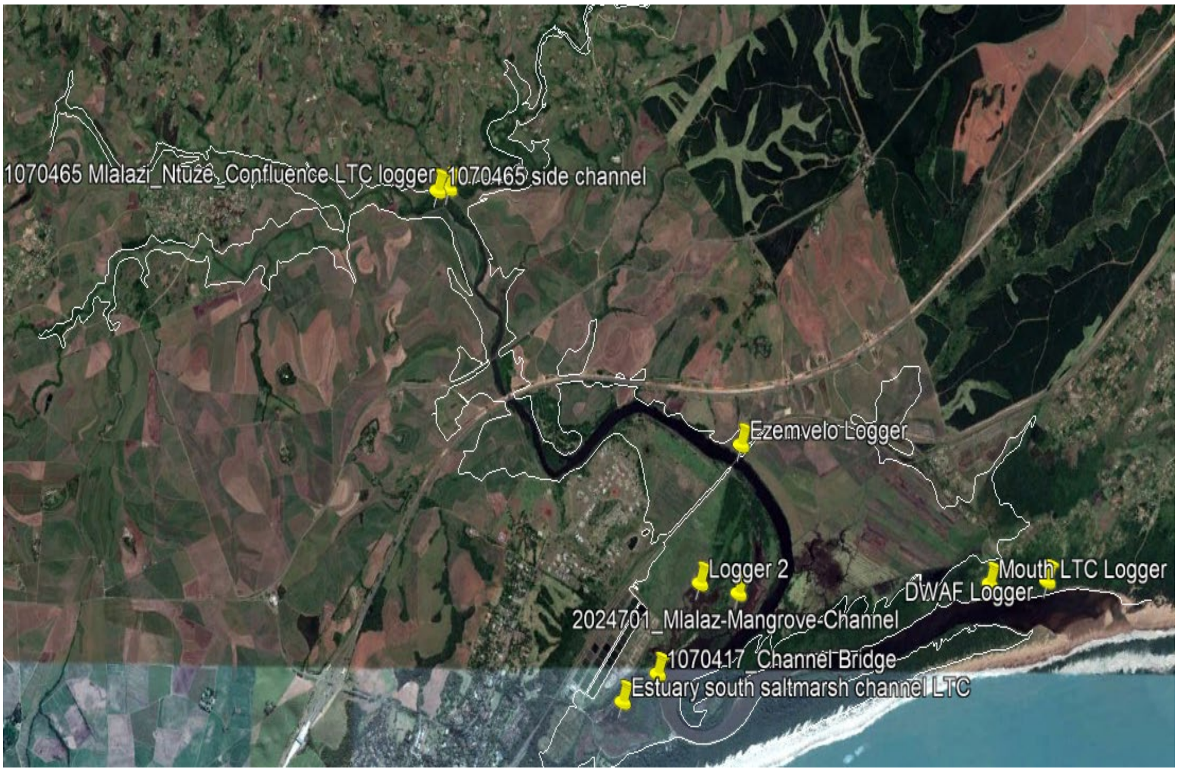


Figure 3-1: A Google Image of the floodplain shown by the white contour and the channel.

3.1 Floodplain

The water level measurements have been used to establish the main hydrodynamic characteristics of the estuary as described in the following section. The main hydrodynamic features of the system are dominated by the estuary channel that extends upstream for about 12 km from the mouth and the adjacent floodplain when the water level in the estuary exceeds a stage of about 2 m. The fluvial impacts on the Estuary have been described above by Mmako.

Covering most of the floodplain (Figure 3-1), the predominant landuse is sugar cane cultivation that is generally planted in rows running parallel to the elevation contours and roughly perpendicular to surface flow lines. These sugar plantations are likely to reduce the flow rate due to increased roughness that will significant affect the rate of surface/overland runoff from the floodplain. However, some sections have a large number of drainage canals, mainly in the north-eastern portion of the middle section that could increase flow rates. This has a significant impact on the propagation of flood waves through the estuary that can cause some floodplain erosion and deposition.

A large storm event in May 2018 that produced over 200 mm of rainfall that fell over a period of 48 hours created a significant flood event in the estuary. The simultaneous flood hydrographs at the top and bottom of the estuary are shown by the flood-waves in Figure 3-2. The water level at the confluence of the Mlalazi and Ntuze tributaries reached a peak water level of 7.26 m that receded to pre-storm levels over a period of about 24 hours. This flood wave peak propagated through the estuary in about 3-4 hours with significant attenuation.

The flood-wave started to overtop the channel at a stage of about 2 m and inundate the upper reaches of the floodplain. The entire floodplain was inundated after about 3-4 hours. Assuming an average stage of 4 mMSL over the floodplain, the peak volume of water stored would have been about 10 M m^3 (Figure 2-11).

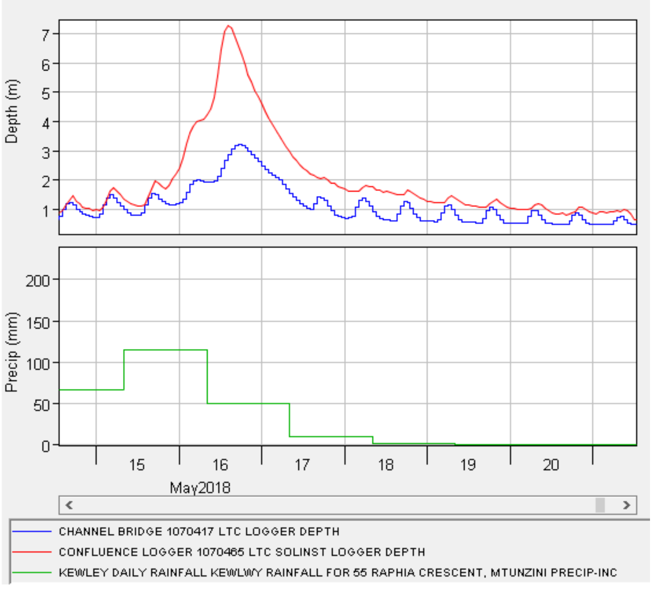


Figure 3-2: The rainfall (lower graph) and the simultaneous measurements of the water level (upper graph) at the confluence of the two tributaries in the upper estuary (red line) and near the mouth (blue line) near the discharge point.

3.2 Estuary channel

The estuary channel is over 12 km in length and has a relatively constant width of between 50-200 m. It has an estimated storage volume of 1 M & 4 Mm^3 at stage elevation of 0.0 mMSL & 2 mMSL respectively. The water level monitoring shows tidal motion for up to 12 km from the mouth under reduced fluvial flows (Figure 3-2 and Figure 3-3).

The tidal fluctuation at the confluence and near the mouth one day after the mouth was breached on the 29th November 2017 was selected to estimate the tidal lag and attenuation at the confluence from the estuary mouth tide. This period was chosen as it would have experienced a significant tidal exchange after the mouth was opened. Figure 3-3 shows the tidal patterns over 4 semi-diurnal cycles that were used to estimate the lag and attenuation of a tidal wave recorded at the upper and lower reaches of the estuary.

There is approximately a 1:00-1:30 hour lag in the propagation time of the tidal wave at the confluence. While the wave attenuation during each tidal cycle varies, there is no clear trend in the head difference.

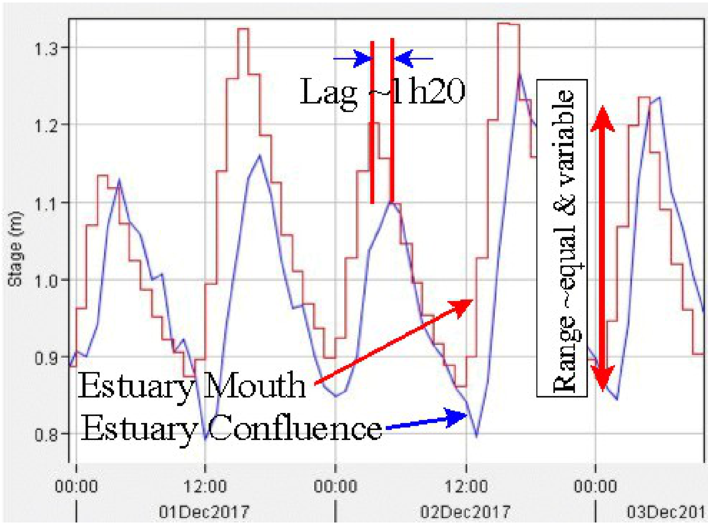


Figure 3-3: The water level measurement near the mouth (red line) and at the confluence of the tributaries (Blue line) illustrating the magnitude of the lag and attenuation during the wave propagation from the mouth to the top of the estuary.

The rising "flood" tide generally commences in the upper estuary 1:00-1:30 hours after the start of the corresponding flood tide at the mouth. Both tides rise for approximately 4 hours until the flood tide at the mouth reaches the slack tide about 1:00-1:30 hours before the confluence slack tide. This suggests that approximately half the estuary channel contains the tidal storage at any time during a flood tide. Similar arguments should hold for the ebb tide.

From the analysis of the estuary hydrodynamic, this storage factor is deemed to represent the "prism storage". Note: this does not apply to storm wave storage that covers a different area of the estuary. It is assumed that the tidal wave at the confluence represents the backup of water in the channel rather than water movement up the channel during periods of negligible fluvial inflow. Consequently, the tidal prism is assumed to be equivalent to the storage of half the inflow of tidal sea water into the estuary that is likely to be contained near the mouth.

The total volume of marine storage in the estuary channel during a tidal cycle is then proportional to change in water level at the mouth covering half the area of the channel. This volume can be derived from the hypsometric curve shown in Figure 2-12. Based on this assumption, the tidal flux into and out of the estuary through the mouth can be estimated. These estimated fluxes have been used in the next sections to estimate features of the mouth dynamics.

3.3 Estuary mouth

There is a significant difference in the marine and estuary tidal wave ranges (Figure 3-4) that is assumed to be due to the hydrodynamic constraints of the mouth channel defined by its width, depth and roughness conditions (Slinger, 2015).
The time and height of the marine and estuary tidal waves where extracted from the sub-hourly data series that was converted to a regular synchronised time series. The head difference between the marine and estuary tides across the mouth is shown in Figure 3-5. The tidal attenuation generally varies from about ~0 m to

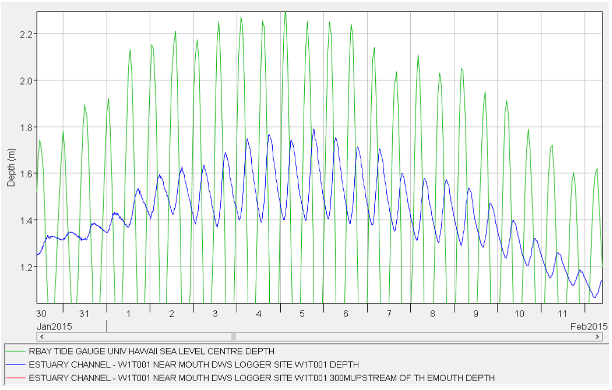


Figure 3-4: Water level measurements of the marine and estuary tides over a complete lunar cycle showing the lag and attenuation of the marine wave through the mouth.

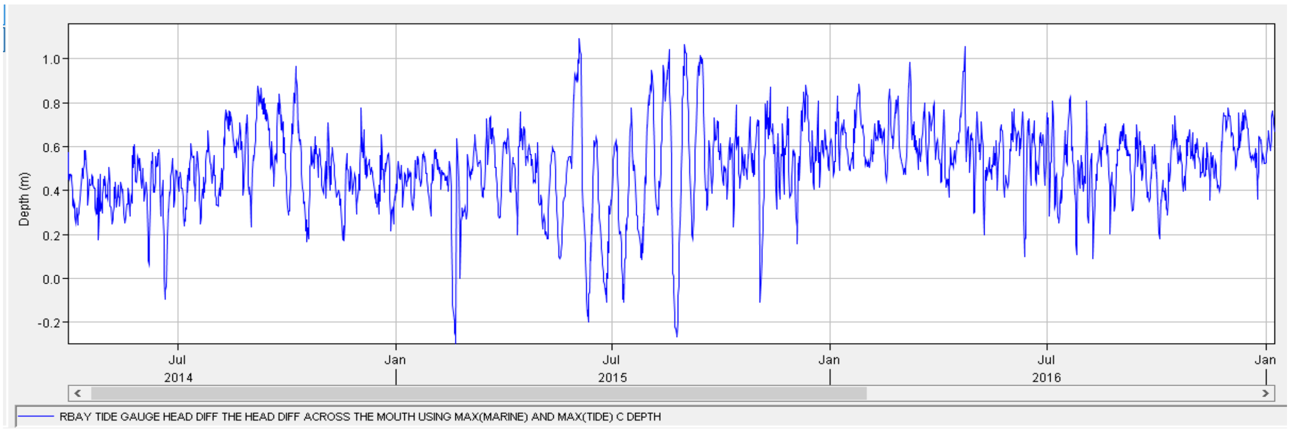


Figure 3-5: The level of attenuation of the marine tide entering the estuary for the observation period from 2014-2016. Some of the extreme values were due to fluvial events.

1 m with an average attenuation of about 0.5 m. However, some of the extreme values may be attributable to fluvial events.

It is assumed that the marine tide at the Mlalazi Estuary mouth is the same as Richards Bay. Ruth Farre (*pers. comm)* at the South African Navy Hydrographic Office, indicated that the time lag between Durban and Richards Bay at spring highs is ~5 minutes so it is reasonable to assume the tidal lag between Richards Bay and Mlalazi mouth is within this range.

The lag in the wave propagations for both the tidal peaks and troughs across the mouth was estimated from the difference between the occurrence of the high and low peak (slack) tides between the marine and estuary waves. Figure 3-6 shows the lag (upper blue arrow) for the tidal peaks between the marine and estuary. The lag was generally found to be between 3-5 hours. However, this is significantly longer than the propagation of the tidal wave up the estuary (1-2 hrs).

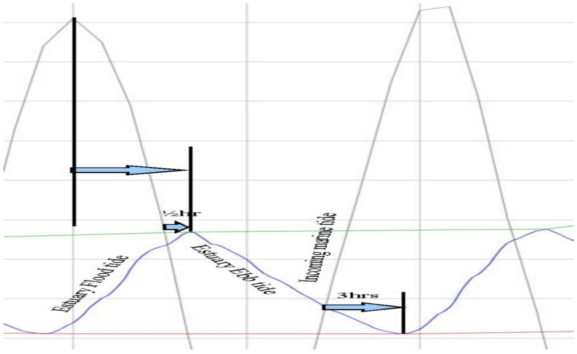


Figure 3-6: An example of the simultaneous marine and estuary tidal variation across the mouth. The lower arrows show the lag for the corresponding water level elevation in the marine and estuary tide across the mouth. The estuary tide would be expected to turn when the elevations were the same.

The lag in estuary response to the falling marine ebb tide is about 2 hours (middle blue arrow for ebb tide in Figure 3-6). This is considerably shorter than the lag in the estuary response to the rising marine flood tide of about 4 hours (lower blue arrow in Figure 3-6).

3.4 Estuary tidal characteristics.

The semi-diurnal tidal action in the estuary (Figure 3-7) comprises;

- the flood tide, when the marine tide stage exceeds the mouth sill elevation and sea water enters the estuary through the mouth channel and basin.
- the ebb tide, comprising the outflow of water when the estuary water level exceeds the marine tide.
- The slack tide between the flood and ebb tides when there is no apparent change in stage in the estuary.

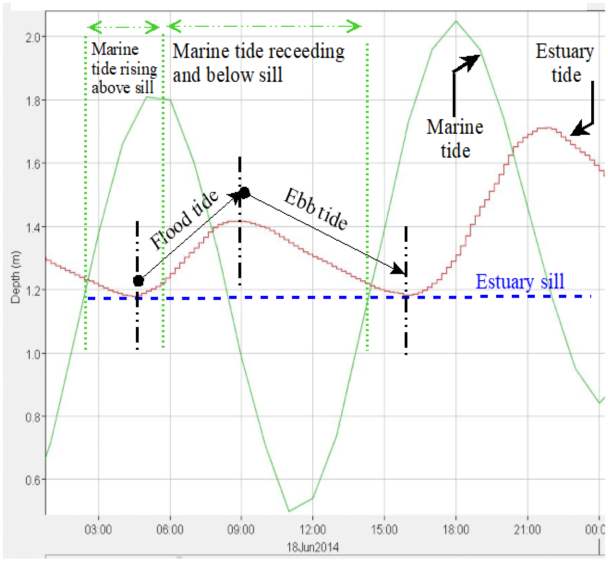


Figure 3-7: The marine and estuary tidal cycle showing the flood and ebb tide features in relation to the marine tide.

The flood and ebb tides are driven by a changing head gradient as the marine tide rises and falls relative to the estuary stage. The flood tide occurs when the marine tide rises above the estuary sill elevation but the ebb tide occurs when the marine tide is falling and when it is below the elevation of the stage. If the estuary sill is at mean sea level (0 mMSL) then the flood tide occurs for ¼ of the marine tidal cycle while the ebb tide occurs for ¾ of the tidal cycle (Figure 3-7). Consequently, the flood and ebb tide should have distinctly different characteristics.

3.4.1 Tidal period

The minimum (low tide) and maximum (high tide) water level elevations at the estuary mouth (W1T001 gauge) were extracted for 12 hourly intervals. The time lag between the alternating low and high tides in the estuary is shown in Figure 3-8. The flood tide has an average duration of four (4) hours while the ebb tide has a corresponding average duration of eight (8) hours. The values of less than 2 hours and greater than 12 hours in Figure 3-8 are due to analytical errors in extracting the high and low tides from a continuous time series that is not an exact harmonic of the tidal wavelength. Also, many of the other outliers could be attributed to fluvial conditions.

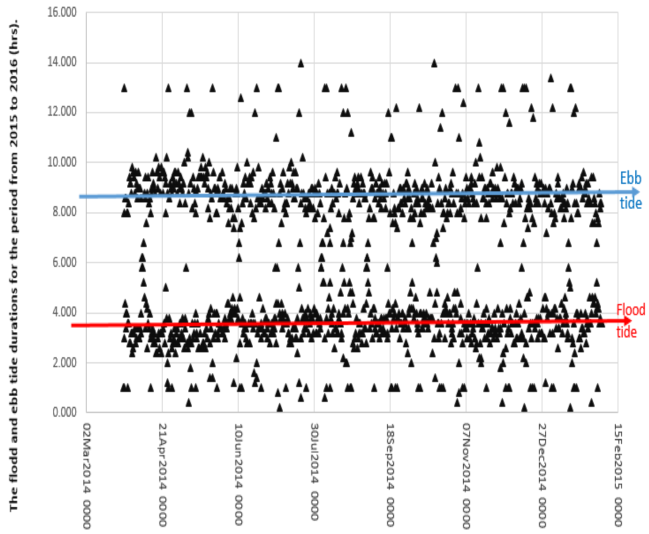


Figure 3-8: The duration of the flood and ebb tide at the mouth taken from the W1T001 logger series.

3.4.2 Tidal range

The flood and ebb tidal range through the estuary show significant difference during the period of observation from 2014 to 2018. There is a high POSITIVE correlation between high tide and low tide (Figure 3-9) in contrast to the marine tides. However, the scatter plot of the DWS logger series from 2014 to 2015 (Figure 3-10) shows that the high and low semi-diurnal tides converge during neap tides but the difference increases during spring tides. This is an indication that the influx of sea water into the estuary during flood tides is generally likely to balance the out flow during ebb tides **under neap conditions** but not during increasing flood tides under **spring conditions**.

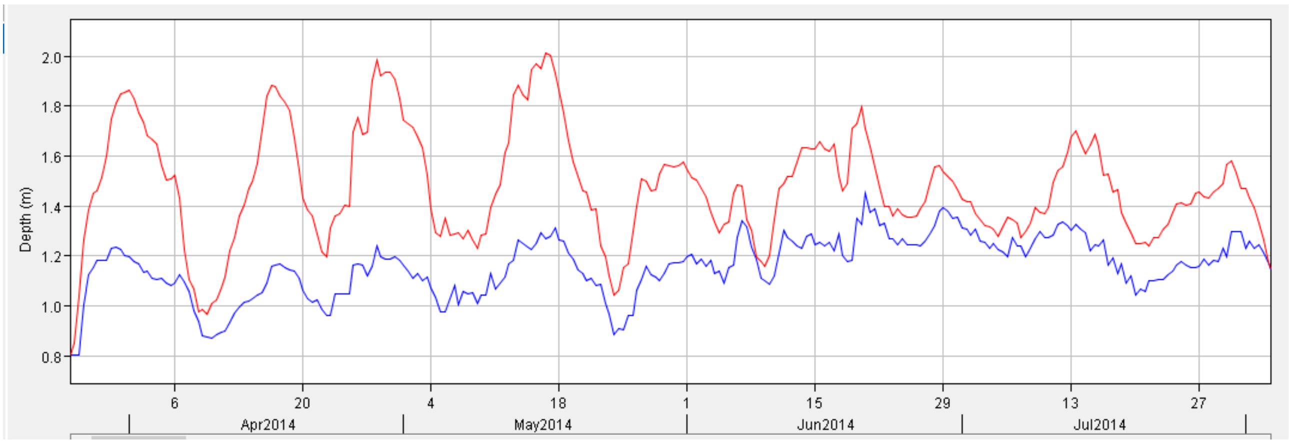


Figure 3-9: The high (red) and low (blue) tide series for W1T001 gauge during Apr-Jul 2014.

Consequently, low tide elevations are more likely to represent the base (sill) elevation of the mouth control section during neap tides but not during spring tides when there is significant water storage in the estuary. This is illustrated by the hourly water level at W1T001 in 2014 (Figure 3-9) that show;

- reduced ebb tide during the onset of spring tides when there would have been increased storage in the estuary resulting in an increased in the low tide elevation,
- followed by a period with equal flood and ebb tidal range when there would have been no further storage during spring tides (17-23 Feb 2015),
- followed by decreased storage during the onset of neap tides that restored the overall water balance.

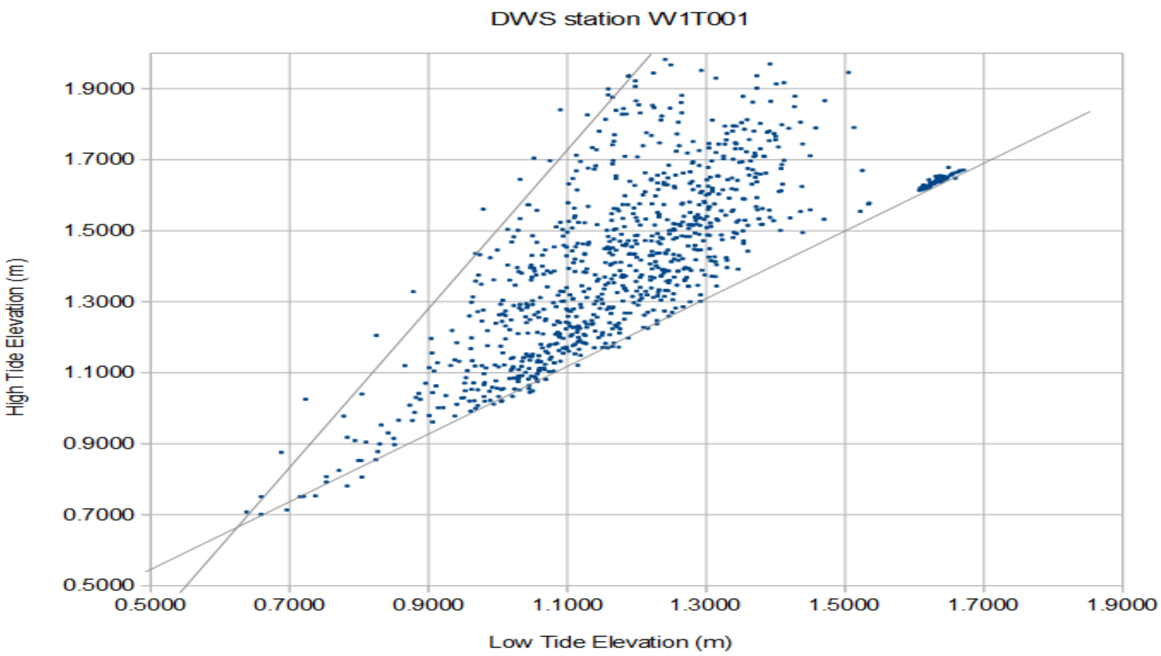


Figure 3-10: Scatter plot of the high and low diurnal tidal elevation for W1T001. The grouping of points at the low tide elevation of1.6 m correspond to the period the mouth was closed.

3.4.3 <u>Low Tide Predictions</u>

The W1T001 logger series is shown in Figure 3-11 by the black line for the semi-diurnal low tides. Based on the relationship shown in Figure 3-10, an estimate of the low tide series has been extracted (red line in Figure 3-11) based on the approximate correlation with the high tide. This estimate of low tide was derived by subtracting a proportion (1/5) of the high tide from the actual high tide. The resulting time series has been used as a possible surrogate indicator of the low tide in the model of the mouth described later in the report. The two series shown in Figure 3-11 indicate a high level of correspondence during certain periods but there is a reduced level of agreement between the actual and estimated series at spring tides. Since the low tide is more conducive to predicting mouth elevation at neap tides, this concept needs further investigation.

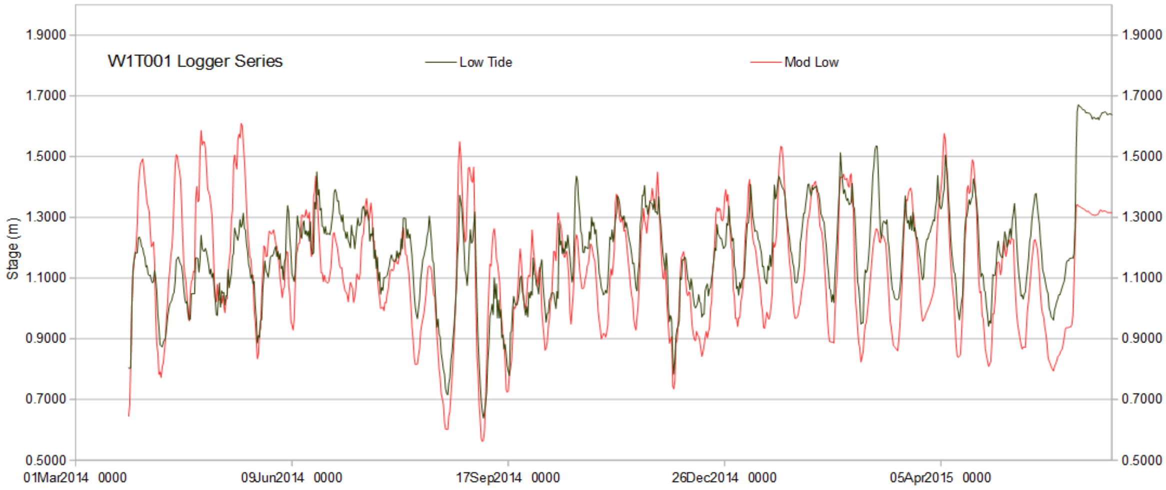


Figure 3-11: W1T001 logger series showing the diurnal Minimum (Low tide) and the modified low tide estimated from a direct proportion of the High Tide (H-H/5)

3.5 Mouth Hydraulic Characteristics

The physical features of the mouth described above form the main hydraulic controls on the two-way exchange of water between the ocean and estuary over a tidal cycle.

- During the estuary discharge cycle, it is assumed that the water level in the estuary does not drop below the elevation of the lowest discharge point in either the mouth basin or mouth channel. Consequently, discharge through the mouth is proportional to the head difference (dh/ds) between the estuary and marine water levels when the marine tide exceeds the discharge level in the estuary. Discharge for water level in the estuary below the mouth sill elevation can only occur if there is sufficient head gradient across the mouth to support groundwater fluxes discussed in the next section.
- During the estuary discharge cycle (ebb tide), the efflux is directly proportional to the head gradient between the estuary and the mouth sill elevation once the marine tide is lower than the water level in the estuary.
- Basic open channel flow indicates that the flux rate of water through a specified channel is related to the head gradient, the dimensions of the channel and a proportionality coefficient (roughness).
- The channel dimension change constantly but it is assumed that during a semi-diurnal cycle they maintain the same control on the flood and ebb tidal fluxes.
- The proportionality coefficient, generally simplified as a roughness factor would include the channel substrate in the controlling section (basin or channel) and other unknown factors such as wave and wind action.

All these controlling features are expected to produce a signal in the tidal patterns and are analysed below.

3.5.1 Lag time during Flood and Ebb Tides

The ebb tide, with an average duration of 8:00 hours, will generally not have drained the estuary to the level of the mouth sill (mouth-base) when the incoming marine tide reaches the same elevation across the mouth, particularly during spring tides. In the example shown in Figure 3-7, the lag in the estuary tidal response across the mouth between the incoming and outgoing marine tides is considerably different for the flood and ebb tides. The flood tide in the estuary continues to rise for at about 1:00 hour before reaching the slack tide. However, for the ebb tide, the estuary continues draining though the mouth for a further 2:00 to 3:00 hrs during the incoming marine tide.

3.5.2 Flux rates through the mouth

The flux of water into and out of the estuary during each semi-diurnal tidal cycle was estimated from the hourly head changes (rate of change) in the estuary water level measured by the logger series. It is assumed that the hourly rise (or fall) of the water level in the estuary near the mouth propagates along the entire estuary creating positive (negative) storage in the channel during the flood (ebb) tides. This storage is estimated to occur over half the area of the estuary at any time during the tidal cycle. This volume of stored water during each incremental change in height represents the mass influx (m^3/hr) through the estuary mouth during that period of rise (fall) in the estuary tide. The tidal elevation during the rise or fall in the flood and ebb tides occurs over an area of the estuary channel represented by the hypsometric curve in Figure 3-12. From the tidal analysis above, the flood tides take approximately 4 hours to reach their peak height (slack period) and a further 8 hours of decline during the ebb tide between the slack periods. During the flood tide, this tidal wave will occupy ¼ of the tidal prism during each hourly interval over the four-hour period. Similarly, the storage area from the start of the ebb tide will be depleted by 1/8 of the tidal prism during each hourly interval over the eight-hour period. From the analysis above, it is assumed that the flood tide is stored over approximately half the estuary volume at the peak of each tidal cycle. Hence the total flux through the mouth was estimated from the change in tidal head (dh/dt) associated with the flood and ebb tides. The calculated changes in flow rate (m^3/hr) across the mouth is shown in Figure 3-12. This discharge rate (flux) through the mouth needs to be converted to flow velocity to estimate the sediment carrying capacity at the mouth.

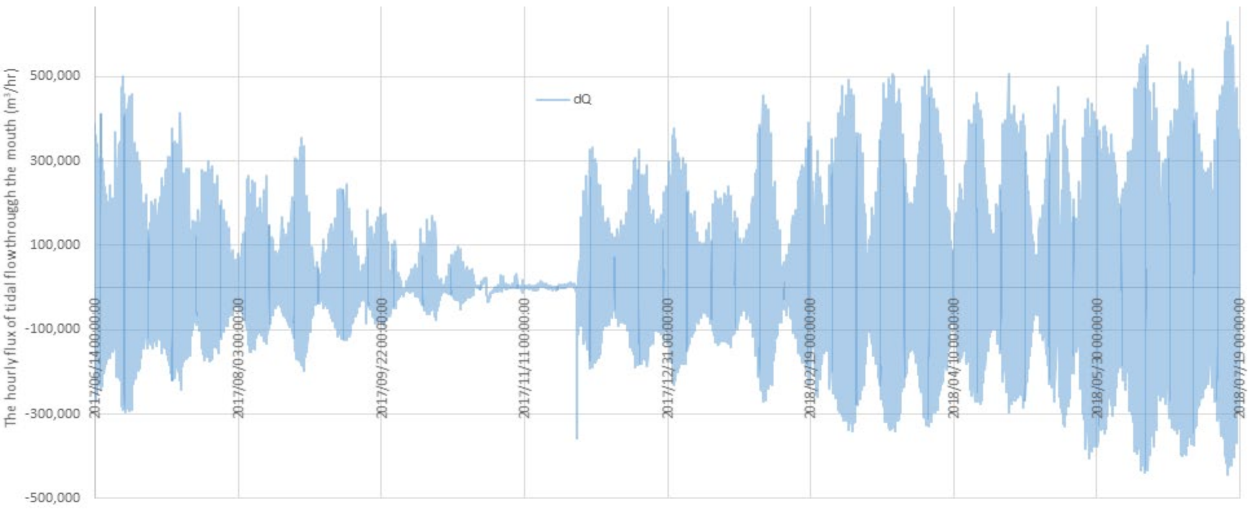


Figure 3-12: The calculated hourly flux (m^3/hr) through the mouth channel from May 2017.

3.5.3 Groundwater fluxes

During periods when the mouth is partially or completely closed there is generally an increase in the estuary water level (storage) that is generally associated with the influx of runoff from the catchment and some over-topping from the marine tides. However, once the tidal interaction has subsided the water level in the estuary is continually being increased from fluvial events and possibly the groundwater interaction through the mouth.

The groundwater fluxes through the mouth berm were modelled using Modflow-USG to determine the losses and gains under various mouth sill conditions. Figure 3-13 (upper frame) shows the configuration of the mouth in Modflow-USG with a cross-section from NE-SW across the beach berm. The lower image shows the water table elevation contours at a specific instant in time during the simulation period (Figure 3-13). The light blue zone shows the measured head in the estuary at an instant in time taken from the logger series. The darker blue zone in the contours show where the water table is exposed during this instant in time.

Mass balance estimates for the zone shown by the brown line across the mouth in the lower frame of Figure 3-13 indicate the net inward and outward ground flow across the estuary berm. Figure 3-14 shows the complete groundwater fluxes for the simulation period from the beginning of Sept 2017 to the end of November 2017 during which the mouth gradually closed and was subsequently breach at the end of November 2017.

In the discussion above on the relationship between the spring and neap tidal range, the elevation of the low tide was considered likely to represent the mouth control elevation during neap tides but not necessary during spring tides. However, when the mouth starts to close due to the raised sill, this relationship may break down because the flood tide is caused by over-topping (wave action) and the ebb tide is supported by groundwater efflux.

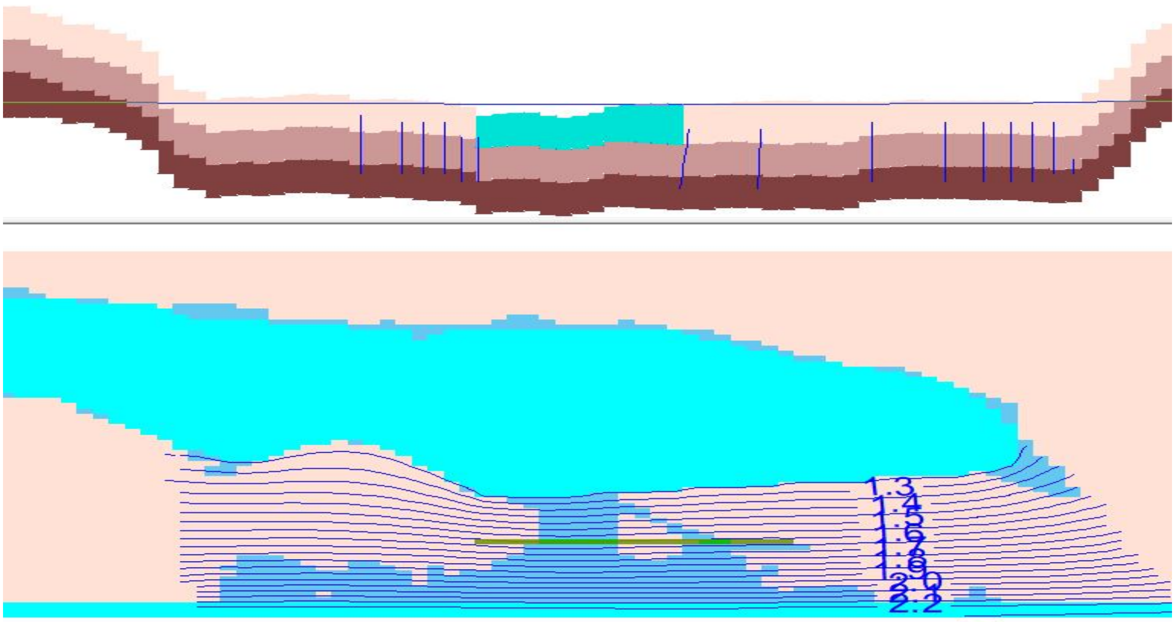


Figure 3-13: The model configuration for estimating the groundwater fluxes through the mouth with varying tidal action.

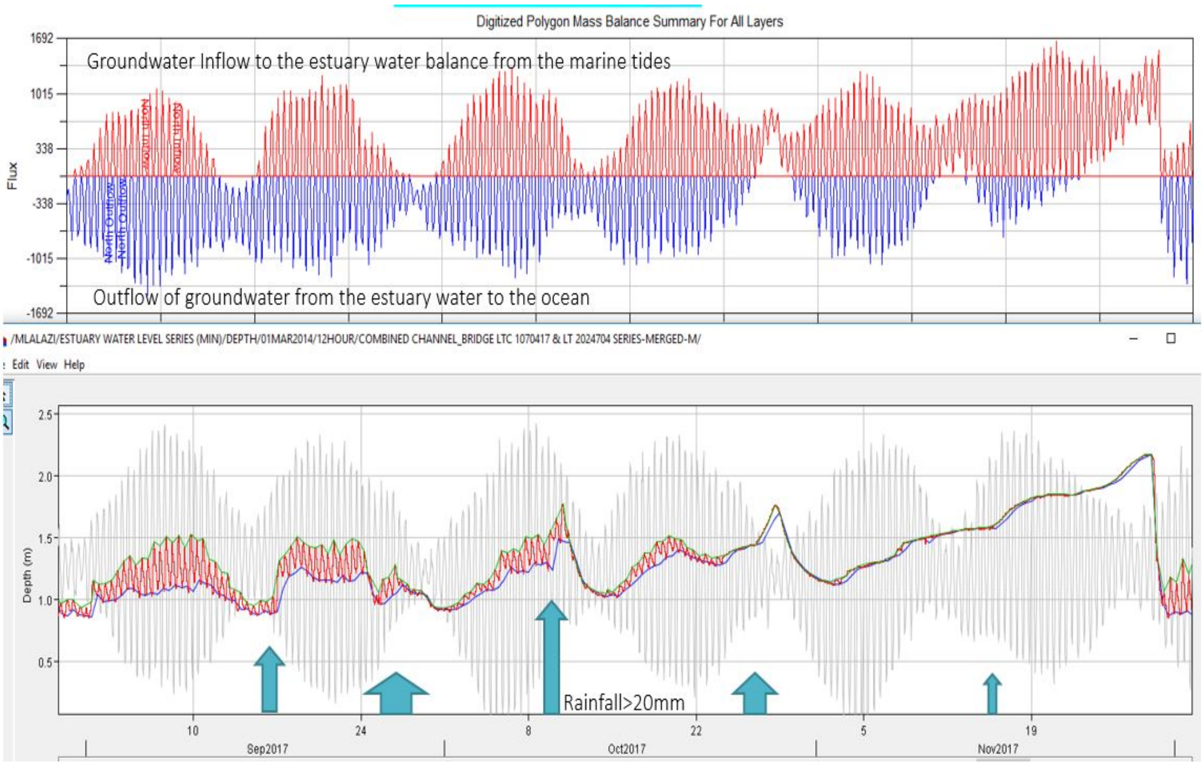


Figure 3-14: (A) The simulated groundwater fluxes out of the estuary (to the south) and the corresponding groundwater inflow during the marine high tides (blue). (B) The lower graph shows the estuary water level tides (red) and their high and low sequence in relation to the marine tides (grey series).

3.5.4 Estimation of Mouth Elevation under Tidal influence.

Generally, the depth of flow though the mouth is unknown. If it is assumed that the flow though the mouth channel is uniform and sub-critical then it can be further assumed that the water level in the mouth channel is the same as the estuary when the mouth is fully open but not when it is partially open (over topping). During partially open mouth conditions, the channel acts as a two-way hydraulic structure that controls the flood and ebb tide flow-through rates. Assuming that the hydraulic characteristics of the mouth channel do not change between incoming flood and outgoing ebb tides, the low tide elevation would approximate the channel elevation if there was no net tidal storage within the estuary (*i.e.* volume in = volume out). However, the low tide elevation varies significantly over a 14-day cycle as shown in Figure 3-9 and is unlikely to represent the mouth sill elevation during spring tides but may approach the sill elevation during neap tides. However, there are examples of the minimum (low) tidal values that are not due to the tidal cycle. Examples of extremely high elevations of "low" tide can be attributed to:

1. fluvial events when the storm hydrograph has not receded during a diurnal tidal cycle as shown by examples in Figure 3-15.
2. mouth closure when tidal interaction ceased as illustrated in Figure 3-14 during Nov 2017.

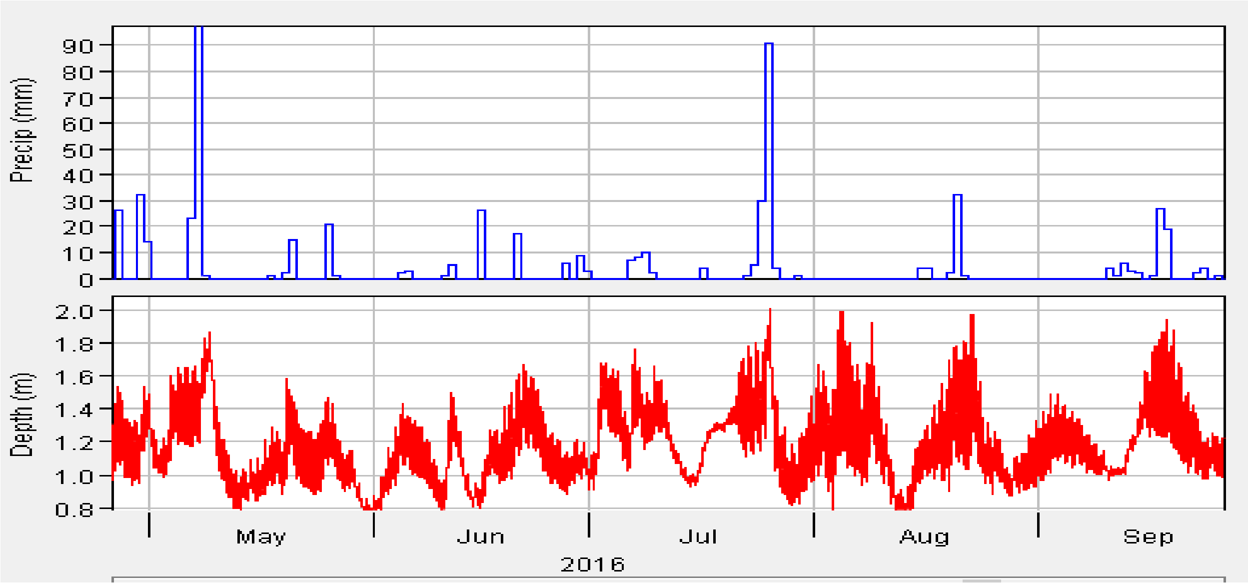


Figure 3-15: Example of the tidal pattern associated with the rainfall in the estuary catchment.

3.5.5 Mouth Elevation after Fluvial/Breach Scour events

The impact of the large fluvial events can be observed in the water level measurement in Figure 3-15. Close examination of the rainfall and tidal fluctuations indicate that the water level increases in response to rainfall events and can disrupt the cyclic pattern driven by the marine tides. It is assumed that many of the irregular spikes in the estuary tidal signal can be attributed to the fluvial component of discharge through the estuary. It is further assumed that the magnitude of the deviation is proportional to the magnitude of the fluvial events. The rainfall regime has been described in previous sections. Assuming that the rainfall is a stochastic process, the impact on the estuary water level and, by implication, the mouth conditions is assumed to be independent of the mouth conditions but that there may be a residual impact on the mouth for extreme events.

Photograph 3-1: The monitoring pipe near the mouth that was installed below the water level before the extreme event was exposed by nearly 05 m after the event.

The monitoring logger at the mouth failed after the mouth breach in 2015 so the measurement in Figure 3-16 were supplemented with measurements from the monitoring stations further upstream in the estuary. A stand pipe near the mouth (Photograph 3-1) that was installed below the water level became exposed by nearly half a meter after the 2018 flood event showing possible scour of the mouth basin that may have resulted in a much lower mouth sill. However, the “apparent” decline in the high tides after the mouth breach in 2017 shown in Figure 3-16, is suspect since the marine tide would have remained the same which suggests that the monitoring station may also have been displaced

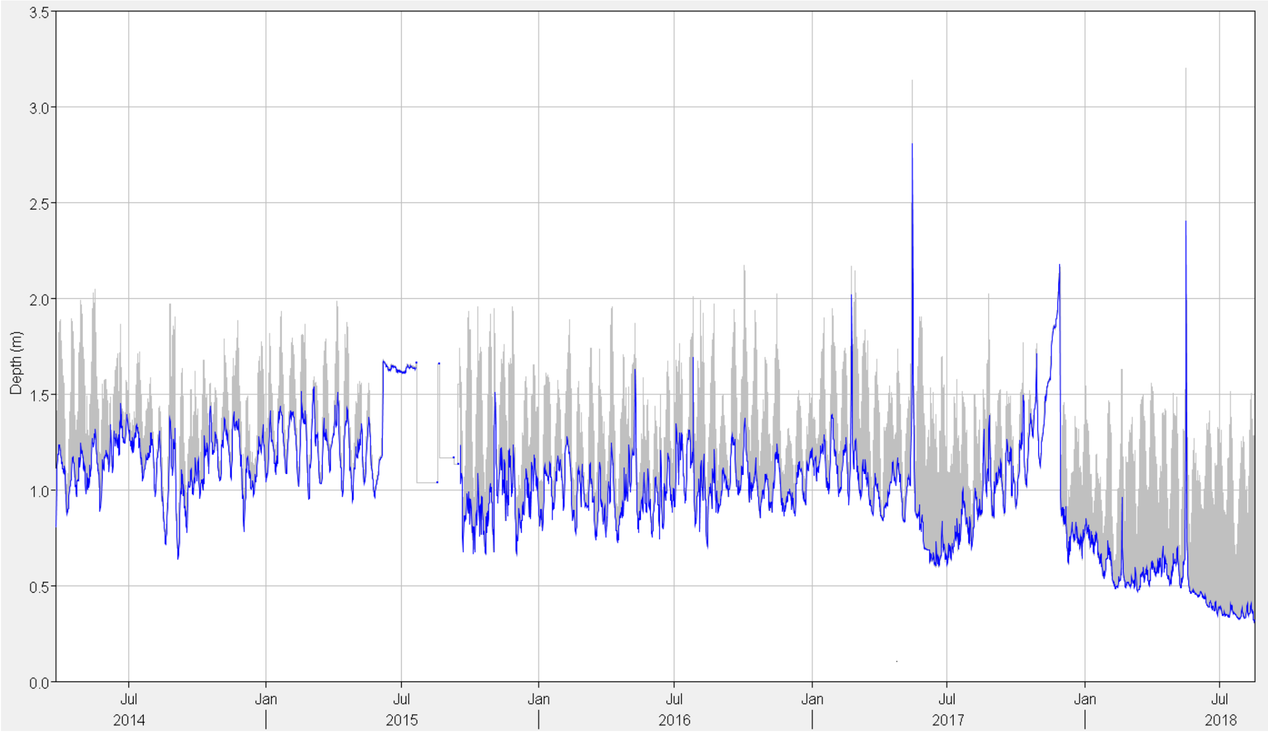


Figure 3-16: The water level measurements for the Mlalazi Estuary. The blue line shows the low tide. The grey lines show the hourly tidal range. The early period represents "drought" conditions when there were few large fluvial events. From 2017 there was a significant increase in rainfall and the occurrence of extreme storm events.

The minimum elevation of the tides shown in Figure 3-16 indicates that the sill elevation slowly increased from 06 mMSL in July 2017 until the mouth closed in November 2017. When the mouth was breached in late November, 2017, the low tide signal indicates that the sill was eroded to a level of 0.8 m which gradually decreased further to 0.5 m where it remained fairly static until a major fluvial event in May 2018 caused the sill to be further eroded over several months to an elevation of 0.3 MSL. The breach event produced a similar low tide response to the two extreme fluvial events and is attributed to the scour of the mouth channel to depths below pre-event conditions. In all three situations, the low tide was not greatly influenced by the neap-spring cycle suggestive of a partial mouth closure described above. This apparent change in the mouth control elevation suggests that the low tide series could be used as a surrogate indicator of the mouth conditions.

3.5.6 Mouth Elevation during Mouth Closure Conditions

Following the extreme fluvial event and subsequent mouth scour in May 2017, the low tides during neap conditions showed a systematic increase in stage indicating reduced marine influence. Eventually the mouth closed and the estuary water level continued to rise due to fluvial inflow that was balanced by evaporative losses and some groundwater fluxes though the beach berm.

The small but regular fluvial discharge through the mouth during the period leading to the mouth closure in 2017 (Figure 3-17) was insufficient to maintain a partially open mouth. The prevailing wind direction was frequently from the south west (220-270°N) that is parallel to the shore line. There were fairly long periods of northeasters that were also parallel to the coastline. The wind speed was seldom above 15-20 km/hr. During a previous period of mouth closure in May 2015, the wind direction was more erratic and the wind speed generally lower (10-15 km/hr). These two cases of mouth closure show no definitive causes of sediment accumulations at the mouth.

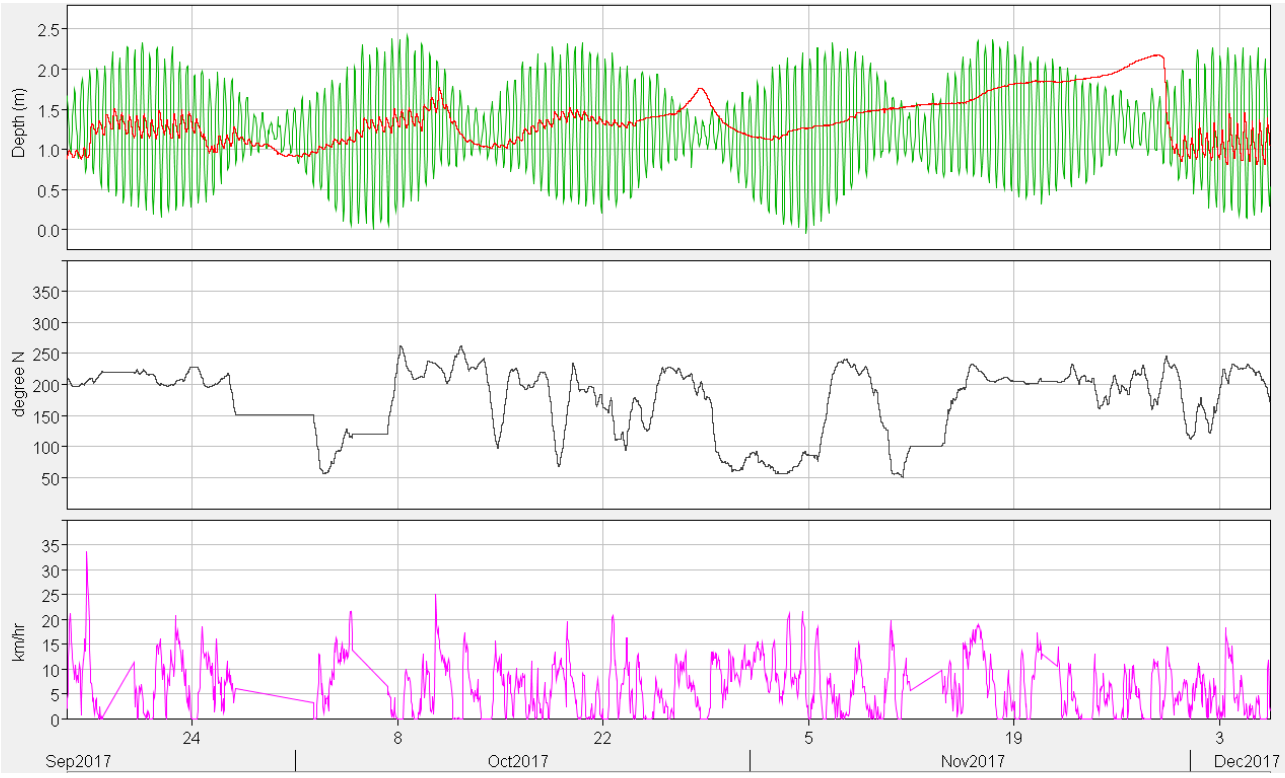


Figure 3-17: The marine tides and estuary water level (Upper graph), the smoothed wind direction (middle graph) and the hourly wind speeds during the period leading up to the mouth closure in Nov 2017.

3.5.7 Summary of Mouth Control Features/Indicators

The above analysis indicates that the tidal signal in the estuary is controlled by the fluvial processes, the temporary water storage between flood and ebb tides and the 14-day tidal flux variation through the mouth. Consequently, the low tide elevation can be considered as a surrogate indicator of the changing mouth conditions leading to mouth closure. There is no indication that the regular weather patterns have a significant impact on the mouth conditions. However, it is not clear what causes the sedimentary deposition at the mouth during periods of mouth closure.

Examples of the constraints on specific mouth conditions are presented in the following example(s) to ascertain the basic building blocks of a conceptual model of the dynamic processes.

4. EXAMPLES OF MOUTH CHANGES

To support the conceptualisation of the model process, examples of the mouth conditions during and after closure events and following mouth breaching events are discussed in this section. The definition of mouth closure is not well defined as it involves

- the often-narrow channel through the beach berm remnants, foreshore and surf zone and
- the estuary mouth basin just upstream of the channel that also has a controlling influence on the flow of water between the marine and estuary

The "narrow channel" is highly transient and moderated by relatively higher velocities and wave action causing scour and deposition of the flow between the sea and estuary through a relatively narrow section that will generally maintain a constant hydraulic radius during flood and ebb tides. It tends to migrate northwards under the influence of the prevailing near shore currents to a northern limit because it has been blocked from further migration by anthropogenic actions. If left to natural long-term processes it is likely to continue moving northwards in a similar manner to the Siyaya estuary. However, it is currently constrained within the extent of the dune gap by anthropogenic activities.

The estuary mouth basin has a general width that is ten times greater than the channel and is filled with mobile sands. These sand bars, berms and banks are often exposed to various depth during the tidal cycles that will change the hydraulic radius during the tidal cycle. The different and changing hydraulic radius of the channel and basin will generally create very different velocity regimes and associated sediment transport.

4.1 CASE STUDY 1: MOUTH CLOSURE – June 2015

An example using the available information for the mouth closure that occurred in May 2015 indicate that several factors may have played an import role in the mouth closure. Figure 4-1 shows two Google images of the mouth channel before and after the mouth closed on about the 31 May 2015. The marine sediments that closed the channel are clearly visible in the later image taken on the 4th June 2015.

The corresponding water level measurements (stage) in the estuary mouth covering this event are shown in the graph below the images in Figure 4-1. The water level in the estuary showed a very small increase in stage with no tidal interaction from 31st May 2015 to the 4th June when the mouth is assumed to be been closed. The stage suddenly stated to rise on the 5th June in three steps to a stage of 1.7 mMSL as shown by the trace in Figure 4-1. The wind regime for the Estuary was derived from the Automatic Weather Station in Mtunzini for the same period and plotted in the lower two graphs in Figure 4-1. On the 3rd June, when the stage was relatively constant the wind was generally in a westerly direction that is synonymous with a front event that could last for up to three days (Kelbe, 1989). This strong onshore wind would have greatly assisted the deposition of marine sediments in the estuary channel. The estimated groundwater flux through the beach berm preceding and during mouth closure is estimated from the groundwater model simulation discussed earlier in Section 3.5.3.

During the mouth closure, the groundwater fluxes will oscillate in unison with the marine tides as the estuary water level is stationary. The model indicates compensating groundwater fluxes across the mouth berm prior and after mouth closure (Figure 3-14). In the example show in Figure 4-1, the mouth sediments closing the channel are much narrower than the berm and is likely to have much higher groundwater fluxes that will help maintain the water level/storage in the channel relic. This groundwater flux could be the cause of the apparent seepage zones in the near shoreline (Figure 4-11 images) where the mouth has closed.

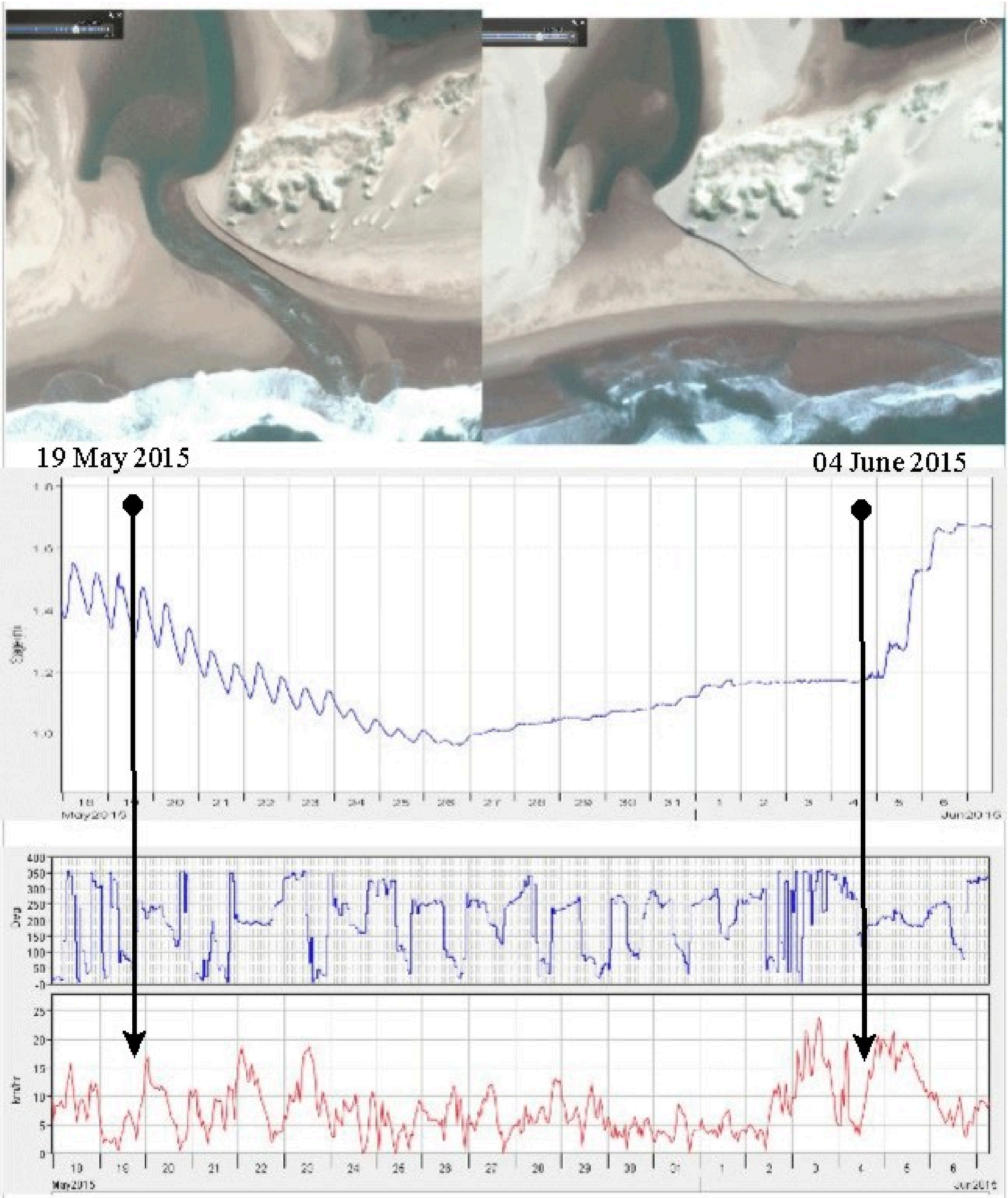


Figure 4-1: An example of the Mlalazi Mouth Closure in 2015. The two Google images show the state of the mouth on two dates in May and June during which the mouth became closed. The upper graph shows the tidal range in the estuary between the two dates shown and indicates that the mouth closed during the neap tide on 27 June 2015 when the tidal interaction ceased. The lower graphs show the wind direction and speed for the same period.

4.2 CASE STUDY 2: MOUTH CLOSURE – November 2017.

There were numerous rainfall events during the four-month preceding the complete closure of the mouth in November 2017 (Figure 4-2). During this period the low tide increased in elevation progressively from 0.5 mMSL to over 1.2 mMSL that is assumed to be indicative of the rising mouth sill elevation that would lead to complete mouth closure. The wind direction was generally out of the South to south-west (200°N), parallel to the coastline. There was one significant storm event from the south-west with winds of over 30 km/hr that had a significant impact on the estuary water level.

It is postulated that the intermittent rainfall events and varying wind regime were sufficient to sustain a measure of interaction between the estuary and marine system though the partially open/closed mouth leading up to the ultimate complete closure at the beginning of November 2017.

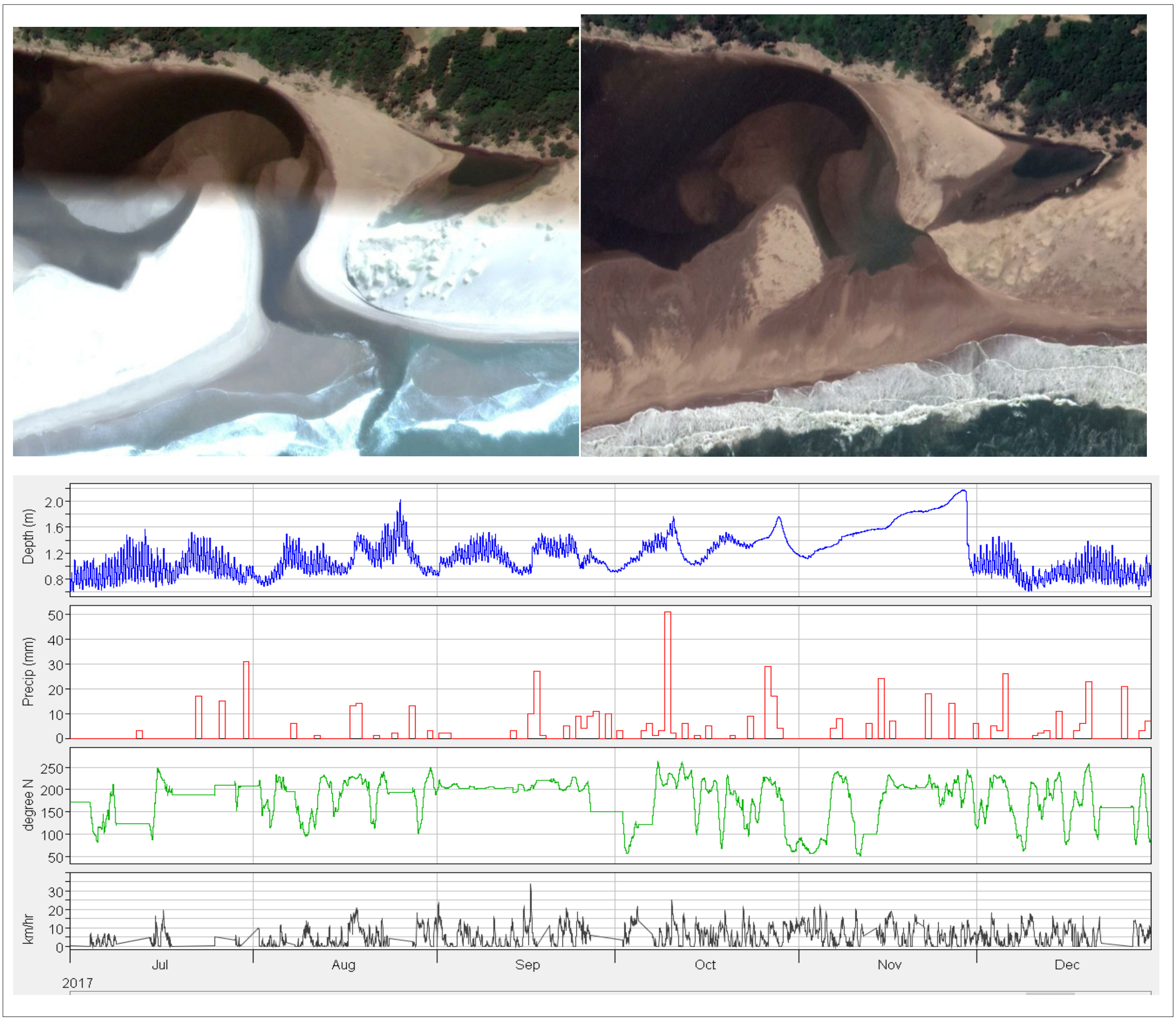
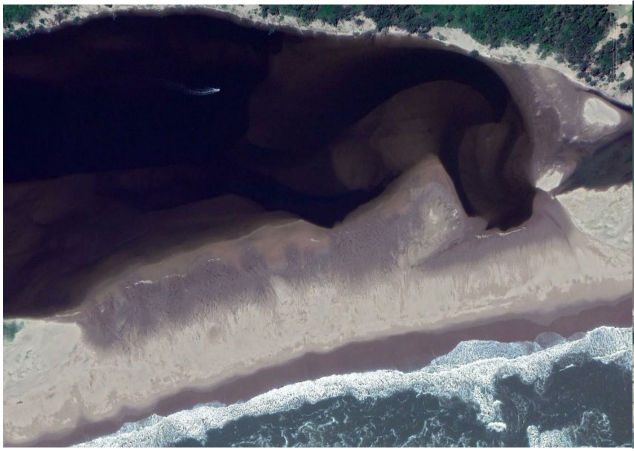


Figure 4-2: Conditions associated with the mouth closure during Nov 2017.

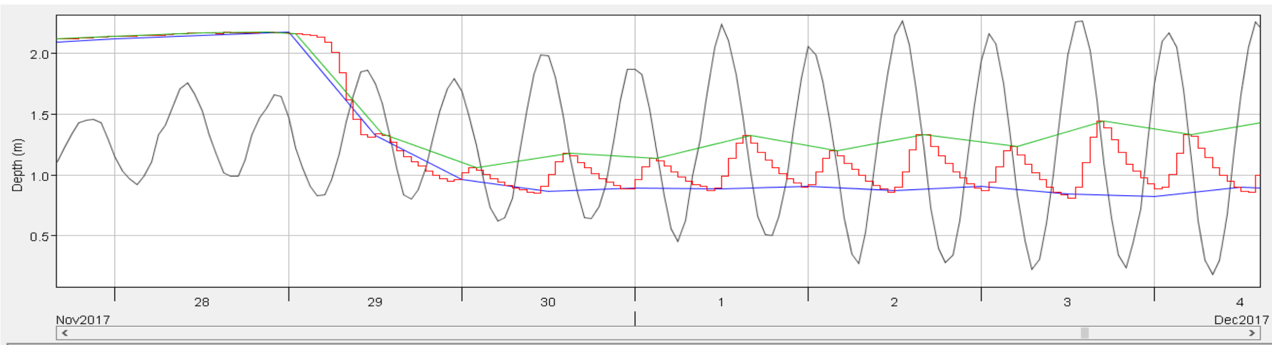
4.3 CASE STUDY 3: MOUTH BREACH – May 2018

The closest aerial image between the mouth closed state and the breach image is nearly 6 months but the extent of the scour can be ascertained from the images (Figure 4-3). The breach occurred at the onset of spring tides. The low tide dropped to a relatively constant head of 0.8 mMSL for at least a week after the breach and then started to drop to 0.65 mMSL with the onset of the neap tides but immediately recovered to 0.8 mMSL at the onset of spring tides. However, the low tide gradually dropped to 0.5 mMSL over the next six 14-day cycles with a diminished tidal range during neap tides.

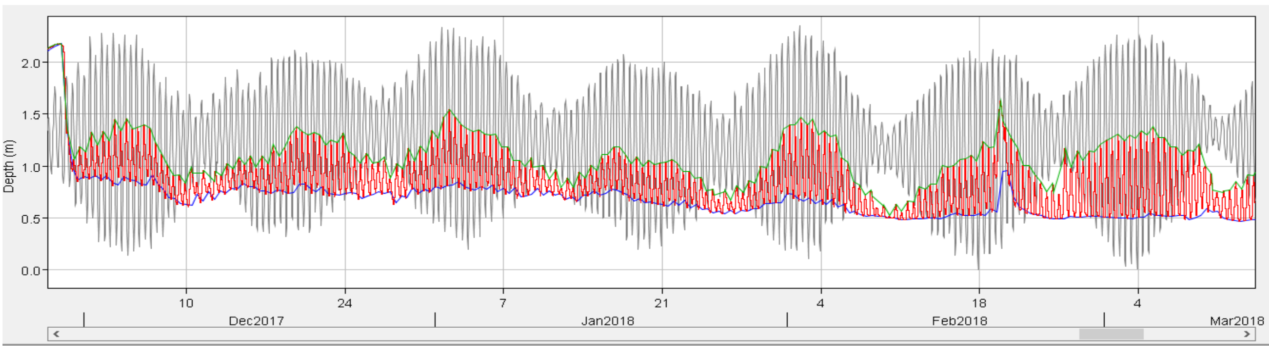


Google Image on 18 Nov 2017

Google Image on 06 May 2018



Water level records during the mouth breach on 29 Nov 2017 showing the marine tides (light grey), Estuary water level (red) and the extracted high (green) and low (blue) tides.



The extended water level record following the mouth breach.

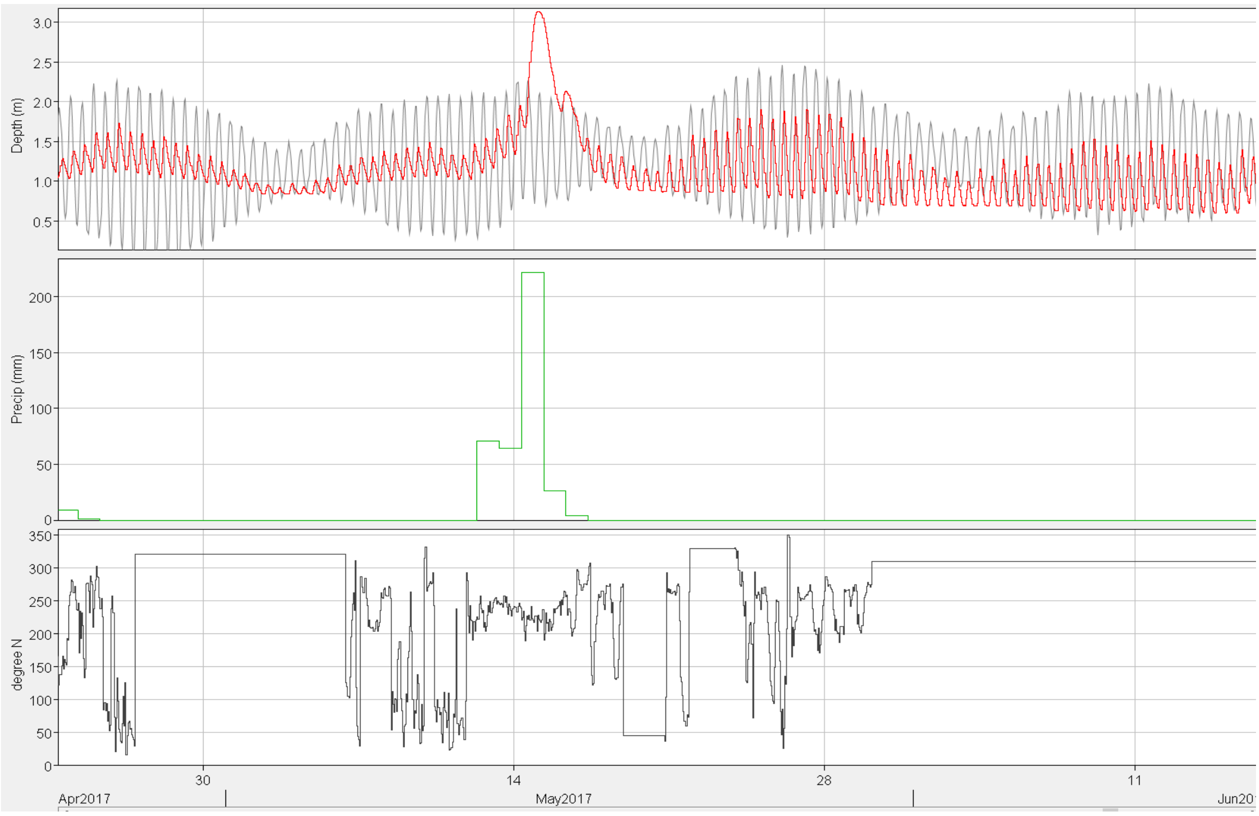
Figure 4-3: Conditions during and after the mouth breaching event in the southern extent of the beach berm to protect anthropogenic activities in the estuary.

4.4 CASE STUDY 4: STORM BREACH

The fourth case study shows the estuary and mouth response to an extreme storm event that occurred from 13-15 May 2017 when over 400 mm of rainfall occurred in Mtunzini (Figure 4-4). The mouth was partially open preceding the event with diminished low tide conditions during the neap tides. The logger was exposed during low tide conditions after the storm event so it is not clear to what depth the low tide reach during the subsequent neap tides.

Google Image on 03 May 2017

Google Image on 21 May 2017



The Marine, estuary water levels (top_, rainfall (middle) and wind direction (bottom) conditions preceding and following the extreme storm event in May 2017.

Figure 4-4: Conditions during and after the mouth breaching event in the southern extent of the beach berm to protect anthropogenic activities in the estuary.

5. MANGROVES

5.1 Introduction

At present there are 40 ha of mangroves in Mlalazi. They are a feature of the estuary and EKZNW, the conservation authority, has constructed boardwalks to make them accessible to the public. Each year they are visited by large numbers of tourists and educational groups.

But the estuary has not always had mangroves. Prior to the 1930s there were no mangroves at all. Understanding why mangroves have colonised the estuary provides insights into mangrove ecology and the functioning of the estuary.

The aim of this section of the study was to describe the present and historical vegetation patterns within the Mlalazi Estuary and describe the drivers that have caused these patterns.

5.2 Present and historical mangrove patterns.

5.2.1 Mangroves during the geological evolution of the Mlalazi Estuary

As has been described in Section 2-1, the present day Mlalazi Estuary is a stage in the geological evolution that is characteristic of estuaries. There is a trajectory of change taking it from a deep-water estuarine bay to a floodplain wetland. Mlalazi is currently in the stage where it is a Temporarily Open/Closed Estuary (TOCE) and most of the original scoured bay has infilled with sediments. This evolution has been driven to a large degree by the rising in sea-level of the Holocene Transgression (Ramsay and Cooper, 2002). The flooding of a scoured river valley formed the ancestral Mlalazi Bay. The sea-level rise then reached an estimated 3.8 m above present day MSL between 6500 and 5500 years BP before it dropped to the present-day level (Cooper *et al.*, 2018). This estuary basin has shallowed as sediments accumulated and barrier dunes formed. As this happened, the connectivity with the sea decreased and there was an increasing fluvial influence. The coastal dunes formed; first a primary cordon, followed as the seashore prograded, by a second line of dunes. The outlet of the Mlalazi was guided in a north-east direction between these two dune lines, resulting in the 4 km long channel with a very narrow floodplain that forms the lower estuary (Figure 2-3). With this change the mouth became constricted and started closing at times. Whenever it closed, the mouth was breached by rising water in the estuary. This water that caused the breaching would have come from the river catchment and from direct rainfall. After a closure event the mouth could have breached almost immediately. But, if the beach berm accumulated enough sediment, it is possible that the mouth could have remained closed for many months or even years at a time. This would have been dependent to a large extent on the quantities of water flowing from the catchment. Thus, the evolutionary progression has been from an Estuarine Bay to a Permanently Open Estuary and then to its present-day state of a Temporarily Open/Closed Estuary.

For mangroves to thrive in a system they have a number of requirements which determine their niche. The ecological niche (Hutchinson, 1957) in which mangroves grow is characterised by the following parameters:

- They occur in latitudes which are seldom or never exposed to frost. Thus, mangroves occur mainly in the tropical and subtropical areas.
- Mangroves grow in the upper intertidal and supratidal zone.

- They require shelter from wave action and extreme currents.
- They do not grow on rocks, and need a mud or sandy substrate that is firm enough to support a tree. They do have roots that enable them to cope with soft sediments but do not colonise very fluid sediments.
- They are adapted to cope with salinity. Although many mangroves can cope with fresh water, salinity in the range from low salinity to above that of sea water will exclude competition with freshwater wetland plants.

These conditions would have been met in the ancestral Mlalazi Bay once the dune barrier had formed enough to reduce wave action. From this stage onwards the bay would have supported a shoreline fringe of mangroves. We have physical evidence that this was the case. Cooper (1996) found shells of the gastropods *Terebralia palustris* and *Cerithidea decollata* in Late Quaternary sedimentary deposits in the present-day estuary. These species are both obligate mangrove-dwellers.

At the point when the estuary mouth started closing, to the extent that there were periods of prolonged back-flooding, the mangroves would have died out. This would have occurred at the stage when the POE changed to become TOCE. Mangroves cannot survive having their roots (including their pneumatophores) flooded for extended periods. They are then unable to respire in water with a low concentration of oxygen. This is the case in most TOCEs in South Africa which are not able to support mangroves (Rajrakan *et al.*, 2009). One exception to this is the Mgobezeleni estuary which has very frequent mouth closures and breachings (Taylor, 2016).

5.2.2 Historical conditions – Mlalazi as an estuary with no mangroves.

Historical records indicate that prior to the 1930s there were no mangroves in the Mlalazi Estuary. However, there is no evidence that informs us how long ago it was that the Mlalazi Estuary lost its mangroves.

Once the Mlalazi had evolved to be a TOCE, no mangroves could have survived conditions with regular and prolonged closures. The only exception to this would have been if there were very long periods (each of several decades) between mouth closures. These periods would have had to be long enough for mangrove recolonisation to have taken place from adjacent estuaries.

5.2.3 The colonisation of the estuary by mangroves and present mangrove abundance and distribution.

5.2.3.1 Historical evidence of mangrove colonisation

Ward (1960) noted that the mangroves seem to have established "in about 1940, or even about 1935". However, he does say that individual mangroves could have been undetected in the system for some time prior to this. The first stands were of *Avicennia marina* on the south bank in the immediate vicinity of Nel's Pool (See Figure 5-6 for the location). He states that conditions that contributed towards the establishment of mangroves were (i) opening of the mouth; and (ii) the deposition of fine silt on previously sandy banks.

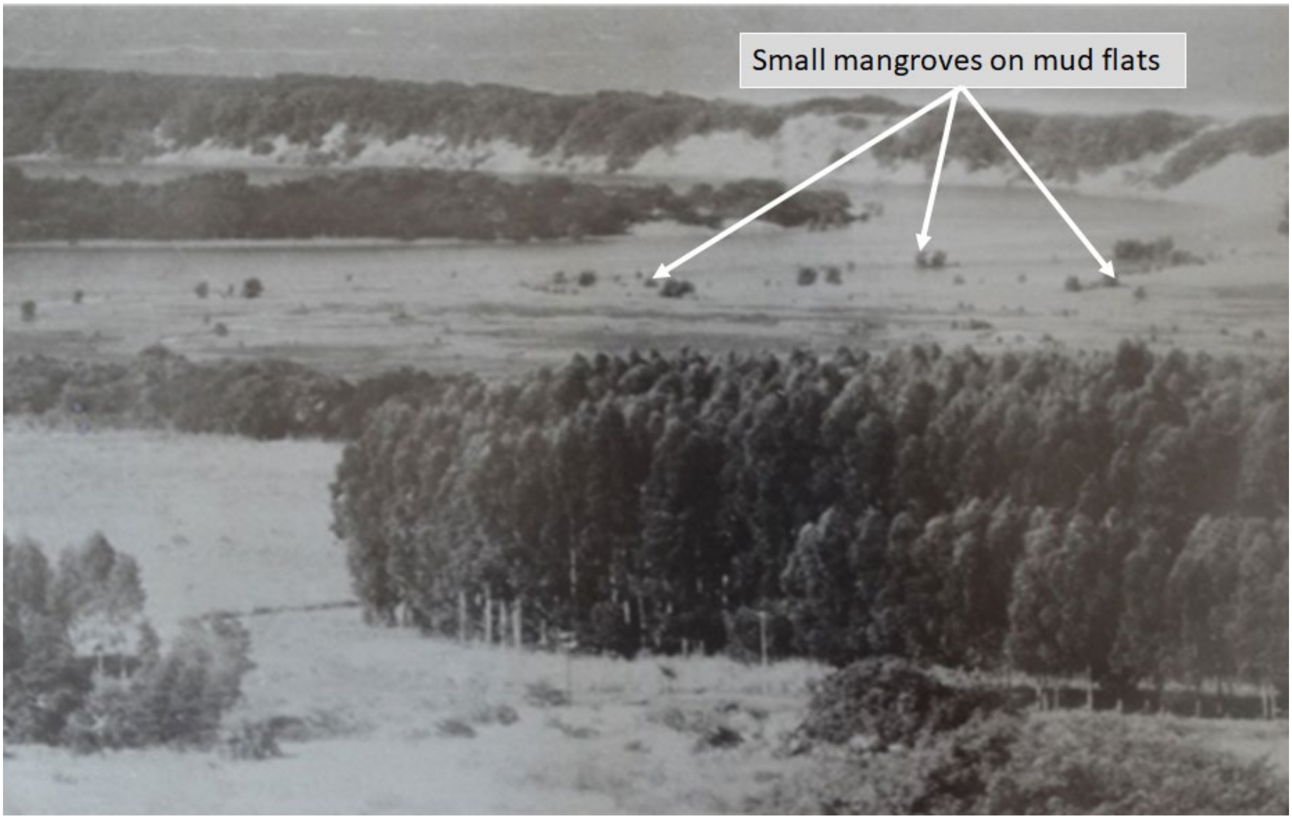


Figure 5-1: The area marked with arrows is the Dunn's Pool area. These mangroves would be in the 'establishment' phase – as discussed in Figure 5-9. Photo from the Mtunzini Public Library. Photographer unknown and the date are unknown. The photo was possibly taken in the mid-1940s.

By 1960 mangroves were establishing at other locations in the lower estuary and at Dunn's Pool. Most of the mangroves were *Avicennia*, but there were 'quite a number of small *Bruguiera gymnorrhiza'* (Ward, 1960). Photographs taken by CJ 'Roddy' Ward, the first ecologist in the Natal Parks Board, in 1960 illustrate the estuary with partially established mangroves. (Figures 5-2 to 5-5).

Figure 5-2: Early colonisation of a mud flat by Avicennia marina mangroves. This is the 'recruitment or establishment phase' stage in colonisation of an intertidal bank. The young trees have many lateral branches and a well-developed shallow rooting system as shown by aerial breathing roots around each plant. (Photo: Ward, 1960)

Figure 5-3: Rapid growth of a single-age cohort of Avicennia. These are closely spaced, straight-trunked and with little lateral branching. These mangroves would be reaching the end of their 'exponential growth'-phase (see Figure 5-10). (Photo: Ward, 1960)

Figure 5-4: Mangrove growth in Dunn's Pool area (beyond the present-day Estuary Car Park). Bruguiera gymnorrhiza are the dark 'conical' trees to left, central background and also to right (along the estuary margin). Avicennia is the primary colonising species which, to a large degree, facilitates the recruitment of Bruguiera. (Photo: Ward, 1960)

Figure 5-5: Mangrove development in the Dunn's Pool area (the Anchorage to the right, and the Estuary Car Park in the foreground) showing colonisation of the area with Avicennia and Bruguiera mangroves. (Composite of photos by Ward, 1962)

Ward (1962) also reports that small areas of the 'right bank' of the estuary were planted with *Avicennia* seedlings obtained from elsewhere within the estuary. This was done to stabilise these banks.

MacNae (1963) in his studies of the mangroves of South African estuaries noted that in Mlalazi "the mangrove is of comparatively recent origin". He recorded saplings of *Avicennia* and *Bruguiera* but no *Rhizophora* trees. Hill (1966), describing the ecology of the Mlalazi Estuary, mentions "the rapidly colonising mangroves". He mapped the distribution of these (Figure 5-6).

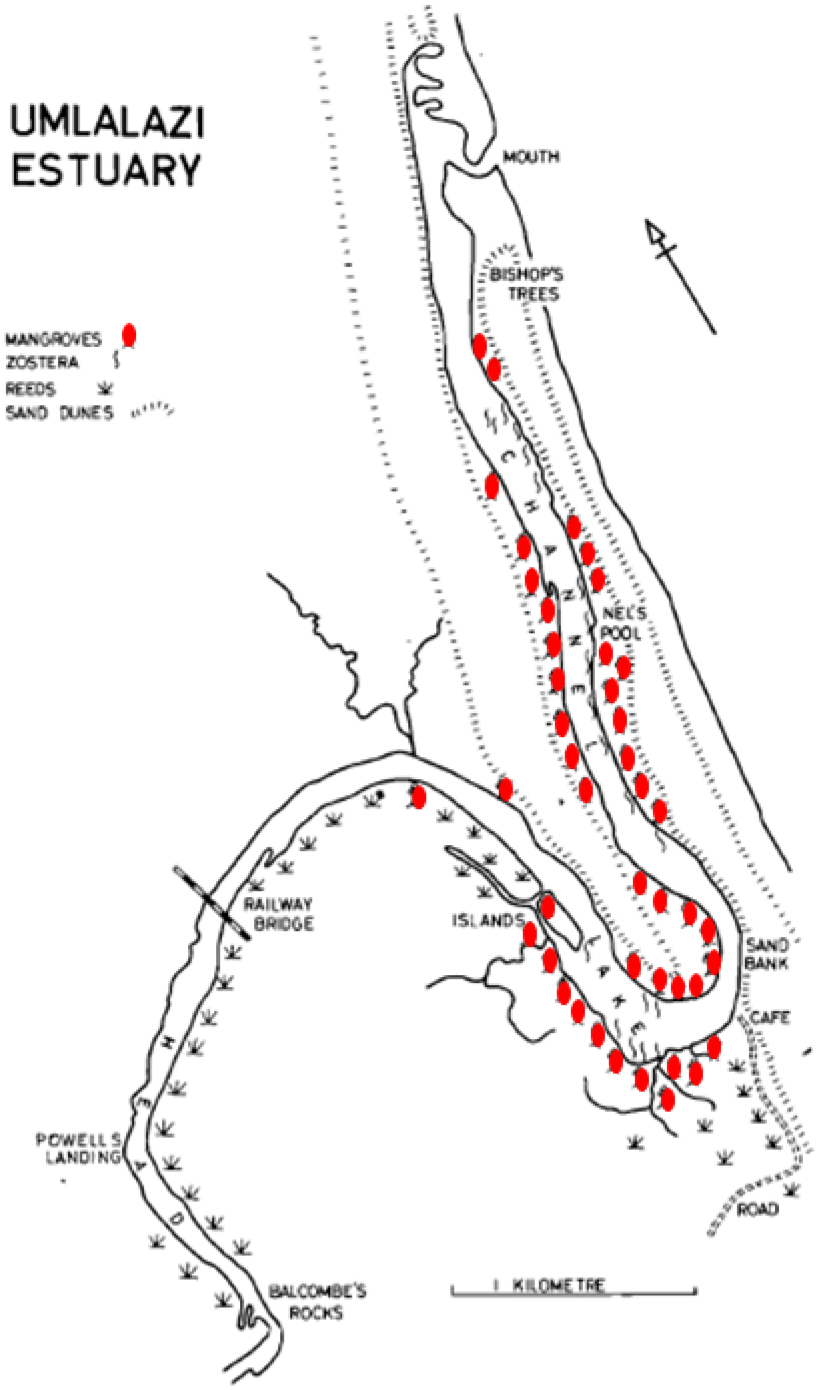


Figure 5-6: Mangrove distribution in the Mlalazi Estuary in 1963 (Hill, 1966)

Note that, at this stage, the mangroves had only colonised up to the 'Islands' (about 5 km from the Mouth) and only at a single site further upstream than this (about 1 km further upstream).

The mangroves continued expanding. Cooper (1968) in his survey of the mangroves of South Africa, estimates that there were approximately 25 acres (slightly more than 10 ha) of mangroves in the Mlalazi Estuary. Steinke (1999) estimates the area of mangroves in the Mlalazi Estuary to be 30 ha and, in 2015, the area was measured to be 45 ha (Taylor, 2015) (Figure 5-7).

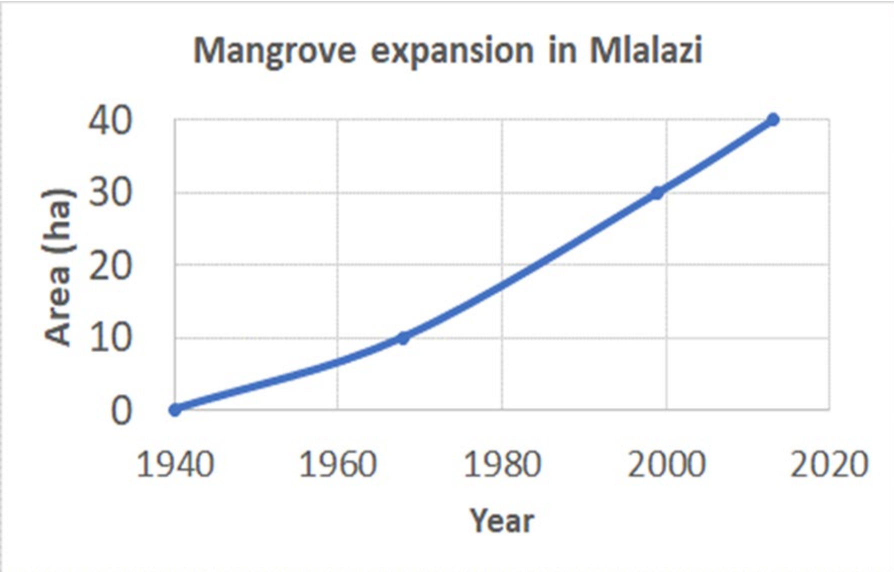


Figure 5-7: Expansion over time of the mangroves in the Mlalazi Estuary

5.2.3.2 Anthropogenic changes and interventions that have facilitated mangrove colonisation

It is clear that there were few or no mangroves prior to the mid-1930s. Since the late 1800s changes occurred that promoted mangrove growth. The most important change is the artificial breaching of the mouth. Other lesser impacts were the expansion of agriculture and forestry in the catchment – affecting river flows and possibly sediment loads. In addition, in about 1900 the railway was constructed. The embankment and bridge for this modified flood flow patterns through the estuary basin.

Mouth breaching

The first recorded artificial breaching of the mouth was in 1896 (Van Jaarsveld, 1998). Mlalazi was the centre for the magisterial district and in the mid-1890s the magisterial office had been built on the banks of the Mlalazi near the existing Estuary Car Park (Van Jaarsveld, pers. comm.). When the mouth closed, access routes were flooded and the backing-up water threatened to inundate the magisterial building. In response the (acting) magistrate organised a team of labourers to manually dig open the mouth.

Subsequent to that there is a record of the mouth being breached in 1912 by the farming community (Ward, 1960). In the early 1900s farms had been demarcated and planted to sugar cane. Some of these were in the low-lying floodplain lands which were waterlogged by the rise in water levels in the estuary when the mouth closed. The assumption is that the mouth would have closed at times, and subsequently been breached to avoid losses in cane production.

Ward (1960) interviewed Mr. C. Powell, a local farmer who was responsible for organising parties of workmen to open the mouth to prevent flooding of low-lying sugar plantations. He recorded that since 1945 the estuary closed on the following dates:

- October 1945
- January 1946

- August 1947
- February 1949
- April 1952.

There were no closures from 1952 to 1966 (Hill, 1966).

Although there is a gap in the records from 1966 until the early 1990s, the mouth was breached on several occasions in this period. Then, between 1993 and 2013 the Mlalazi Estuary experienced five closure events (Ezemvelo KwaZulu-Natal Wildlife unpublished data), and an additional two closures between 2013 and 2018 – in June 2015 and in November 2017.

Each time the mouth closed, the farmers, and later EKZNW, would wait until there was a head of water before breaching the estuary. The outflowing water scoured the mouth to a degree. If it was breached prematurely, the mouth would not scour and hence was likely to close again shortly thereafter.

From these records we can make the assumption that, since the mid-1890s, it is most likely that the Mlalazi estuary was always been breached soon after closure. There are no records of any prolonged closure or of extensive flooding caused by backing up water. There are no records of any mass die-off of mangroves, or of any other vegetation, due to flooding caused by a mouth closure event. Thus, this is a period of 120 years in which the natural prolonged backing up that occurs on closure and the loss of connectivity with the sea has not occurred to any significant extent. In this period Mlalazi changed from a system that previously had prolonged closed-mouth periods, to one where closures are short. Many of the characteristics of a TOCE were lost and effectively this breaching has reversed the geological trajectory of the mouth. It now has many characteristics of a POE. One characteristic is that estuaries that close for prolonged periods do not have mangroves (Rajrakan, 2011). The artificial breaching regime has allowed mangroves to re-colonise the Mlalazi Estuary.

Because of this artificial breaching, the Mlalazi Estuary has now been considered a POE by Ortega-Cisneros and Scharler (2015). This is a perspective based on analysis of the zoo-benthos and zooplankton. The estuary certainly has characteristics associated with a high-degree of connectivity with the sea. However that it is a TOCE certainly is the perspective of the estuary managers who breach the mouth whenever it closes; a large and expensive task.

Mangrove planting

In the late 1950s Mlalazi was used extensively for boating and the general perception was that the Mlalazi Estuary was 'silting up'. The argument was that there had been sediment accumulations that had shallowed the estuary. Ward (1960) assumed this to be the case, and considered that deposition of fine sediments on the sand banks was a contributing factor to the colonisation by mangroves. He noted that mangroves would grow on bare mud banks which they would stabilise. This concept encouraged a small-scale transplanting of *Avicennia* seedlings to bind mud flats. Seedlings were collected on the north bank and transferred to the south bank in the middle part of the estuary (Ward, 1962). It is not known how extensive or effective this transplanting was.

Dredging

Concerns about sediment accumulations led to the initiation of a dredging programme to remove sediments. It was started in 1965. The objective was to deepen the estuary and the excavated material was dumped into adjacent marshes and mangrove swamps. (Hill, 1966). Very little has been recorded about the quantities dredged and in what parts of the estuary the dredger worked. However, on the ground there is still evidence of berms and dredge spoil that indicate that dredging was very extensive in the area from about 2 km from the mouth all the way to the Railway Bridge. This would have reduced the intertidal area – where mangroves grow. It also deepened the shallow parts of the estuary increasing the volume of water exchanged during each tidal cycle. This possibly helped to reduce the frequency of mouth closure events.

Although, after the 2017 flood there had been a lot of concern expressed about the system being filled in with sediments, there is still no conclusive evidence that this has actually occurred.

5.2.3.3 Present distribution of mangroves

At present there are 40 ha of mangroves in the Mlalazi Estuary (Taylor, 2015) (Figure 5-8). These consist of three species – mainly *Avicennia marina* and *Bruguiera gymnorrhiza* but also a few *Rhizophora mucronata.* There is also the mangrove fern *Acrostichum aureum* – which may be regarded as a mangrove species, but is not considered in this study.

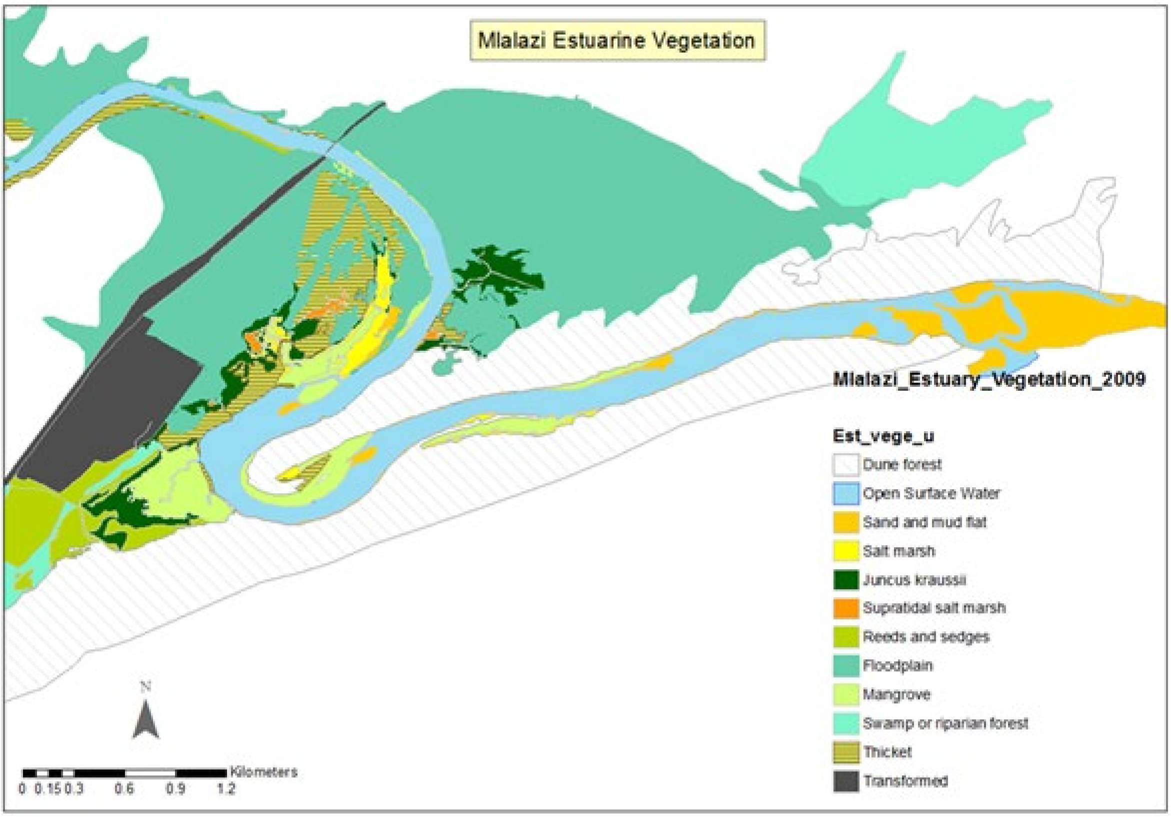


Figure 5-8: Vegetation map of the Mlalazi estuarine system (Taylor, 2015). Based on 2013 aerial photos.

The distribution of mangroves is taken to be the zone between mean sea level up to the extreme high-water mark (EHWT). For illustrative purposes this range is taken to be on average 50 cm. Then, from the depth-area curve (Figure 2-11), the area of potential habitat in the Mlalazi Estuary is in the region of 50 ha. There are weaknesses in this assumption: (i) mean sea level is not the same as mean estuary level; (ii) the DEM used is not accurate enough to place much confidence in this figure; (iii). most of the mangroves are downstream of the Railway Bridge – where there is the most intertidal habitat due to the topography of the land and also, to a lesser extent due to the diminishing tidal fluctuation with distance from the mouth; and, (iv) the fresher conditions upstream which promote the growth of reeds which shade out mangrove seedlings.

The extreme upstream limit of *Avicennia* is the shoreline between Balcombe's Rocks and the Old Main Road Bridge (R102) (about 9.5 km from the Mouth). *Bruguiera* extends further upstream, and scattered seedlings occur all the way to the Causeway (12.3 km from the Mouth). However, the figure of 50 ha of potential habitat for mangroves indicates that there is possibly still some habitat available for expansion of the mangroves. The main low-lying area that is without mangroves is in the floodplain along the north bank 1.5 km downstream of the Railway Bridge. No mangroves grow in that area at present as a result of the farm drains and also because of remnant levees constructed during the dredging operations.

5.2.3.4 Mangrove population growth – spatial expansion

Detailed measurements of the stand of mangroves adjacent to the Estuary Car Park have been made from aerial photos. This has been used to obtain estimates of 'r' (the intrinsic rate of growth) and 'K' (the maximum habitat that can be colonised under present conditions) (Figure 5-9).

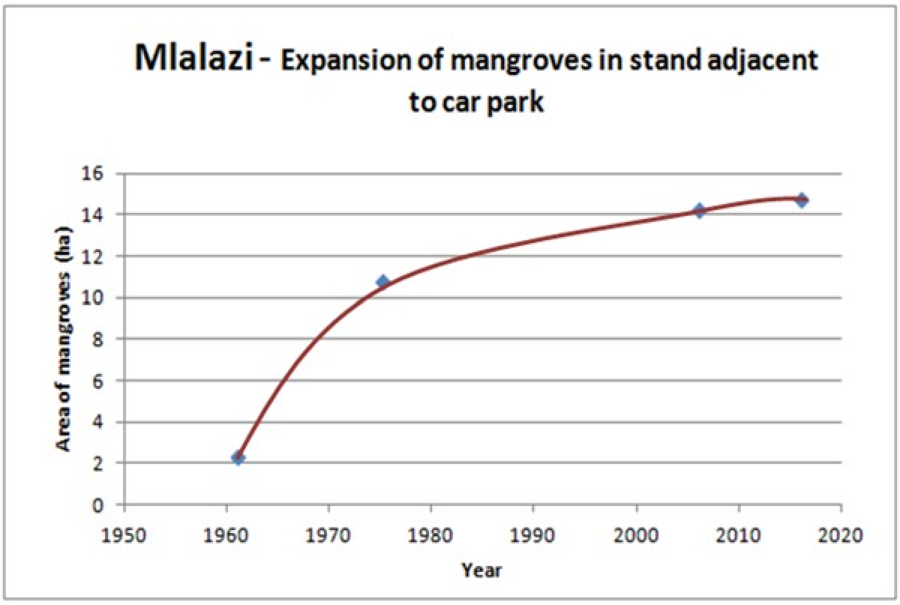


Figure 5-9: The expansion of the mangroves at the Estuary Car Park since 1960. The data were used to estimate the logistic rate of growth of mangroves in Mlalazi, using the technique described by Neal (2004).

From this curve, three phases in growth are distinguishable (Figure 5-10). We assume that there were no mangroves in Mlalazi Estuary prior to 1935. So, the establishment of these mangroves must have taken place between 1935 and 1960 (when there were approximately 2 ha of mangroves). This is the establishment phase (phase 1) when there is recruitment and the first plants colonise the estuary. This can be a very slow and prolonged phase. Then in the second phase (phase 2) the rate of growth is at its maximum, unhindered by competition for resources between individual trees. The growth is exponential at the intrinsic growth rate 'r'. Then (in phase 3), the rate of growth slows due to density dependence effects. The expansion of the mangroves will cease once the carrying capacity "K" of the site is reached.

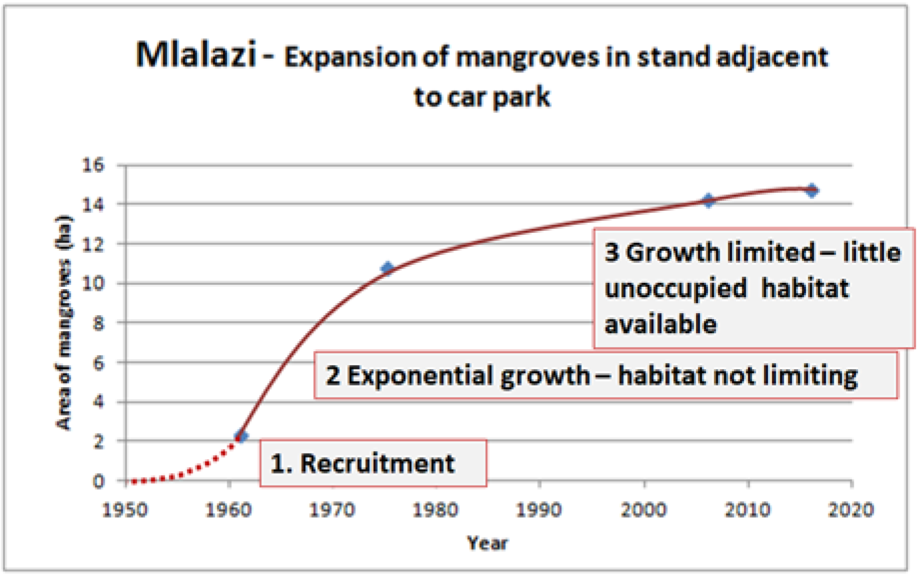


Figure 5-10: The three phases of growth of the mangrove population in the stand at the Estuary Car Park. The dotted line in the recruitment phase is theoretical, based on the fact that there were no mangroves in Mlalazi in 1935. This initial phase, when colonisation and establishment occurs, can be very slow and spread over a long time.

The 'r' value (intrinsic rate of growth) is close to 13% per annum. The level of confidence in this is low so this should be taken as a 'ball-park' figure. The reasons for the low confidence are: There are too few points to derive the growth curve with much accuracy. The population considered is not a closed population and mangrove propagules do come in from other, older, stands of mangroves. The population is not a single-species population. It is composed of *Avicennia*, the primary coloniser, and *Bruguiera.* Recruitment is facilitated by the presence of *Avicennia*. In time the longer-lived *Bruguiera* replaces *Avicennia*. In addition, recruitment is not evenly distributed. The expansion of the mangrove stand is not at random in the available area, but has been along an advancing front – displacing mud flat, succulent salt marsh and reeds.

Given these violations of assumptions made when fitting the growth curve to the car park mangrove stand a maximum growth rate of 10 to 15% per annum can be used. This exercise does provide insights to the theoretical rate of population expansion. From this we can estimate rates of expansion after an initial colonisation after a total die-off; or for recolonization from a remnant mangrove population after a partial die-off. After a partial die-off, it is the number of surviving trees, within the estuary, that are producing seeds that affects at what point in the growth curve the resumption of expansion is initiated. It is to this point that the mangrove population is 'reset'. As an example, if 30 ha of the mangroves are killed, leaving 10 ha, it will then take between 10 and 15 years for the population to regrow to cover 40 ha (given that 'r' is 10 or 15% pa and assuming that there are no density dependent effects).

However, this also does not take into account the growth to maturity of the trees. In forest studies measurement of population size classes (stem diameter and height), as well as species composition, provide an indication of growth rates and successional changes in that forest. Applying this to the mangroves of Mlalazi; each stand of mangroves has a different establishment history and there is often a gradient of physical conditions. Hence there is a high degree of size (age) variability within a fine grain of resolution within the Mlalazi mangroves. Quantitative analysis of the stand in the Estuary Car Park mangroves was undertaken to illustrate the changes in size classes. This was done in 5 x5 m sampling quadrates along a line that is perpendicular to the expansion of the mangrove establishment front.

Figures 5-11 and 5-12 show the location of the study area and the sites where the mangroves were sampled.

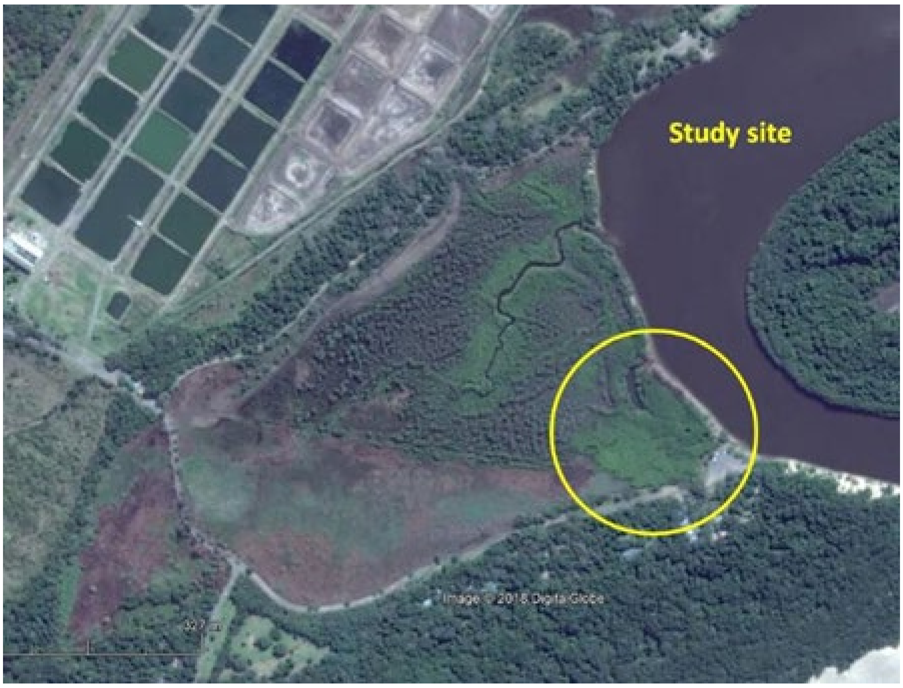


Figure 5-11: The study area in the Estuary Car Park mangroves in which the sampling sites were located. (Photo from Google Earth)

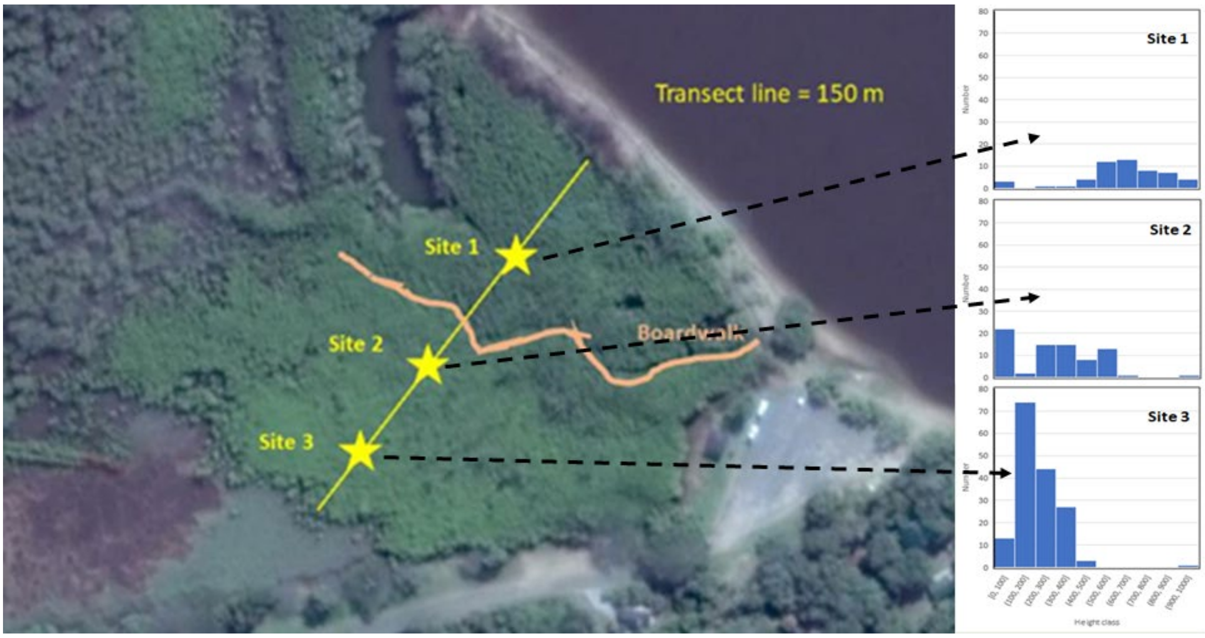


Figure 5-12: Location of the 25 m^2 sampling quadrates relative to the boardwalk. The histograms show the size classes of the trees on the x-axis (1 m class intervals) and the number of trees along the y-axis. (Photo: Google Earth)

As expected, (Figure 5-12), the trees in site 1 are mainly tall trees, those in site 2 are shorter while site 3 has an abundance of small trees. As the height of the tree is related to age, the oldest trees are in site 1 getting younger progressing towards the periphery. The only living *Avicennia* in the sampled quadrates was a single tree in site 2. All the sites had dead *Avicennia* trunks. This is the population composition that is expected. Also evident from this is that the trunk diameters were greatest in site 1 and least in site 3; and the density of trees (excluding the seedlings of the year) was least in site 1 and greatest in site 3. What we do not have is the age at which saplings start to produce propagules. This needs to be investigated in future population studies.

The population metrics show the progression of the expansion of the mangroves that has occurred – as is also evident from aerial photo analysis. Analysis of the size composition of a mangrove stand will also show whether the stand has been subjected to partial die-offs or not. Had such die-offs occurred then it would be evident as a mosaic of different tree sizes.

5.2.3.5 The spread of mangroves from adjacent estuaries

After a total die-off of mangroves in the Mlalazi estuary, recolonisation would come from an adjacent estuary that has mangroves. The closest sources are Durban (Beachwood and Durban Bay) 123 km away, and Richards Bay 26 km away. Both these sites have all three species of mangrove found in Mlalazi. The inshore currents are from the south – so it is likely that mangrove propagules came from the Durban mangroves.

Probabilities for the spreading of mangroves between estuaries are low and depend *inter alia* on the abundance of propagules produced (an *Avicennia* tree produces many more seeds than the other two species.); the coincidence of seeds being available at the time when there is a storm event or suitable tides to flush the propagules from the source mangroves into the sea; the rate which the seeds are carried by the currents; and the duration of survival of the seeds before they can enter the receiving estuary; and then the chance of being deposited in a location where they can anchor and grow.

We can only guess the conditions that culminate in propagules being flushed into the sea. However, we do know that Durban Bay which used to have extensive mangroves now only has remnant areas. Beachwood is more extensive. Conversely, the mangroves in Richards Bay have expanded in the Mhlatuze area – which was created with a new mouth when Richards Bay was made into a harbour in the early 1970s.

There have been some studies relating to the survival of mangrove propagules in the sea, and their dispersal. Clarke (1993) suggested that the range for dispersal of *Avicennia* marina propagules in South-Eastern Australia is limited to up to 10 km. However, Steinke (1999) notes that the southern African genotype of *Avicennia* seems to be able to survive for longer periods in seawater than in Australia. They retain the pericarp enclosing the propagule for longer than the Australian ones and thus they have the ability to float in sea water for longer. The other species of mangroves have larger propagules and hence survive in seawater for longer.

Steinke and Ward (2003) dropped uniquely numbered drift cards into the sea at various places along the South African coastline and monitored the location and time since release of returned cards. "A high percentage of the cards dropped at Durban were transported northwards by the inshore counter-current." But, cards from Richards Bay did, at times, move southwards – so sources of propagules could be from either direction.

Genetic work done by De Ryck *et al.* (2016) for *Avicennia* along the African coast shows "a genetically depauperate situation in peripheral populations, most likely as a consequence of historical sporadic arrival of founders with subsequent inbreeding and dispersal limitation due to the coastal geomorphology in combination with range-edge effects." This is evidence that the frequency of exchange of genetic material between estuaries is low.

In October 2017 clear evidence of the possibility of propagules from Durban arriving in Mlalazi was obtained when, during floods and associated storm conditions, a container load of plastic pellets called nurdles fell off a ship in Durban Harbour. These nurdles were washed out of Durban Bay by the flood waters and tides and rapidly spread up and down the coast. These nurdles were recorded in large numbers in the Mlalazi Estuary less than 16 days later (Taylor pers obs) (Figure 5-13).

Figure 5-13: The white plastic 'nurdles' washed up in the Mlalazi Estuary after having spilt in Durban Bay 16 days previously

From historical notes we know that it took 30 years or more for *Avicennia* and *Bruguiera* to establish in Mlalazi.

In all of Mlalazi we have only found 5 mature (producing flowers and seed) *Rhizophora* trees growing in two clumps, and about 12 seedlings or sapling. Because they are in different localities, it is assumed that this was a natural colonisation from an adjacent estuary. If this is the case, the colonisation and establishment of *Rhizophora* has taken about a century of artificial mouth breaching before colonisation – an indication of the low probabilities of effective dispersal via the sea.

5.3 Drivers and concepts needed to develop a conceptual model of mangrove growth in the Mlalazi Estuary

This section analyses the main habitat requirements for mangroves, what physical processes are driving their biology and what concepts we have that will aid us in our understanding of the mangroves in Mlalazi.

For simplification we lump the three species of mangroves together because their main responses to mouth closure and subsequent growth is similar. Species differences are highlighted where it is necessary.

Mangrove trees occur in the mid to upper inter-tidal zones of an estuary, sometimes extending into the supratidal zone. Geological evidence indicates that when the ancestral Mlalazi system had a permanently open mouth mangroves were present. Then, with natural geological evolution, the system changed from a permanently open to a temporary open/closed estuary (TOCE). Under this condition it is likely that the mouth would close and then stay closed for long periods (months to years) after closure. This flooding would have killed all the mangroves in the estuary – and shorter closures would have killed a proportion of the mangrove population each time. This condition has been altered by the artificial breaching of the mouth whenever backing up of water occurred after its closure – thus retaining water levels for all but short periods in the range within which mangroves grow. Artificial breaching has allowed mangroves to establish and grow; and little die-off related to mouth closures has occurred in the past 100 years.

Thus, most important controlling factor affecting the growth of mangroves in the Mlalazi Estuary is the prolonged backing-up of water in the estuary after mouth closure. A prolonged closure – possibly between 6 months and a year would kill mangroves. If it occurs frequently, the Mlalazi Estuary will have no mangroves in it.

After a prolonged closure had resulted in the total die-off of the mangroves within the estuary recolonization is from another estuary. This can only occur when there is the coincidence of a number of stochastic events. These are events that occur in the source estuary, in the sea where inshore currents transport the propagules and, in the entry and establishment of the trees in the receiving (sink) estuary.

The probability of a propagule from a parent tree in a source estuary surviving until it roots as a sapling in the receiving estuary are extremely low. Thus, mangrove colonisation in an estuary without mangroves is an event that may take many decades to occur once there are suitable conditions.

In the receiving estuary the new trees are subjected to many stresses which determine survival rates. It is only after several years that these trees produce seeds that contribute to the development of a population of mangroves. This is the establishment stage – which may be prolonged. It may be only after several age cohorts of trees are at the stage when they are producing seeds that the founder population enters the exponential growth stage.

The important controls of this are the proportion of trees that survive to maturity (to be seed producers) and the time it takes for a tree to grow from a thriving sapling to maturity.

Then the population enters the exponential growth phase. This happens when the founder population has increased to a viable size. In some cases there would not have been a complete die-off of the mangrove population after closure. If this is the case then it is not necessary for propagules to enter the estuary from an adjacent estuary and go through the establishment phase. The remnant trees become the population of trees to re-establish the mangrove population. This is a rapid process as the remnant trees are mature and could be fairly abundant. Whatever the source of the trees, they grow at the intrinsic rate of growth when there is an abundance of available habitat.

When there is 'vacant' habitat available the mangrove population grows exponentially. The limits at this stage to growth are the numbers of propagules produced and their survival. It is also limited by mortality

– of the propagules until they are rooted and of the saplings as well as of the mature trees. The intrinsic rate of growth incorporates these. The intrinsic rate of growth is the difference between additions to the populations and those that die. Included in this is the time taken to progress from seed to maturity. Avicennia has a faster intrinsic rate of growth 'r' than Bruguiera which is one of the reasons why it is the primary coloniser. In both this and the previous stage, competition with other plants and predation by animals can be important

Once available habitat becomes limiting, the growth of the population slows until all available habitat is filled.

The density-dependent controls are (i) a very large increase in propagule mortality, and; (ii) increased mortality of the mature trees as self-thinning occurs. In addition, there is competition between Avicennia and Bruguiera and between mangroves and other plants, such as Phragmites. In this phase of population growth, the dynamics of the population are largely related to the ageing of the stands of mangroves.

5.4 Conceptual modelling

5.4.1.1 Purpose of the models?

For this study modelling is a means to learn about the Mlalazi system. This focus of this component of the study is mangroves; specifically, on the effects of mouth closure and the subsequent recovery once the mouth is open. The system which had no mangroves in it a century ago now has 40 ha of mangrove habitat containing three species of mangrove trees. This is likely because there has been artificial breaching of the mouth shortly after each closure.

The processes involved can be broken down into a few discrete conceptual models – which may be linked at some stage in the future when better parameter data and probability estimates are available:

5.4.1.2 Conceptual model 1: A die-off model

The mangroves in Mlalazi die in response to being flooded by an extended mouth closure event. This is in response to the flooding of the mangroves by anoxic water backing up behind a closed mouth. The die-off would be a partial die-off or a total die-off. What is crucial is the length of time that the mangrove is exposed to anoxic conditions once the roots (and pneumatophores) have been flooded. Factors that modify the rate of die-off may be water temperature and water nutrient levels and each mangrove species responds differently.

The consequences of a partial die-off and a total die-off are quite different as the system will recover very much more rapidly if there is a founder population of trees still alive in the estuary as opposed to total mortality which necessitates recolonization from an adjacent estuary. This recolonisation from another estuary is a process that has a high degree of stochasticity and can take many years or decades.

The input parameters required for modelling are:

- Frequency of mouth closures that result in the backing up of water – to the extent that it floods the mangrove pneumatophores
- The probability of a closure event (i.e. water backing up to the level where pneumatophores are flooded) persisting for the time needed to cause partial or total die-off of the mangroves. It is likely that a prolonged closure would occur during a

protracted period of below-average rain. Breaching would most likely be effected by a flood event or an extended period of above-average rainfall.

At this stage we are not able to provide reasonable estimates of the probabilities of occurrence of these events. We do not know enough about mangroves to know how long they would take to die (either a partial or a total die-off) after inundation. Without more understanding, little is to be gained to go beyond this as a conceptual model.

5.4.1.3 Conceptual model 2: Transport and recolonisation of mangroves from another estuary.

After a total die-off, recolonization would be from another estuary. The closest ones are Durban Bay and Beachwood 125 km to the south and Richards Bay and Mhlathuze Estuary 26 km to the north. It is likely that the inshore current patterns would favour recolonization from Durban.

The model would need to address the coincidence of several stochastic events – several of which have a low frequency of occurrence. These include:

A. In the source estuary

i. The abundance of propagules available from the founder mangrove population which is dependent on the size of population and number of propagules produced per tree (there is a big difference between species);
ii. Season when the propagules are shed from the parent trees;
iii. The frequency of flood or tide events that flush propagules from the source estuary in the season when propagules are being shed;

B. Transport in the marine environment

iv. The longevity of survival of propagules in sea water;
v. The speed of currents moving towards the receiving estuary;
vi. The probability of propagules entering the receiving estuary from the sea, and then being deposited in a suitable site to grow. This is affected by state of mouth, tides, river flows and wave action.

C. In the receiving (sink) estuary

vii. Movement of propagules within the estuary;
viii. Once the propagule has rooted, its mortality is high while it is small, but lower once it is established. An important parameter is the survival of the plant until it is mature enough to produce seed.

We know that it took in the region of 30 years for *Avicennia* and *Bruguiera* to establish in Mlalazi, and about 100 years for *Rhizophora*. Other than these once-off scenarios, we can only speculate on the probabilities of colonisation. This is a stochastic event with a very low probability of occurrence.

5.4.1.4 Conceptual model 3: Establishment phase

The numbers of plants colonising from another estuary are likely to be very small. Of these plants, those that survive must also reach the seed-bearing stage before being part of the effective population. The probability of this is affected by many factors – which include predation by crabs, competition with other plants and being scoured away by river floods. The survival is also affected by mouth closures as the

seedling/sapling trees are susceptible to short-term flooding. It may take several years for these trees to produce the few successive generations of trees needed to attain a viable population – one that no longer has a high probability of a complete die-off.
It is difficult to estimate the duration of this phase of population growth as it can be very slow and can be affected by a number of stochastic variables.

5.4.1.5 Conceptual model 4: Population spread once established – the exponential growth phase

Once there is a small, but viable, population, the growth of the population can be described by the standard population growth equation (dN/dt=rN where N= population size, t = time interval and r = rate of growth). This growth phase is the same if it is from a newly-colonised population or the expansion from a remnant population. In the latter case the number of surviving trees will determine the point on the population growth curve where population recovery is initiated.

We have an estimate of the intrinsic rate of growth ‘r’ to be about 10 to 15% per annum. This would apply to a small population where available habitat is not limited.

5.4.1.6 Conceptual model 5: Density dependence phase

The area of potential habitat for mangroves is limited. As mangroves colonise the habitat that is suitable, density dependent factors increase. These relate to competition for resources. The most important of these is sunlight, but nutrient availability is also important. As competition increases, so the rate of growth slows down until all available habitat is taken up. The standard growth equation is modified to take into account density dependence. It becomes dN/dt=rN(K-N/K) where ‘K’ is the carrying capacity. The present area covered by mangroves is 40 ha. The maximum theoretical area available ‘K’ (at present-day sea levels) is possibly about 50 ha. However, as density dependent effects operate at the level of sub-populations (i.e. discrete patches of mangroves) they are already in effect in several localities within the estuary.

We have little information about the dynamics that change the proportion of *Avicennia* to *Bruguiera*. *Avicennia* is regarded as a relatively short-lived pioneer tree. Thus, an initial *Avicennia* domination is likely to shift to a *Bruguiera* domination with time after establishment. *Rhizophora* has a more specific habitat, and hence is likely to spread along the banks of channels and will not become a widespread plant.

5.4.1.7 Conceptual model 6: Succession of species and ageing of the population

Often, but not always, the first trees to establish are *Avicennia.* At Mlalazi, *Avicennia* is abundant in the younger stands of mangroves. *Bruguiera* grow amongst these. The *Avicennia* senesce at an early age leaving the *Bruguiera* as the dominant mangrove. As they grow taller, they exclude sunlight. Seedlings of both species are shaded out. Quantification of species, numbers and size can be used to inform us about the age of a stand of mangroves.

M Buthelezi, a UniZulu student is developing a life-stage-structured spreadsheet model of the *Bruguiera*. This model will be used to show the impacts of events that may cause selective of partial mortality – and how will affect population structure over time. This model will not be reported on in this report.

5.5 Discussion

Since the early 1800s the catchment and estuary have been affected to a large degree by human impacts. The main changes have been the breaching of the mouth whenever it closes. During this time, Mlalazi has changed from a system that previously had prolonged closed periods to one where closures are short. Effectively this breaching has reversed the geological trajectory of the mouth. The artificial breaching has allowed mangroves to re-colonise the system.

The conceptual modelling provides insights as to what we can expect in the future, and what the consequences are of various management actions. It allows consideration of two possible scenarios relating to management of the estuary mouth:

Scenario 1: **Retain the status quo where the mouth is <u>always</u> breached shortly after closure.**
Under this scenario the mangroves will expand until they reach the carrying capacity of the estuary. Within the mangroves *Bruguiera* will become more dominant – with the reduction of *Avicennia*. *Rhizophora* is likely to expand to line the channels. The population dynamics will progress to having more older, and taller *Bruguiera* trees – at lower stem densities.

There are likely to be perturbations – such as small-scale mortalities due to extreme river flooding. An unknown impact could be due to the invasion of the alien Polyphagus Shothole Boring Beetle (*Euwallacea fornicatus*) which may infest some of the trees. This allows fungi to enter and kill trees. It is more likely to affect *Avicennia*, which has relatively soft wood, rather than the other two species which have hard wood.

Under this management scenario any rise in sea level is likely to be compensated by the mangroves shifting up in the upper intertidal zone.

Scenario 2: Have a non-interference approach to mouth management. The mouth is never breached artificially.

Under this scenario the mouth is likely to close for long periods and backing up water will flood and kill the mangroves. If the duration of closure is not long enough to kill all the mangroves a founder population will remain in the estuary, from which regeneration will occur. The mouth would be allowed to breach naturally.

What is also important is the frequency of occurrence as well as the duration of mangroves being subjected to back-flooding. The duration of being flooded will determine if the die-off of mangroves is partial or total. The consequences are quite different as a total die-off will result in long periods without mangroves. It is only after colonisation, or in the case of a partial die-off, that the mangrove population will expand.

The intervals between closures are important. This will determine whether the mangroves be able to reach their carrying capacity between die-offs or not.

The guiding principle for estuarine management should be to maintain or restore natural processes where possible. If this is applied at Mlalazi Estuary, artificial breaching should not be permitted. But, should there be no artificial breaching, the Mlalazi Estuary mangroves would be exterminated. With this would be the loss of all the species relying on mangrove habitat.

However, cognisance should be taken of the fact that there have been catchment transformations which have affected runoff quantities, flow patterns and sediments. The Mlalazi Estuary is affected by these and having a ‘hands-off’ management strategy will not restore all the natural processes. Without these processes the estuary will never be in a ‘pristine’ state.

Decisions relating to mouth breaching should take into account the values of having mangroves, and mangrove-associated fauna in the estuary. The current policy to breach the mouth artificially does maintain the mangroves which are an important asset. It is of benefit to society to continue with this intervention. A century of development of the mangroves will be destroyed by allowing a prolonged mouth closure. Humans value mangroves as a habitat, as a fish nursery area and as an aesthetic asset. **Any decision to cease artificial breaching should not be taken lightly and not without full understanding of the consequences of the action.**

6. SUBMERGED MACROPHYTE PLANTS IN THE MLALAZI ESTUARY AND FLOODPLAIN.

6.1 Introduction

This section summarises our knowledge and provides a conceptual understanding of those aspects of the Mlalazi Estuary that are relevant to submerged aquatic plants.

In many estuaries, submerged macrophytes are an important component of the primary producers. At present this is not the case for the Mlalazi Estuary. The only submerged macrophyte recorded is *Zostera capensis*. This is present in small quantities in the lower part of the estuary where there is a strong marine-influence. *Zostera* is only present some of the time – when salinity is within its tolerance range. However, conditions may have occurred in the past, and may occur in the future, when other species of submerged macrophytes could become very abundant in the estuary. This section considers the patterns of growth of *Zostera capensis* as well as the conditions when other submerged macrophytes could occur.

6.2 Approach and methods

The approach has been to map present day submerged macrophytes in the estuary and its tributaries as well as in off-stream pans. Historical records provide a picture of macrophytes over the past several decades.

The regional context of Mlalazi is considered in relation to other estuaries and coastal lakes in the vicinity – especially the Amatikulu/Nyoni Estuary, Mhlathuze Estuary, Siyaya Estuary and Lake Nhlabane. These water bodies provide insights into the environment for submerged water plants that could occur in Mlalazi.

Data relating to salinity tolerances have been obtained from the literature and the salinity patterns in Mlalazi since 2013 have been obtained from EKZNW.

The above information is then synthesised to develop a conceptual understanding of possible future patterns of submerged macrophytes in the Mlalazi Estuary.

6.3 Study area

The Mlalazi Estuary is a Temporarily Open/Closed Estuary (TOCE). It does close periodically, but whenever the mouth does close it is breached artificially soon after closing. This has been the case since the late 1890s (see Section 2.2). Hence the estuary exhibits many characteristics that are more typical of an estuary with a permanently open mouth than that of a TOCE.

As well as considering the permanently inundated area of the estuary, this study includes the area of the estuarine floodplain that is affected by back-flooding events. For the submerged macrophytes this includes that area of the floodplain that may flood for prolonged periods (up to a few years) after a mouth closure event that results in the backing-up of water. Given sufficient time for a substantial berm to form at the mouth, this could raise the water level by between 1 and 4 m (Booysen, 2017).

Without human intervention, the raised water level could possibly stay at an elevated level for periods of a several months to a few years – only breaching in response to a moderate flood or a protracted period of above-average river inflows.

6.3.1 Water levels, areas and volumes

The water-level: area/volume curves (Figure 2-11) have been used to quantify water volumes and, from these, the dilution of salinity as volume increases. From these curves the area of habitat with a suitable depth range for submerged macrophyte growth at different water levels was calculated.

In addition, for the section of the estuary downstream of the Railway Bridge, the bathymetry measured by Le Roux *et al.* (DWS, 2018) has been used to estimate the maximum area of available habitat for *Zostera* relative to mean sea level when the mouth is open.

For the purposes of this study the depth range of available habitat for submerged macrophytes in the floodplain is taken to be from 0 to -60 cm. For *Zostera*, which grows in tidal water, the suitable range for growth is in the range of 0 (MSL) to -100 cm.

6.3.2 Estuary zones

Ecologically, the estuary is divided into four different reaches and their adjacent floodplain areas. Each reach is subjected to specific tidal and salinity regimes, and the adjacent floodplain has specific flooding characteristics. For the purposes of this project these are (Figure 2-10, Table 6-1):

- Mouth area (Lower-estuary) – from the Mouth to the Estuary Car Park
- Mid-estuary – from the Estuary Car Park to the Railway Bridge
- Upper-estuary – from the Railway Bridge to the Ntuze Weir/road drift across the Mlalazi River. (See Figures 6-1 and 6-2).
- The Tributary area. This is the river-estuary interface which occurs upstream of the weir/road drift. It also includes the small creeks and drainage canals that cut into the floodplain.

Table 6-1: Description of the main features of each estuary zone

Zone	Distance from Mouth (km)	Water features	Floodplain features
Mouth. (Mouth to Estuary car-park). Lower estuary	0 to 4.4 km Total length of stretch = 4.4 km	High connectivity with the sea. When the mouth is open there is a strong marine influence. Rapid currents – tidal and river flows due to narrowness and as it is relatively straight. Sediments mainly sandy – but muddy places Greatest tidal range	Narrow floodplain
Mid-estuary. (Estuary car-park to Railway Bridge.)	4.4 to 7.3 km. Length of stretch = 2.9 km	Main channel sandy, lateral channels muddy. During large floods there is backing up of water in this section. There are two main lateral channels: (i) one that drains the fish farm and town sewage system – and hence has elevated nutrient levels. (ii) From the north, a canalised one that drains the sugar fields and the stream from the Port Durnford area.	Wide floodplain
Upper estuary. (Railway Bridge to Confluence)	7.3 to 12.1 km. Length of stretch = 4.8 km.	Although tidal – there is attenuation of tidal range. Deep with coarse-sand sediments on the outer bends and shallow and muddy on the inner bends. The Railway Bridge and the raised embankment carrying the rail focus floods through the bridge.	Wide in patches. Much of the floodplain is under sugar. Water is drained via excavated canals.
Tributary zone (River-estuary interface zone) (From Confluence to Ntuze weir = 0.8 km. From Confluence to causeway = 1.0 km and a further 1.8 km that is tidal)	12.1 to 12.9 km to the Ntuze Weir. 12.1 to 13.1 km to the Causeway and 14.9 km to the upper tidal extent. Length of Ntuze tributary = 0.8 km Length of Mlalazi tributary = 1.0 km to the Causeway and a further 1.8 km to the tidal limit.	Strong riparian influence. Structures (weir and causeway) prevent or reduce connectivity of the river with the estuary.	Affected by river floods. Planted to sugar

The salinity range for each of these zones is discussed later in the text.

Figure 6-1: The weir on the Ntuze Stream that separates the Upper Estuary from the Tributary portion of the estuary. Here the wall is a barrier to upstream flows and biotic movements. There is no longer a gradient in physical changes, but an abrupt change.

With present-day management the area above the weir is never flooded with water from the sea – either during very severe storm-surge events while the mouth is open or due to backing-up water behind a closed mouth. However, if there was no mouth management and a prolonged mouth closure occurred, raising the water level by 3 to 4 m, then estuary water would flood to upstream of this weir.

Figure 6-2: The road-crossing in the upper portion of the Mlalazi Estuary. High tides rise above the rocks to flood the tributary area upstream of this causeway. (Photo R Taylor, 28 August 2012).

The Tributary Section of the estuary and floodplain is affected by a causeway on the Mlalazi River – which partly blocks tidal water movement. A backing-up flood would submerge this causeway and provide limited connectivity with the rest of the estuary. So, in effect, the causeway does not reduce downstream flows, but limits high water upstream penetration to the top part of the hydrograph during very high tidal conditions. By doing this it 'skims' the upper stratification of the water moving upstream and little of the heavier saline water will move up.

6.3.3 Salinity in the Mlalazi Estuary

In estuaries salinity is the main environmental factor that affects submerged plant growth. Salinity data for the Mlalazi have been obtained from EKZNW. Salinity has been measured at irregular intervals every few months at 11 sites from the Estuary Mouth to the Confluence since January 2013. The measurement sites are shown in Figure 6-3. Surface, water-column and bottom salinities are measured. For the period for which the data have been collected the mean bottom salinity throughout the system is 23.6 ppt. The mean surface salinity is 17.6 ppt. This 6 ppt difference is due to the greater density of saline water relative to fresher water. For consistency, when discussing the growth of submerged macrophytes, the bottom salinity has been used as this is the salinity that affects the plant roots.

Figure 6-3: Salinity measurement sites within the estuary.

Important to plants is the salinity range; not just the average salinity. Each species has a tolerance envelope that it can survive in but will die-back if salinity is above or below this tolerance envelope. Once there has been a die-back, there is a recovery period before the population is back to pre-dieback levels. So, the constancy of the salinity range remaining within this salinity tolerance envelope is important. Figure 6-4 shows the ranges of salinity at the 11 measurement sites for the period 2013 to 2018.

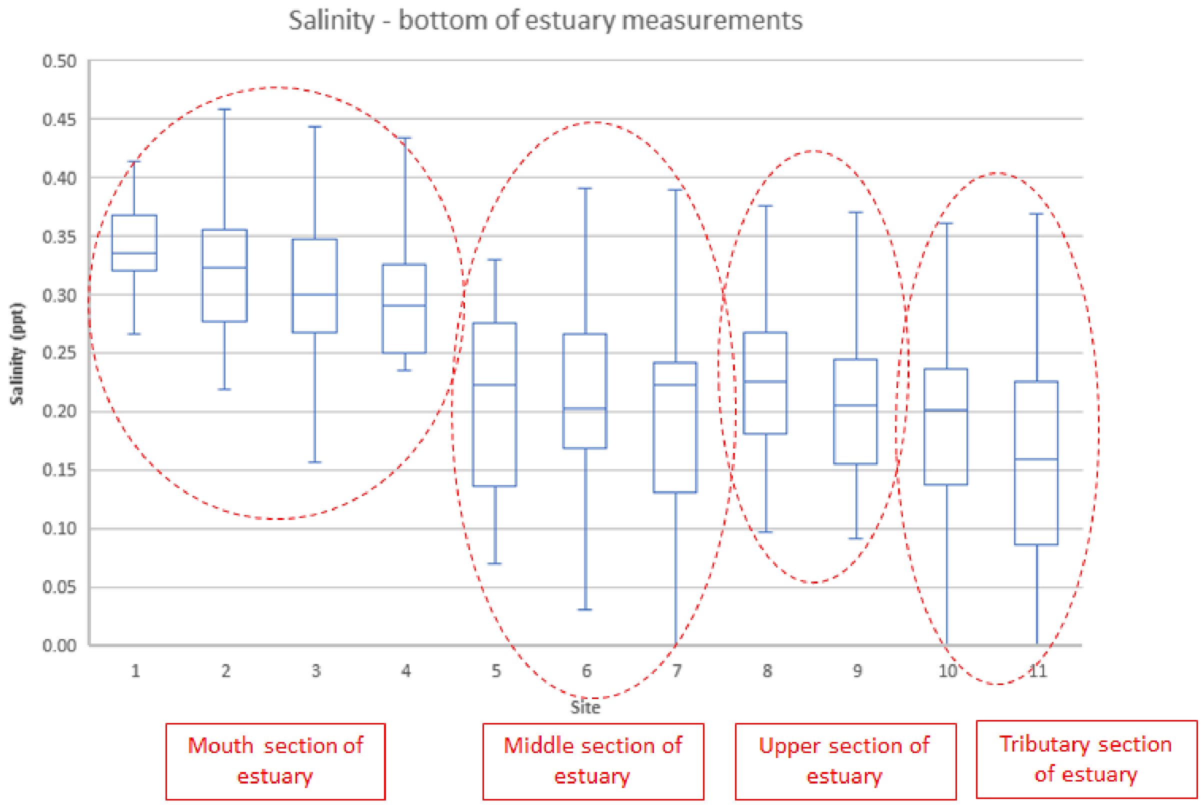


Figure 6-4: Salinity at the 11 salinity sampling stations (shown in Figure 6-3) for the period from January 2013 to mid-2018. Each box shows the distribution of the data for that site in quartiles. The mid-line is the mean of the data. The 'whiskers' indicate the range of the data. Note that the two sampling stations in the Tributary section of the estuary are downstream of the weir/causeway.

We know little about salinity patterns during a back-flooding event. The quantity of salt in the estuary at closure is important as salt is conservative. If we have the average salinity of the estuary and know the water volume at closure, then the mass of salt trapped (the salt load) can be calculated. The salt load does not change rapidly after closure, however, there is some salt loss when saline water flows seawards through the beach berm and is replaced by freshwater coming in from the rivers. As water volume increases (from direct rain and river inflows) so the salt concentration is diluted.

The above assumes that the vertical and horizontal stratification of saline water breaks down as mixing by wind and flow currents occurs. Full mixing is unlikely, but for simplification this assumption is used. Figure 6-5 shows salinity dilutions at increasing water volumes, given different starting salt concentrations.

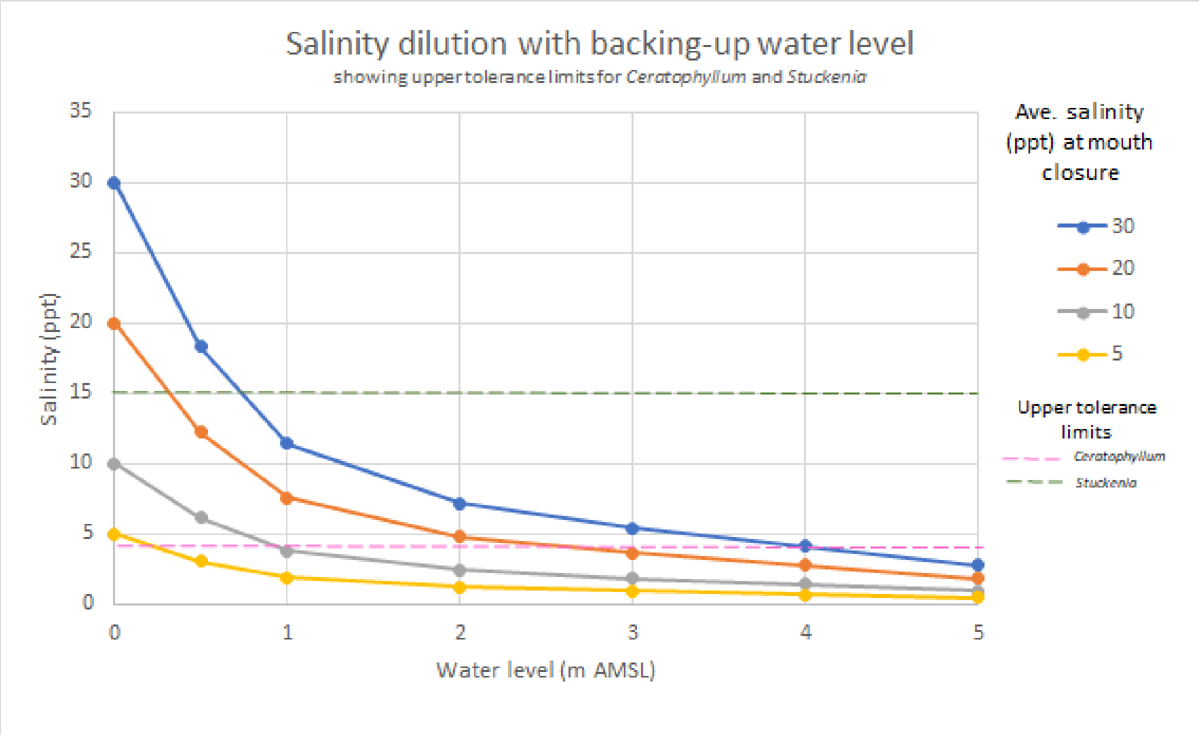


Figure 6-5: The graphs calculated using salinity dilution at different estuary volumes – using different mean salinity values at the time of mouth closure. The assumption is made that water level is at MSL on closure. Also shown on the graph are upper tolerance limits for Ceratophyllum and Stuckenia. This graph assumes complete mixing of the water, a situation that is unlikely to occur.

6.4 Historical and present distribution of submerged macrophytes

Currently (February 2019) there is no evidence of any submerged macrophyte within the Mlalazi Estuary. However, at times, when conditions are suitable, *Zostera capensis* does occur in the estuary, and there is the potential for the occurrence of other species.

6.5 Zostera capensis:

Zostera has only been recorded during a few periods in the past. From aerial photo analysis, Table 6-2, the evidence we have of *Zostera* is from aerial photo analysis:

Table 6-2: Aerial photos inspected for the presence of submerged macrophytes in the Mlalazi Estuary.

Year	Assessment
1937	fairly extensive submerged macrophyte beds
1957	no submerged macrophytes evident
1961	no submerged macrophytes evident
1975	no submerged macrophytes evident

The evidence from the 1937 aerial photos shows beds of submerged plants in the lower estuary (Figure 6-6). This is an area where there is strong connectivity with the sea while the mouth is open. Salinity at the time of photography was likely to have been within the salinity tolerance range for *Zostera*. However, this is also a range that is suitable for *Ruppia cirrhosa* which cannot be distinguished from *Zostera* in air photos. *Ruppia cirrhosa*, however, has yet to be recorded in the Mlalazi Estuary.

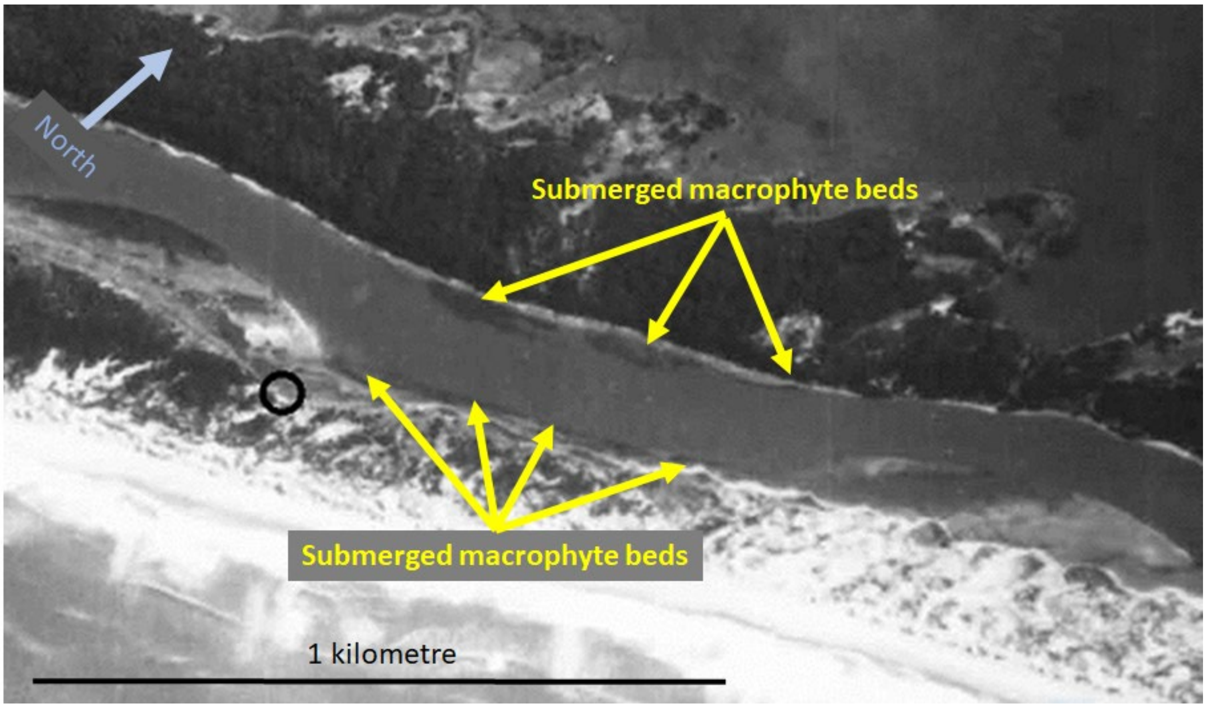


Figure 6-6: Submerged macrophytes, likely to be Zostera capensis, in the 1937 aerial photograph. This is the section of the estuary that is bounded by the current-day salinity sampling sites 2 and 3.

Further records of the presence of *Zostera* in the Mlalazi Estuary are from specimens in the Bews Herbarium (University of KwaZulu-Natal, Pietermaritzburg) (Table 6-3). These are:

Table 6-3: Herbarium records of Zostera collected in the Mlalazi Estuary

Collector	Estuary	Date	Water depth	Location	Abundance
Ward	Mlalazi	Feb-62			
Ward	Mlalazi	Aug-62	5 inches water at low tide	1 mile from mouth	
Ward	Mlalazi	Aug-62	5" at low spring	850 yards from mouth in shallow creek	plentiful
Ward	Mlalazi	Aug-62		550 yards upstream of Anchorage*	
Ward	Mlalazi	Aug-62		650 yards from mouth	very common

* The 'Anchorage' is the area immediately upstream of the Estuary Car Park.

The distribution of the *Zostera* beds, recorded in 1963 by Hill (1966) is shown in Figure 6-7. He stated that "the *Zostera* beds in the Umlalazi in 1963 were insignificant in comparison with those of Richard's Bay".

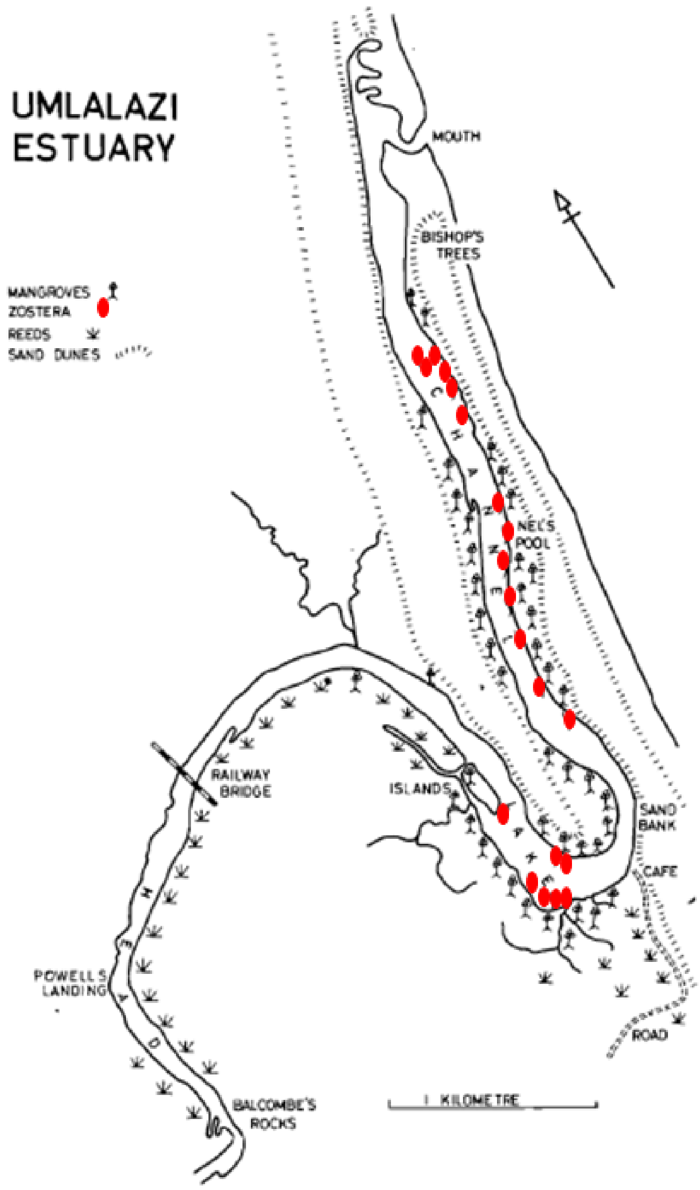


Figure 6-7: Map showing the distribution of Zostera in 1963 from Hill (1966). At this stage its distribution was much more widespread than its present distribution. It occurred in both the Mouth Zone and the Mid-estuary Zone of the estuary.

In the 41-year period from 1963 until November 2014 no *Zostera* was recorded in the estuary. This could be partly due to the dredging of the estuary in 1965 and a few years after that. Even after recovery from the dredging, it is unlikely that *Zostera* would ever have been abundant. There could well have been periods in the 1963 to 2014 period when *Zostera* was present, but not detected.

When *Zostera* was found again in the Mlalazi Estuary in 2014 it was found in much the same locality as shown in the aerial photo of 1937 – about 1.8 km in from the mouth (see: https://www.inaturalist.org/observations/11063996) (Figure 6-8).

Figure 6-8: A small clump of Zostera growing in Mlalazi Estuary, 15 Nov 2014 (Photo: Ricky Taylor).

Zostera dies-off when exposed to fresh water. After a die-off, when the water is once again at a suitable salinity, the plants regrow. If the die-off is total and there are no dormant plant or seeds in the estuary, then *Zostera* has to recolonise from an adjacent estuary. The closest sources of propagules are the Mhlathuze Estuary 25 km to the north and the Amatikulu/Nyoni Estuary 21 km to the south.

Once habitat conditions are suitable for *Zostera* it starts its growth in the population establishment phase. Establishment is the process where there is a founder population which is in very low abundance which acts as the nucleus of a new population. This can be either surviving plants or seeds which have been dormant within the estuary or the colonisers from other estuaries. This establishing population may take a long time to grow under suitable conditions before the population reaches the stage where there is exponential growth. Once in this phase, the population will grow at the intrinsic growth rate for the plant, until density-dependant effects slow the expansion of the population. This occurs as the population reaches the carrying capacity of the habitat that is available for *Zostera*.

In early 2015 the total area of *Zostera* in Mlalazi Estuary was estimated to be 0.1 ha (Taylor, pers obs). The measured area of the estuary with a suitable depth range for *Zostera* (i.e. the zone of 0 to -100 cm relative to MSL) is 247 ha for the Lower Estuary and 154 ha for the Middle Estuary (Calculated from the bathymetry survey done by DWS 15 to 17 September 2017 (Le Roux *et al.*, 2018)). The very small area of this potential habitat that is colonised by *Zostera* indicates that either the population had not progressed much along the exponential growth stage, or there are determinants other than depth and salinity, that limit the area inhabitable by this plant. The required habitat could include suitable substratum, locations without excessive wave action, turbidity which affects light penetration and protection from excessive currents.

Hill (1966) found *Zostera* in the Middle Estuary. It is not known why it has not been found there since them. Possibly this is a difficult area to colonise – due to its sloppy mud substratum and high turbidity. Dredging in the mid to late 1960s also deepened the area. This could have been important.

It is likely that prolonged mouth closure events would exterminate *Zostera* from the Mlalazi Estuary. As is the case with the mangroves (see Section 5), *Zostera* is a plant that requires good connectivity with the sea (Adams, 2016) and hence the current presence in Mlalazi is likely to be due to the mouth always being breached soon after closure every time since the 1890s.

6.5.1 Recovery of Zostera after a die-off

If we consider when *Zostera* has been recorded in relation to the measured salinity in the period 2013 to 2018 it appears that from 2014 onwards salinity was in the tolerance range for Zostera. This is shown in Figure 6-9.

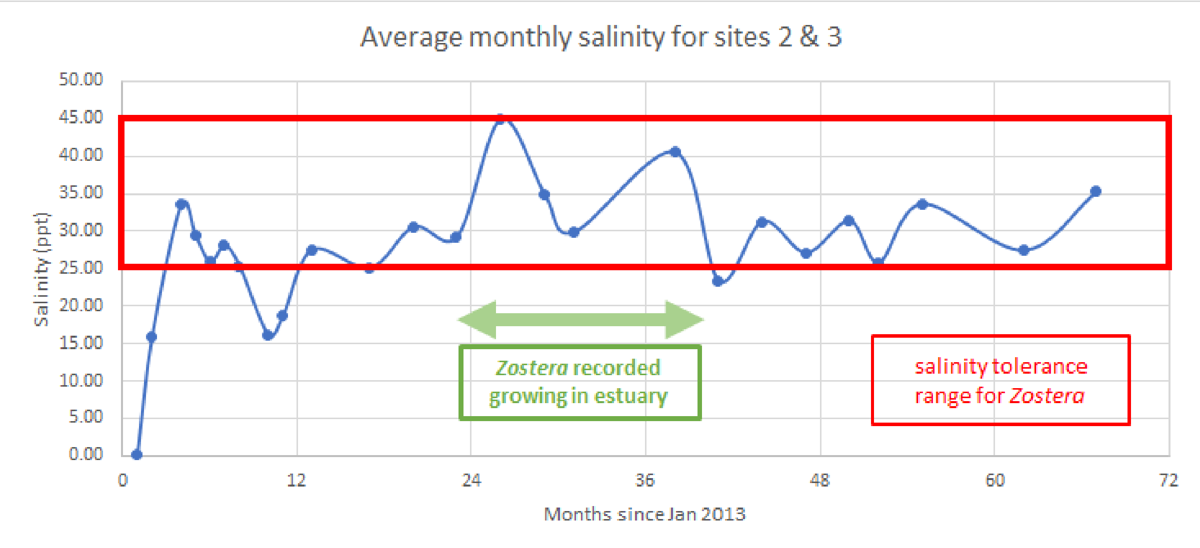


Figure 6-9: Salinity measured in the lower portion of the estuary (mean of salinity stations 2 and 3). The red box is the preference window for Zostera (above 25 ppt). The green arrow shows the period when Zostera was recorded in the estuary. (Salinity data from EKZNW).

Assuming that a large river flood would flush the estuary and that the flow as well as the freshwater would kill the *Zostera*, the following records are informative (Table 6-4). This indicates that in each case *Zostera* has been recorded within two years of such an event.

Table 6-4: Recovery of Zostera after flood events

Flood	Record of *Zostera*	Time between a flood event or unsuitable salinity conditions, before this record of the presence of *Zostera*
June 1935*	1937	2 years
December 1960*	Feb 1962	14 months
January 2013**	Nov 2014	22 months (from Figure 6-9).

** Data obtained from simulations of the largest floods recorded in the 85-year period from 1920 to 2004, where the December 1960 flood was regarded as the 7th largest flood in this period, and June 1935 the 16th largest (DWS, 2015).*

*** Based on the EKZNW salinity measurements, January 2013 was too fresh for Zostera to survive, and February, October and November of 2013 had salinity levels that were below that which Zostera can thrive. (Figure 6-9), hence the Zostera seen in 2014 had been able to grow within a year of suitable conditions occurring.*

Intuitively, the times taken to recover after a flood or low-salinity seem to be too rapid for colonisation to have occurred from an adjacent estuary, and even from the germination of seeds from a local seedbank. It is most likely that this is vegetative growth from *in situ* rootstock that had survived the adverse conditions. The implication of this is that *Zostera* is able to recover rapidly as long as there are surviving sections of underground rhizomes.

Within the estuary salinity is most suitable in the lower reaches. Figure 6-10 shows the locations where *Zostera* would have had suitable salinity conditions to survive in the 2013-2018 period.

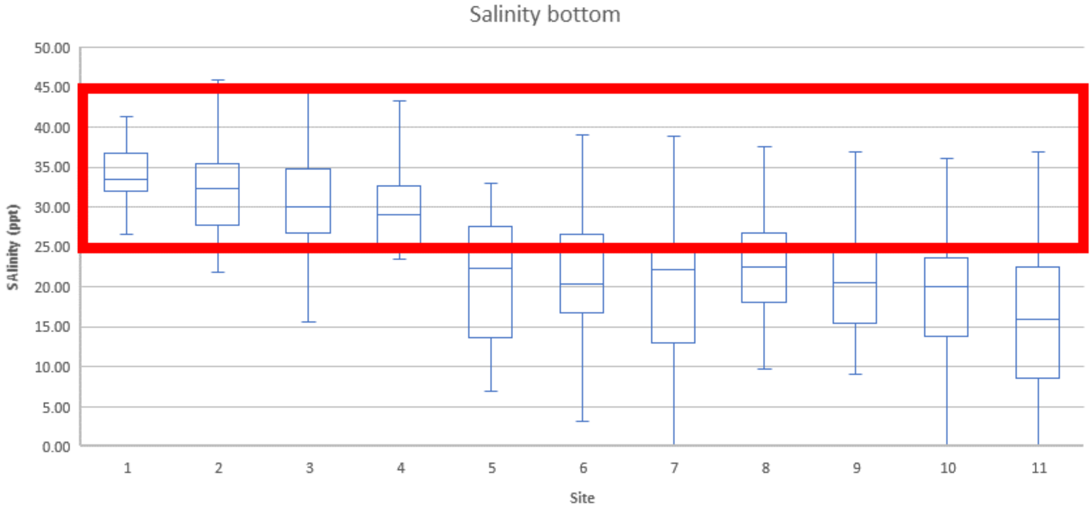


Figure 6-10: Zostera has a preferred salinity tolerance range of 25 to 45 ppt. The red box shows this range superimposed on the salinity ranges measured in the 2013 to 2018 period. This indicates that suitable conditions for its growth are mainly in the lower-estuary, but occasionally in the mid-estuary. This supports the distribution pattern shown by Hill (1966) shown in Figure 6-7)

6.5.2 Submerged macrophytes other than *Zostera*

Although no submerged plants other than *Zostera* have been recorded in the Mlalazi Estuary, there is the potential for several to colonise should suitable conditions occur for their growth. These conditions would occur if there was no artificial breaching of the mouth. To gain insights about this potential colonisation we do need to extrapolate using evidence from elsewhere on the Mlalazi floodplain and from nearby estuaries.

Within the Mlalazi floodplain there is a small population of *Ruppia marina* in a supratidal saline pan (https://www.inaturalist.org/observations/11297361). This is an off-stream water body much of the time – linking with the estuary only during extreme high-tidal conditions. *Ruppia marina* is a plant that usually is found in these shallow water conditions – but recently has been found in large patches in deeper condition Lake St Lucia (C Fox, pers comm) (https://www.inaturalist.org/observations/11305918).

There are also submerged macrophytes thriving upstream of the weir on the Ntuze tributary. These include *Najas horrida* (https://www.inaturalist.org/observations/11061455) and *Ceratophyllum demersum* (https://www.inaturalist.org/observations/11061461). This site could act as the source of the propagules for these two plants to spread into the floodplain whenever there is backing up of water after a mouth closure.

The Amatikulu-Nyoni is a TOCE. It has an abundance of submerged water plants. These include *Zostera capensis*, *Ruppia cirrhosa*, *Ceratophyllum demersum* and *Stuckenia pectinata* (Taylor, 2015). This estuary has a well-defined salinity gradient – both when open and when closed. This is due to its linear nature and the suppression of currents by the extensive beds of water plants. This creates the range of salinity habitats needed to support all the species – including *Zostera* after mouth closure. (Taylor, 2015). What we learn from this is that backing up water in Mlalazi may not have a homogenous salinity. This goes against the assumption that the backed-up estuary is well mixed. Thus, as in Amatikulu/Nyoni, a range of salinity conditions could support a several different plant species at one time, each with its specific salinity tolerance range. The Amatikulu/Nyoni Estuary is about 20 km from Mlalazi; close enough to be regarded as a seed source for the colonisation of Mlalazi – with the seeds being transported by birds or by ocean currents.

The Mhlathuze Estuary has extensive beds of *Zostera capensis*, but no other submerged macrophytes have been recorded there. This is a Permanently Open Estuary. The *Zostera* thrives mostly in beds which are flushed by daily by tidal movement. The flood tide carries low-turbidity seawater over the *Zostera* allowing for light penetration in what is generally a highly turbid estuary. This, as well as the Amatikulu/Nyoni could act as a source for *Zostera* propagules should *Zostera* die-out in Mlalazi.

The Siyaya Estuary, a TOCE adjacent to the Mlalazi Estuary, is infrequently connectivity with the sea. It is rich in emergent vegetation. As salinity is very low, the main submerged water plants are *Ceratophyllum demersum* (https://www.inaturalist.org/observations/8682769) in the upper reaches and *Stuckenia pectinata* in the lower reaches. (https://www.inaturalist.org/observations/8682768) Being close to Mlalazi (the mouths are separated by 5 km) the Siyaya Estuary is a possible source of propagules (seeds or fragments of the plants) of these species whenever there is a flood that would wash them into the sea, or the seeds may be transported by birds.

Lake Nhlabane used to be an estuarine lake. Its connectivity with the sea was lost in 1977 when a weir was built to exclude saline water and to raise the water level. This system is very similar to what the Mlalazi system would become after a prolonged mouth closure and the associated backing up of water. The system has an abundance of submerged water plants. The main ones include *Ceratophyllum demersum, Najas horrida* and *Stuckenia pectinata*. Although Lake Nhlabane is now a freshwater system, these plants are able to survive in low-salinity water. The submerged water plants have the highest biomass in the southern basin which is relatively shallow and protected from wave action. (Adams *et al*., 2006; Kelbe *et al*., 2014).

What we learn from these systems is that there are several species of submerged freshwater plants that do tolerate low salinity conditions and thrive in nearby estuaries and coastal lakes. We gain insights into what plants could occur should there be a prolonged flooding of the Mlalazi Floodplain caused by a long-duration mouth closure and the ensuing backing up of water.

6.5.3 Future possible scenarios for submerged macrophytes.

We can be optimistic that *Zostera* will survive in the Mlalazi Estuary as long as the current management practice of breaching the estuary soon after closure is maintained. This situation would change markedly should a 'natural' breaching regime be implemented at any stage and the mouth is no longer breached artificially. Under these circumstances there could be long periods (months to years) when the estuary remains closed, water backs up behind the mouth to flood the floodplain and salinity in the backed-up water would be low. With these specific conditions there would be no *Zostera* but several other submerged macrophytes are likely to occur.

The *Najas* and *Ceratophyllum* plants that are in the water held by the Ntuze weir (Figure 6-3) both have the capacity to rapidly spread into the backed-up estuary water during a mouth closure event. Plants that are not recorded from the Mlalazi Estuary or floodplain, but which occur in abundance in nearby estuaries include *Ruppia cirrhosa* and *Stuckenia pectinata*. These have the potential to colonise the basin, and could possibly have occurred in it in the past. There is also a likelihood that Charophytes could, under mouth-closed or post-flood conditions, play a prominent role in the primary production of the estuary – as they do in the main lake at Kosi Bay.

Ruppia maritima which is in a supratidal shallow pan within the Mlalazi saltmarsh habitat is unlikely to spread much as salinity of backing up water would be too low.

There are also a few other submerged macrophytes found in the Zululand coastal plain that could colonise Mlalazi if it is in a freshwater or very low salinity state for a prolonged period – but are not considered. These include:

- The submerged plants *Lagarosiphon* major and *Utricularia stellaris*.
- The plants that are anchored but have floating leaves *Nymphaea caerulea, Trapa natans, Nymphoides thunbergiana*. These all require freshwater and stable water levels but do grow in wetlands of the region and could colonise Mlalazi.
- The free-floating plants *Salvinia molesta*, *Pistia stratiotes*, *Eichhornia crassipes*, *Azolla* sp., *Spirodela polyrhiza*(?) and *Wolffia arrhiza* would colonise in sites protected from wave action if conditions are fresh enough.

Ecologically important, but also not considered, are the emergent plants that would grow along the margins of the estuary if water levels do not fluctuate much.

6.6 Ecological drivers

It is possible to develop a conceptual model with the purpose to predict submerged macrophyte changes with time in relation to the mouth being open or to mouth closures and associated back-flooding. This model has to be conceptual as there is no possibility of verifying its output at this stage, and it would need to use several 'best guess' parameters.

For this we first consider the sub-tidal part of the estuarine system where, given the existing mouth management regime (i.e. open or closed for only very short periods), the only submerged macrophyte recorded from the Mlalazi estuary is *Zostera capensis*. This habitat and mouth management regime may also be suitable for *Stuckenia pectinata* and *Ruppia cirrhosa.*

6.6.1 A conceptual model for *Zostera* in the estuary

Zostera grows when the mouth is open and salinity in the lower part of the estuary is within its tolerance limits (Figure 6-10). Floods and mouth closure alter this – most importantly by reducing salinity or scouring away the portions of the plants that are in the water column. Conceptually, the rhizomes embedded in the sediment are able to survive for some time – often for long enough to tide the *Zostera* over low-salinity periods (e.g. a flood and a post-flood low-salinity period). *Zostera* seeds, conceptually, can survive for much longer periods in a seed bank.

Long-duration closures would completely kill off all the *Zostera* (plants, rhizomes and seeds) from the system. If this occurs then, after breaching, colonisation would need to be from adjacent estuaries. Amatikulu is possibly the most likely source as the nearshore currents are predominantly from the south.

6.6.2 Conceptual model for water plants, other than *Zostera*, in the estuary

Salinity is often the main determinant as to whether a submerged water plant can grow or not. Considering the different species of submerged macrophytes that occur frequently in similar habitats in the region (Section 6.5.3), Table 6-5 provides their salinity tolerance ranges.

Table 6-5: Salinity ranges of these plants used in this report

Species	Salinity tolerance range	Already present in the estuary or its floodplain
Ruppia maritima	0-25 (0-13)	Yes
Ruppia cirrhosa	12-35 (0-30)	?
Ceratophyllum demersum	0-4	Yes
Stuckenia pectinata	4-25 (2-15)	?
Najas horrida	0-12	Yes
Characeae	0-12	?

For the purposes of conceptual modelling the salinity ranges used are given above. Numbers in brackets indicate the ranges given by Adams & Riddin (2007) for the Cape estuaries in which the plants can exist. The figures used are considered to be more representative in Zululand – based on empirical observations (Taylor, pers obs).

Based on their individual salinity tolerances, Figure 6-11 indicates which plants could have grown in the estuary at the following salinity sampling stations for at least some of the 2013 to 2018 period:

	1	2	3	4	5	6	7	8	9	10	11
Zostera capensis	x	x	x	x							
Ruppia maritima					x	x	x	x	x	x	x
Ruppia cirrhosa	x	x	x	x	x	x	x	x	x	x	x
Ceratophyllum demersum											
Stuckenia pectinata					x		x			x	x
Najas horrida					x	x	x	x	x	x	x
Najas marina					x		x			x	x
Characeae					x		x			x	x

Figure 6-11: Given the individual salinity tolerances for each plant species (left column), this figure summarises which parts of the estuary (the salinity sampling stations 1 to 11 in the top row) have had salinity conditions in the 6-year period since January 2013 that could have supported each plant The red shading indicates sites that are at times within the salinity tolerance ranges for each plant.

Within the estuary, under the present-day mouth management regime, responses similar to *Zostera* can possibly be expected from *Ruppia cirrhosa* – just with a different salinity ranges which means it could possibly grow further up in the estuary. This species would also be dependent on the mouth regime, but possibly more resilient to mouth closures. *Ruppia cirrhosa* is possibly less persistent than *Zostera* after a flood and hence is absent at present.

Stuckenia pectinata is also a plant that could occur in the estuary with the present-day management regime – given extended periods of low-salinity conditions.

If we consider the case where there are no interventions to breach the mouth after closure, then habitats would be available for various submerged macrophyte species at various levels of backing up of the water. Salinity tolerance is the basis for making predictions, and the area that is shallow enough (taken to be <60 cm) to allow for sufficient light penetration for photosynthesis. Other important parameters, which we do not have, are the frequency that the water would inundate different elevations of the floodplain once the mouth has closed, and also how long these flooding events would last. These parameters will influence the growth of submerged macrophytes.

Another unknown is the probability of founder populations of each species establishing in the estuary, and then, an estimation of the rate of expansion of the population after a founder population has established.

At present the estuary has no submerged macrophytes other than the occasional occurrence of *Zostera*. However, there are other plant species in upstream or off-stream refugia which would spread into the estuary during floods. These plants include *Ruppia cirrhosa, Ruppia maritima, Ceratophyllum demersum, Stuckenia pectinata, Najas horrida*, and some of the Characeae. Figure 6-5 shows the dilutions needed for these plants to survive, and shows the cut-off line for *Ceratophyllum* and *Stuckenia* – the two most likely of the plants

6.6.3 A conceptual model for submerged macrophytes in an inundated floodplain.

Using the depth-area rating curve (Figure 2-11), we are able to calculate the available area of suitable submerged macrophyte habitat given the elevation of the water – assuming that the plants prefer to grow in water 0 to 60 cm deep (Figure 6-12). As well as knowing the area that has suitable water depth, salinity scenarios have been calculated from the water level: volume curve. These indicate which plants could grow at different water levels – given scenarios with different average salinity at the time of mouth closure (Figure 6-5). This graph shows that a plant with a higher salinity tolerance such as *Stuckenia* would have an advantage over a plant that prefers fresher conditions, such as *Ceratophyllum*. From this we can see that, once the mouth closes, and if salinity at closure is reasonably high, then *Stuckenia* would be able to thrive much sooner (at lower water levels) than *Ceratophyllum*.

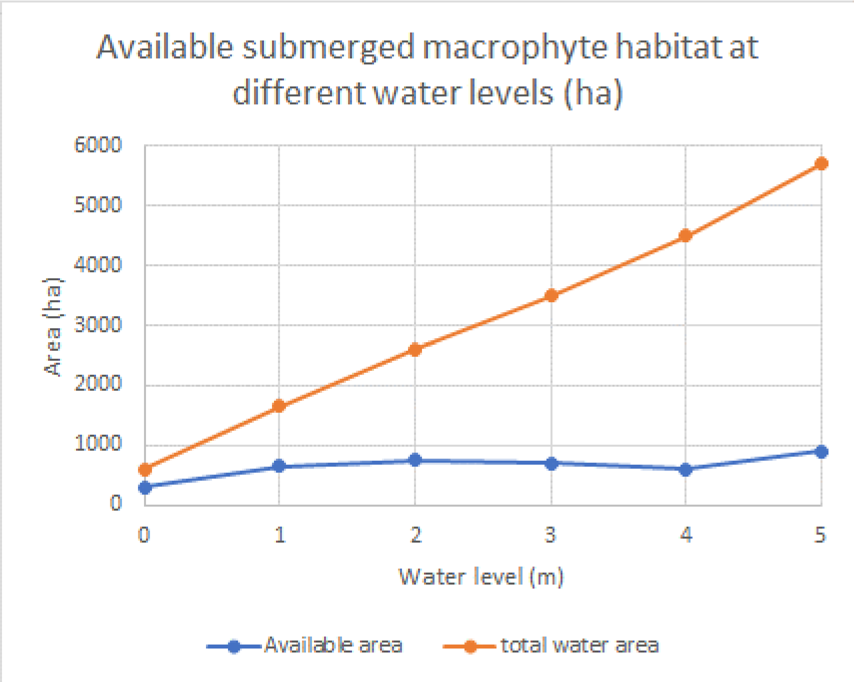


Figure 6-12: Area of habitat suitable for the growth of water plants (<60 cm deep) in Mlalazi at different water levels. Although <60 cm has been used, this is for illustrative purposes. The different plants have different tolerances to low light penetration. Water clarity is likely to increase as plant biomass increases, reducing waves and currents. The responses of the plants will also be affected by the rate of change in water level and whether the water is rising or dropping. Of interest is that the amount of available area is similar at all levels.

A note on salinity variability:
Salinity must be within its salinity tolerance range for a plant to thrive. However above and below that range sub-optimal conditions may occur. These are conditions where the plants may be dying-back slowly, or just eking out an existence. Within an estuary, conditions are never homogenous – often there are pockets of water with higher or lower salinity which form small refugia in which the plants can survive are left. These act as nuclei for recolonisation. The spread of a plant is greatly facilitated by the occurrence of such refugia which act as source populations which provide propagules that can be dispersed.

Water depth variability is also important. As water level lowers, so new habitat becomes available for colonisation. As submerged macrophytes grow, so turbidity is reduced – allowing deeper light penetration and hence expanding the depth limits that the plants may grow in.

6.7 Modelling

We have the building blocks for a model, but there are still too many unknowns to move from a conceptual model at this stage to a more formal model. Future modelling of the submerged macrophytes will need inputs relating to the probability of the mouth closing, and once closed, probability estimates of how long it would stay closed and the rate of water level rise. With this information, it is necessary to know the average salinity of the estuary water at the time of mouth closure – in order to estimate when salinity will be low enough for each species of water plant to thrive.

What is also important to know is the time it takes for the individual species of plants to establish and the rate at which the founder populations can expand. This is also affected by the variability of conditions within the estuary such as the rise and fall of the water level and horizontal salinity stratification patterns. Given a long period of closure (up to a few years) we need to take into account loss of salt through seaward seepage of water.

Once we understand the above, we will be able to better predict the responses of the plants to different management strategies. The understanding gained here could be applicable to other estuarine systems of KZN.

6.8 Discussion

Under the present mouth-management regime, submerged macrophytes have little ecological influence on the Mlalazi estuarine system. Only *Zostera* has been recorded in the sub-tidal areas of the estuary – and only in small quantities and only when there has been a period of two years or more when salinity conditions are suitable. However, this could change. If *Stuckenia pectinata* and *Ruppia cirrhosa* are able to establish in the system. Their establishment would be promoted by salinity in a suitable range, low currents and raised nutrient levels – all conditions that are likely to occur in association with increased mouth closure frequencies and longer durations of closed mouth conditions. These are both important plants in a number of the KZN estuaries.

These two species, and several other species are likely to establish in the floodplain if there is a prolonged mouth closure. One that results in backing-up of estuary water to flood the lower portions of the floodplain.

The salient control of estuary conditions for Mlalazi is the mouth opening/closing regime. For the past century artificial breaching has maintained the estuary in a state where its biota are more similar to that of a Permanently Open Estuary than a Temporarily Open/Closed Estuary. This would change if the mouth was allowed to function naturally. If the mouth were to stay closed for a prolonged period, then high biomasses of submerged macrophytes may develop.

7. FLOODPLAIN VEGETATION

The Mlalazi Estuary is a relatively small estuary set within a wide floodplain. This estuary and floodplain formed during the rising sea levels of the Holocene. This part of the study investigates the main determinants of the vegetation of the floodplain. It summarises our knowledge and provides a conceptual understanding of the Mlalazi Floodplain and its ecological functioning.

7.1 Approach

Very little is known about the ecology of the Mlalazi Floodplain. It is a highly transformed landscape, much of which is privately-owned farmland planted to sugar cane. As a result, most of the study does not focus on the full floodplain; only on that portion of the floodplain that is within the Mlalazi Nature Reserve (Figure 7-8). Much of what is presented is a synthesis of our knowledge, some of which is based on a series of small studies conducted by UniZulu honours students in the period 2016 to 2018.

The floodplain is very dynamic, driven by stochastic flood events which then trigger sequences of ecological responses. As we were unable to monitor changes subsequent to flooding events most of our findings provide a ‘snapshot’ understanding of the floodplain. To counter this, our approach has been largely descriptive – based on available observations and knowledge to support concepts.

7.2 Descriptive ecology

7.2.1 <u>The nature of floods and the floodplain</u>

A floodplain is defined as a periodically inundated area adjacent to a river or estuary. For the purposes of this study the boundary of the Mlalazi Estuary Floodplain is determined by the extent of the largest recorded flood. This was in 1987 and rose to close to 10 m above MSL. A feature of this floodplain is that it passes through a coastal plain. Downstream of the railway Bridge there are no rock structures to act as geological controls. Another feature is that the estuary is set in a coastal environment that is prograding seawards at an average of about 2 m per annum (Weisser, 1982; Van der Elst and Everett, 1999). Thus, from the geological perspective, these features result in this being a rapidly changing system.

Floodplains are event-driven ecosystems. The main events are floods. Other natural events of much smaller significance include fire and grazing. Floodplains are landscapes that are prone to being modified to a large extent by human impacts. They have fertile sediments that attract agriculture, they often have an abundance of water and they provide good grazing. But, by definition, they are prone to flooding and to protect from flood impacts, the users construct flood-protection structures and excavate drains.

There are different types of floods, each with discrete characteristics, which affect the Mlalazi Estuary Floodplain. These are mainly stochastic in nature, occurring at different intensities and at irregular intervals, and each having a different magnitude and type of influence. The flood types are:

- **River floods** which are catastrophic events (in the geological sense) where the water rises and falls over a few days and are associated with fast flows. These floods are associated with rainfall events in the catchment and are of varying magnitudes. The largest river flood in recent years was that of 1987 (Badenhorst *et al*., 1989).

- **Back-flooding** of the floodplain when the estuary mouth closes and water backs-up as the 'storage' volume increases. The rate of backing-up is slow; often taking many weeks or months to rise. The maximum flood level is determined by the height of the beach berm and the quantities of water gained from river inflows and direct rainfall minus the water lost through evaporation and seaward seepage through the beach-berm and dunes. In the past century this type of flooding has not occurred to its full extent as the mouth has always been breached artificially. However, it is likely that, in the absence of human interventions, the mouth could on occasions stay closed for up to several years at a time. Natural breaching would have occurred by overtopping of the beach-berm, resulting in a rapid draining of water from the floodplain. The natural closure of the mouth in October-November 2017 raised the water level by 1.2 m over a period before the mouth was artificially breached.

- **Marine storm events** may result in storm-surges which enter the estuary mouth. They are often associated with high-rainfall events in the catchment area. When these are combined with extreme high tides, they may flood parts of the floodplain with seawater. A severe storm event occurred in 2007. This flood killed trees such as *Ficus trichopoda, Trema orientalis, Acacia kosiensis* and *Bridelia micrantha* growing above the supratidal level. It flooded the trees with saline water (R Taylor, pers obs.). These are all fast-growing pioneer trees which are possibly killed every several years by such flooding.

- **Marine tides** result in regular flooding of the intertidal area twice a day. The marine tidal range is attenuated by the mouth constriction. Although the estuary is still tidal above the Causeway (Tidal rise and fall extends up to about 15 km from the mouth), the tidal range does diminish with distance from the mouth. Associated with extreme high tides there is the flooding of the supratidal regions of the floodplain – areas that are not affected by every spring high tide. In addition to this, Figure 3-14B shows how the average water level of the estuary rises and falls in relation to the spring-neap cycle and in relation to the dimensions of the mouth. This affects the extent and elevation of the intertidal zone.

Ecologically, the floodplain can be divided into zones which are subjected to different flood types and regimes. These are:

- The intertidal zone flooded by normal diurnal sea tides
- Above this is the supratidal zone – flooded by seawater in response to high-sea conditions caused by storm events (often combined with high tides)
- Flooding resulting from a backing up of water during a closed-month period.
- River floods caused by intensive rain events in the catchment.

These zones are depicted schematically in Figure 7-2.

In addition to the stochastic flooding, there are also portions of a floodplain which are inundated or maintained in a permanent waterlogged state by freshwater streams and groundwater seeps. The constant inflows of this freshwater from beyond the boundaries of the floodplain maintain these sites as perennial wetlands which support sedge-swamps or swamp forests.

The geomorphological features used to define the upper margins of the floodplain are likely to have been formed at a time when the MSL was above that of the present day (see Section 2-1). Thus, this upper portion of the floodplain may have floodplain sediments but, with present day sea levels may no longer be subjected to flooding. In effect this is a palaeo-floodplain upper margin to the present-day floodplain.

The floodplain areas associated with the Mlalazi Estuary extend to more than 15 km from the estuary mouth. The areas closest to the mouth have strong connectivity with the marine environment and have saline soils. Further upstream this connectivity diminishes until the floodplain areas are more typical of those associated with a river.

The widths of the floodplain are shown schematically in Figure 7-1, which also shows the four floodplain tracts used in this study (Figure 2-10). These sections are:

- Mouth Floodplain (Mouth to Estuary Car Park)
- Middle Floodplain (Estuary Car Park to Railway Bridge)
- Upper Floodplain (Railway Bridge to Confluence)
- Tributary Floodplain (Above the Confluence)

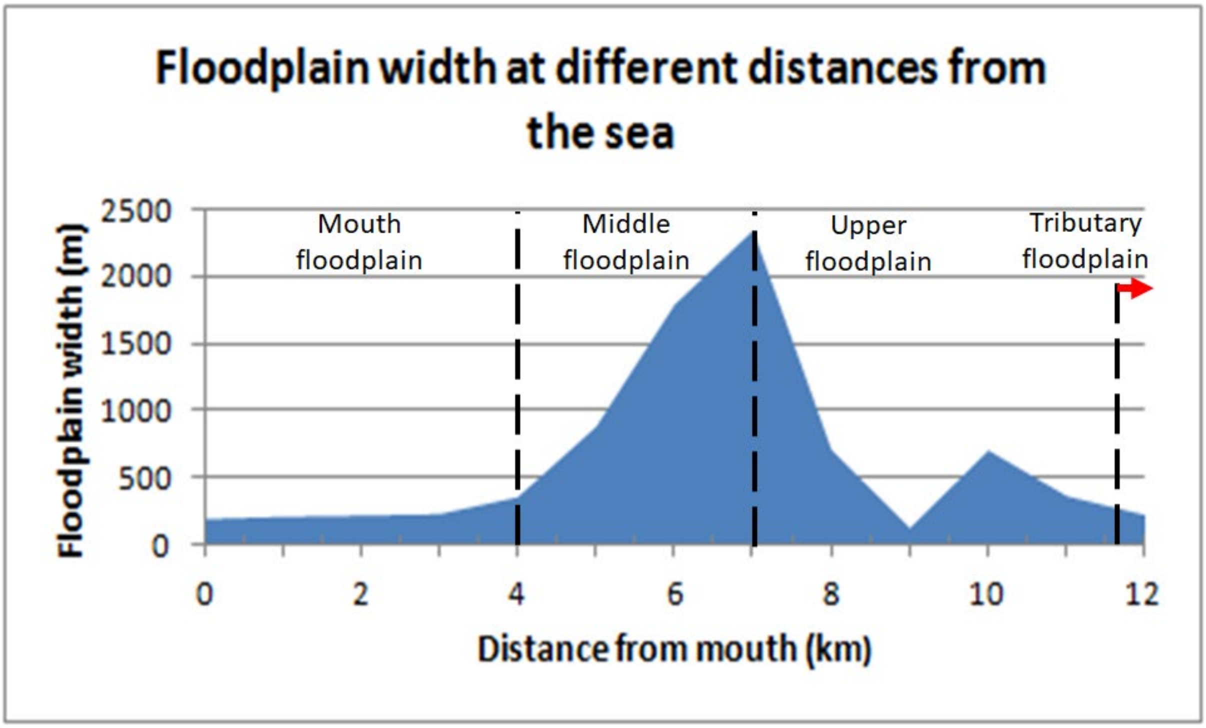


Figure 7-1: The floodplain width relative to distance from the mouth.

7.2.2 <u>Flood inundation classes</u>

Watson (1928) developed the classic concept of “Inundation Classes” for different sites within a mangrove forest – in which he defined 5 categories which described the elevation of flooding due to tides and hence the number of times a site is inundated per month. The mangroves in Mlalazi are, by global standards relatively small, and Watson’s classes would be masked by the narrowness of the sites. His classes are shown in Table 7-1. When considering the Mlalazi Floodplain only classes 1 to 4 (as one class) and class 5 are useful. However, we should also include a Supratidal class above these. This is a class that is inundated only a few times a year by the highest of tides. It is an area which can have high groundwater salinity – where the salt is concentrated by evaporation. This class exhibits bare mud flats, succulent salt marshes or *Juncus kraussii* beds.

Table 7-1: Inundation classes for mangroves as described by Watson (1928)

Inundation class	Flooded by:
1	All high tides
2	Medium high tides
3	Normal high tides
4	Spring high tides
5	Abnormal high tides (Equinoxal)
	Supratidal areas (not recognised by Watson (1928))

When considering the floodplain at elevations above the supratidal level, additional classes can be described. These are the portions of the floodplain that may be affected by storm-surge flooding, by back-flooding and by river floods (Figure 7-2). The difficulty in using flood inundation classes is that the upper elevation of a flood is never a fixed elevation, but is a fuzzy margin. The probability of a specific type of flood attaining the upper elevation level reduces with a rise in elevation.

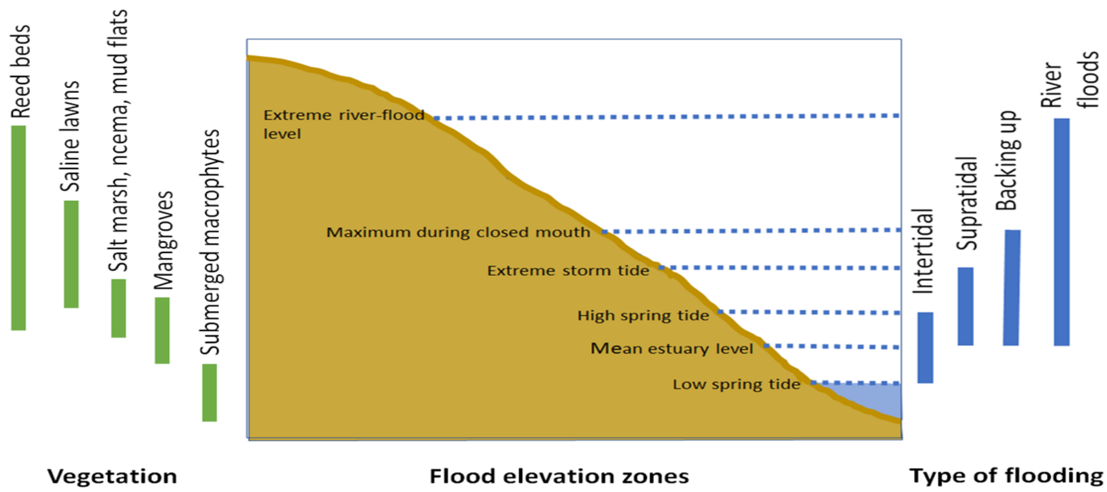


Figure 7-2: Schematic depiction of the extreme water levels associated with the different types of flooding of the floodplain. In addition to the flooding depicted, there can be perennial or seasonally waterlogged sites where groundwater seepage enters the floodplain. The source of this water is beyond the boundary of the floodplain.

In addition to the above types of floodplain, estuarine managers do recognise an Estuarine Functional Zone (EFZ). This is the area contiguous with an estuary which has an influence on the functioning of the estuary (DWA, 2010; van Niekerk *et al.*, 2013). As a default this is defined as the area below the 5 m AMSL contour. However, where there is scientific evidence to do so, this boundary is modified to include a larger or smaller area. This then becomes a legally defined area in which specified activities are not permitted. (NEMA). This has become a legislative/ administrative classification rather than an ecological one and therefore is not used in this study.

7.2.3 Characteristics and effects of different types of flooding

7.2.3.1 Marine tides

The intertidal zone is the area of the estuary that is affected by normal sea tides during open-mouth conditions

In the sea in this region, sea tides have a normal range at spring tides of a little over 2 m. As this tide enters the estuary, so its range reduces to about 1 m at the Mouth when the mouth is fully open and then is reduced until it is small, but still measurable at the Confluence. As the mouth constricts, so the mean water level in the estuary rises and the tidal range gets less (see Figure 3-14B). There is also a fluctuation of mean water level in the estuary between spring and neap tides (Figure 3-14B). This shows a rise in mean water level in the estuary during spring tides, which drops during the neap tide periods. It also shows a gradual rise in mean estuary water level over several consecutive spring-neap cycles as the mouth constricts. With this rise in mean water level, there would be less water exchanged each tide (i.e. a reduction in the tidal prism), the tidal signature diminishes and this may then lead to closure if there is no fluvial event to scour the mouth.

The physical habitat in this intertidal zone is characterised by the twice daily wetting. The water may be saline if the estuary is in a marine dominated state, or fresh water if in a fluvial state.

The predominant plants in this intertidal area are mangroves. Mlalazi has three species – *Avicennia marina, Bruguiera gymnorrhiza and Rhizophora mucronata*. The mangrove trees live in the upper part of the intertidal zone. This is taken to be within about -0.2 to +0.5 m AMSL (i.e. about from mean estuary level to upper spring tide). This is an approximation as there are variations in sea level, in mean estuary levels and the lower level of mangrove colonisation may be affected by the mouth-breaching regime.

Towards the Confluence the estuary banks are steep and the vegetation may be dominated by *Phragmites australis* and *Schoenoplectus scirpoideus* in places

7.2.3.2 Extreme marine tides and storm-surge flooding

The supratidal zone is that portion of the estuary floodplain that is inundated with seawater during normal extreme high tidal events when the mouth is open. This flooding occurs several times a year – usually during the equinox spring tides. The supratidal area is a harsh environment which may have hypersaline groundwater. Salt, brought to the surface by capillarity, precipitates on the surface to form a salt cap. The habitat may be bare mud flats. In places the succulent salt marsh plant *Sarcocornia natalensis* may grow. Sparsely interspersed in this area may be stunted *Bruguiera* trees. In slightly elevated sites there may be dense stands of *Juncus kraussii*. The upper boundary of this supratidal range is usually clearly marked as it is the interface between *Juncus kraussii* and *Stenotaphrum secundatum*.

When these high tides combine with storm-surges, flooding will also occur above the normal supratidal area. This usually occurs once every few years. For example, in March 2007 there was a combination of extreme high tides, a storm at sea and high winds. This raised water levels in the estuary to above the supratidal level (Smith *et al.*, 2007). Flooding with saline water killed the pioneer *Bridelia micrantha,* and other trees that were growing above the supratidal elevation mark.

These storm-surge events may build up over a few successive tidal cycles. They bring in sea water and may raise the water levels in the estuary for a few days. We have no data on the frequency of their occurrence.

The impact of this type of flooding is the salinization of soil and possibly the addition of saline water to the groundwater. The flooding at the time kills plants that have grown since the previous such flooding, and the after-effect is that the vegetation recovery is affected by the salt.

7.2.3.3 Backing up of water during a closed-mouth event.

When the mouth closes, it can remain closed for weeks, months or even years. Water levels can back up slowly or rapidly or can remain static at any particular level for long periods (depending on the catchment rainfall regime). We have not experienced anything other than the backing up of water for periods lasting a few weeks. After this the mouth has been breached artificially. So, understanding any conditions beyond this has to be speculation.

We do know that the salt trapped at closure will be diluted as water volume increases (Figure 6-5) and that the rate of water accumulation is dependent on inflows and losses. And we have a hypsometric curve that gives the relationship between water volume and the area of the water surface area in the floodplain (Figure 2-11). As the water level rises, so the groundwater will be recharged.

The maximum elevation of the water depends on the height of the beach berm. We have no measurements of the rate of accumulation of beach sand on the berm that separates the closed estuary from the sea, or of its height. Booysen (2017) has studied the elevations of the berm crest for estuaries around the country. The three KZN estuaries in his study do attain elevations of 3 to 4 m above MSL. We can assume that Mlalazi would be in this range (Figure 7-3).

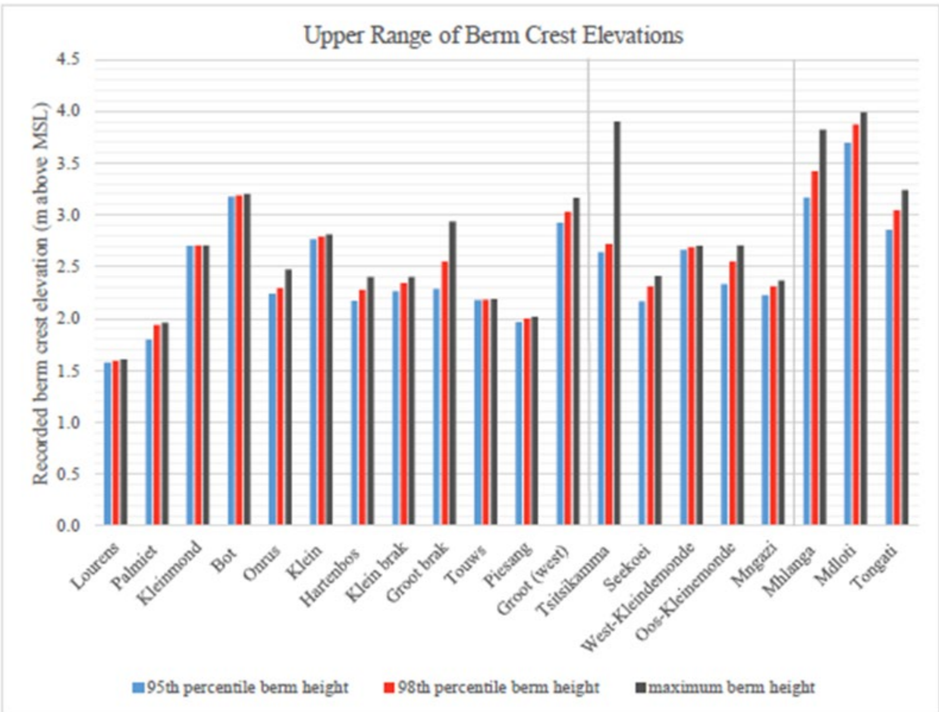


Figure 7-3: The upper ranges of recorded berm crest elevations of selected South African TOCEs (from: Booysen, 2017)

Most floodplain vegetation will die after a period of inundation. This is variable, depending on the resilience of individual species and the oxygen levels in the water.

The feature of backing-up flooding is that there are no high-energy flows while the floodplain basin is filling. However, breaching can result in rapid outflows and the draining of the basin over a period of a few days. A breaching event after the mouth has been closed for several months will leave the lower parts of the floodplain devoid of most terrestrial vegetation. The soils would be moist as the groundwater level lowers (which is likely to be over a period of weeks or months). At the initial stage after draining the floodplain would be colonised by pioneer plants.

7.2.3.4 River floods and areas affected by them

These are short-duration (usually 3 to 4 days) high-energy events. The flood water has no salinity and is highly turbid. Their main effects on the estuary are the rapid flushing of the estuary and the inundation of the floodplain. Inundation is for a few days only and does not cause extensive die-off of the vegetation. In places there may be flood flow channels, while elsewhere the flood inundates backwaters. In these latter areas there would be the settling of fine-particle sediments. Where there has been scouring or deposition, vacant habitat is left after the flood – which is colonised by pioneer plants.

7.2.3.5 Wetlands in the floodplain caused by freshwater seeps and streams

Groundwater fed wetlands, with freshwater that originates from beyond the floodplain are in the form of seepage zones, hygrophilous areas where the groundwater table is close to the surface, or as streams that cut across the floodplain. These support sedge-swamps and freshwater swamp forests.

The main streams cutting across the floodplain are those coming from the north (Port Durnford area) or from the south (from near the Mtunzini Forest Lodge). These both gain much of their water from the dunes to the west. Both are perennial, slow-flowing streams. The swamp forests supported tends to be above the area affected by back-flooding or marine storm-surge events. Within the flood plain the streams tend to support sedge-swamps or, in places *Barringtonia racemosa* swamps (which are resilient to low-salinity conditions)

Seepage also drains from the Zini Estates dune into the previously cultivated area adjacent to the Fish Farm. Here the herring-bone drains excavated to drain the lands are still evident. This land has highly disturbed hygrophilous grassland and reed beds.

7.2.4 Groundwater effects

In the areas where there is groundwater close to the surface the effects on vegetation of depths to groundwater and salinity of the groundwater were investigated. These are shown in Figures 7-4 and 7-5.

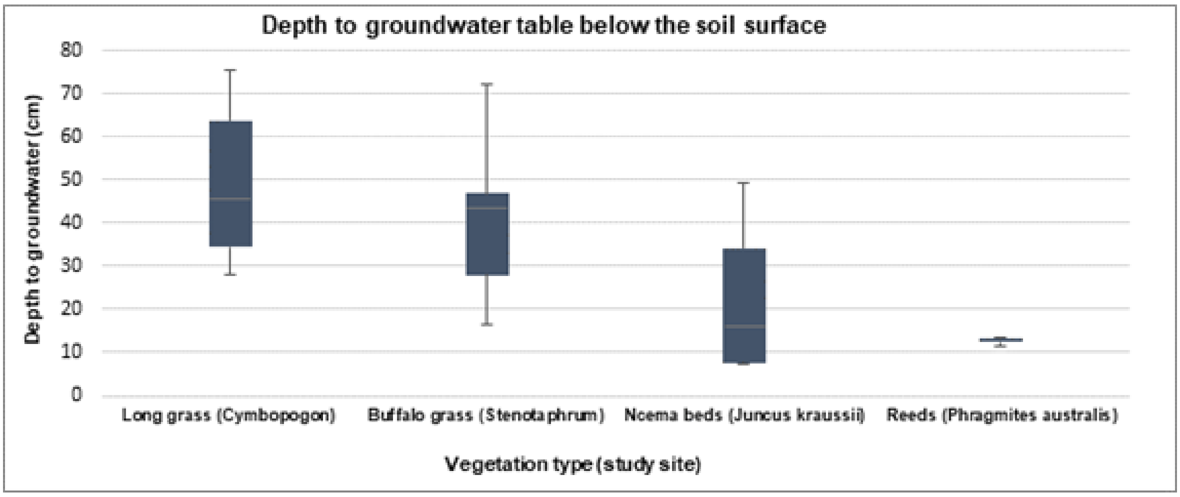


Figure 7-4: **Relationship between vegetation and depths to groundwater – (Hlabisa, 2017)**

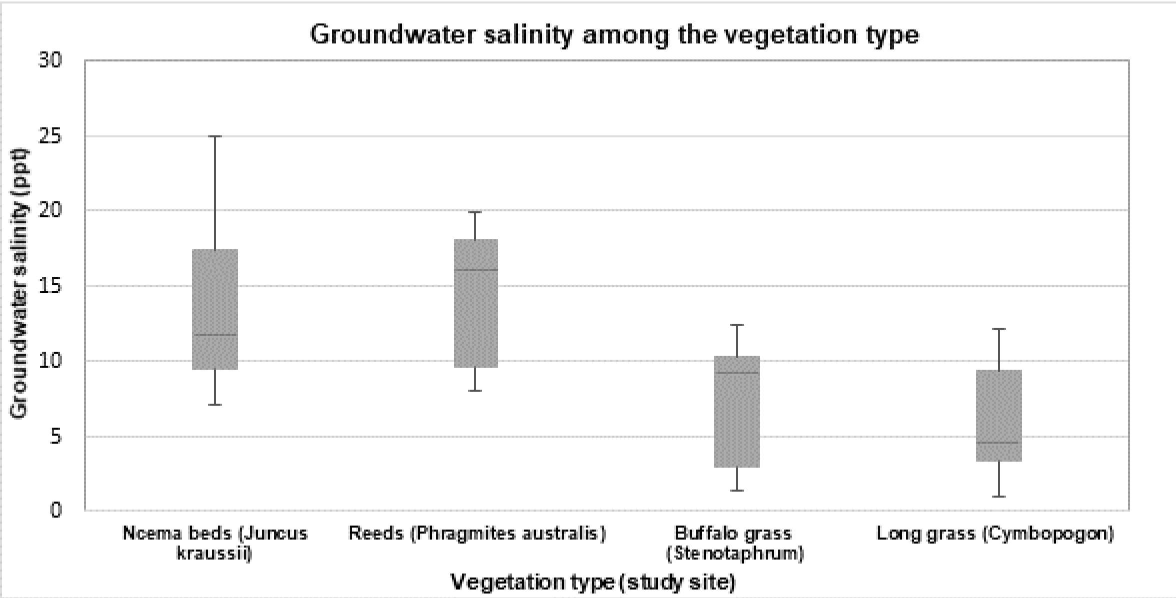


Figure 7-5: **Relationship between vegetation and groundwater salinity. (Hlabisa, 2017).**

The interpretation of this is that the *Juncus* and *Phragmites australis* are both able to grow in areas of high groundwater table – but the soil salinity defines the habitat for each. The *Juncus* is in the supratidal area which is flooded with salt water on occasions. The reeds are flooded with freshwater from seepages. The two types of grass (*Cymbopogon* and *Stenotaphrum*) occur above the supratidal elevation where the groundwater table is not as close to the surface. These effects are manifested by there being sharp boundaries between the *Juncus*, the *Phragmites* reeds and the two grasses.

Groundwater salinity in the study area was measured to giving the patterns shown in Figure 7-6. This shows the large difference between salinity in the supratidal areas and that of the floodplain area beyond that.

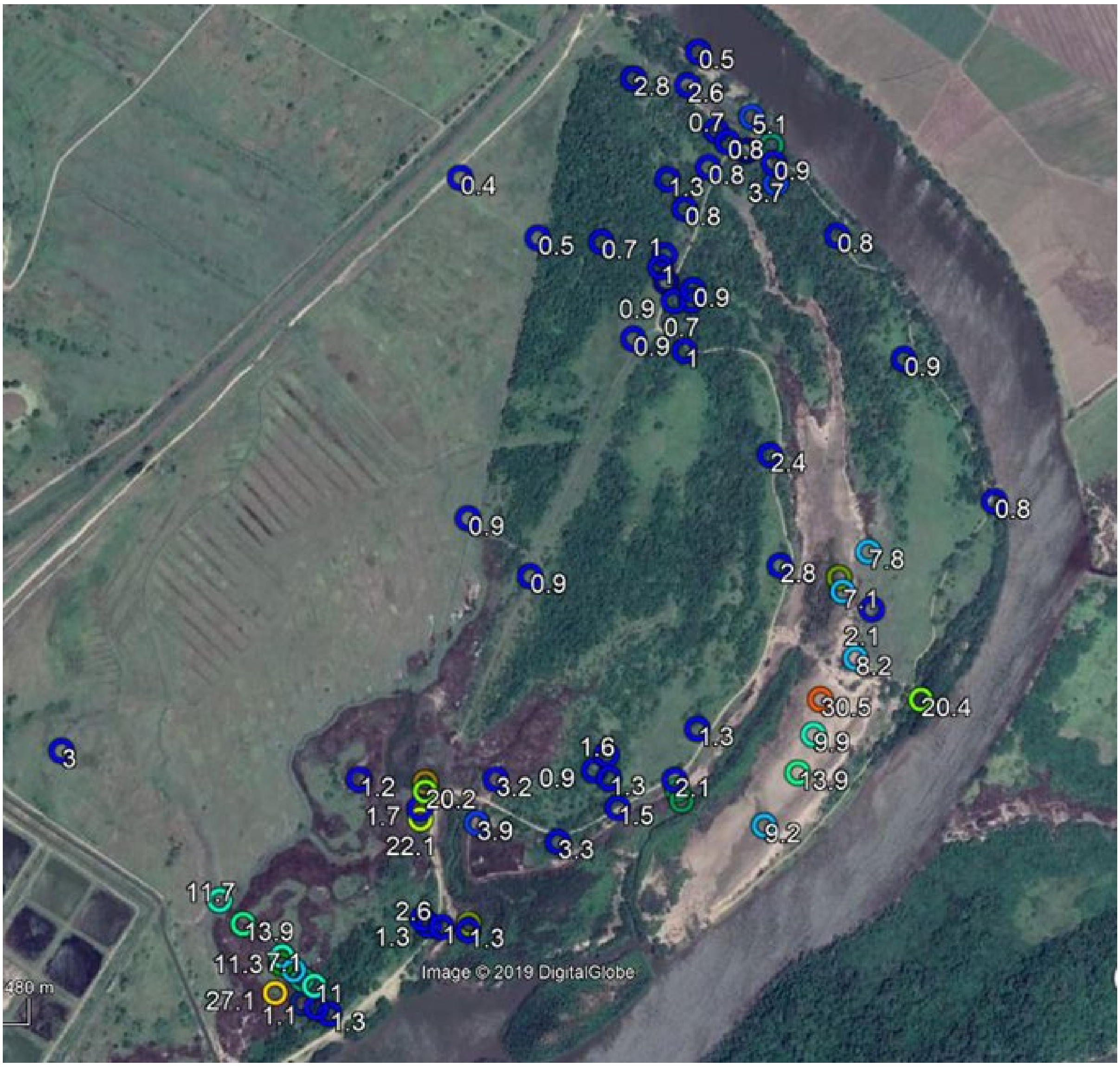


Figure 7-6: **Groundwater salinity. The number is salinity measured in ppt. The dark blue colour is fresh or minimally saline water. The raised salinity is in the supratidal areas**

In the saltmarsh flats groundwater was at its highest. In these sites, where the groundwater is close to the surface, salt capping occurs. These are the sites with succulent salt marsh (*Sarcocornia natalensis*) vegetation, or which are devoid of plants.

7.2.5 Geomorphological units

Several geomorphological units have been identified. These, shown in Figure 7-7 are:

Delta fan is the area where there is channel avulsion during river flooding. Sediments deposited here have created a slight elevation colonised by woody plants.

Intermediate 1 is the site recovering after having been cultivated for sugar. The 'herring-bone' drains still alter the hydrology of the area by preventing water accumulation.

Intermediate 2 is a site where the levee from the dredging in the 1960s has channelled flows during floods to form a flow pathway parallel to the main estuary. As water drops fine sediments are deposited here. The area is vegetated with a robust stoloniferous grass (tentatively identified as *Cyanodon nlemfuensis*, the alien 'star-grass' used by farmers to protect erosion areas).

Supratidal area is a low-lying saline area which is flooded by very high marine tides a few times each year. Evaporation has concentrated the salinity of the soil.

Intertidal drains. These are the channels in the mangroves which carry inflowing seawater during high tides, and carry the outflows of seepage and rainwater.

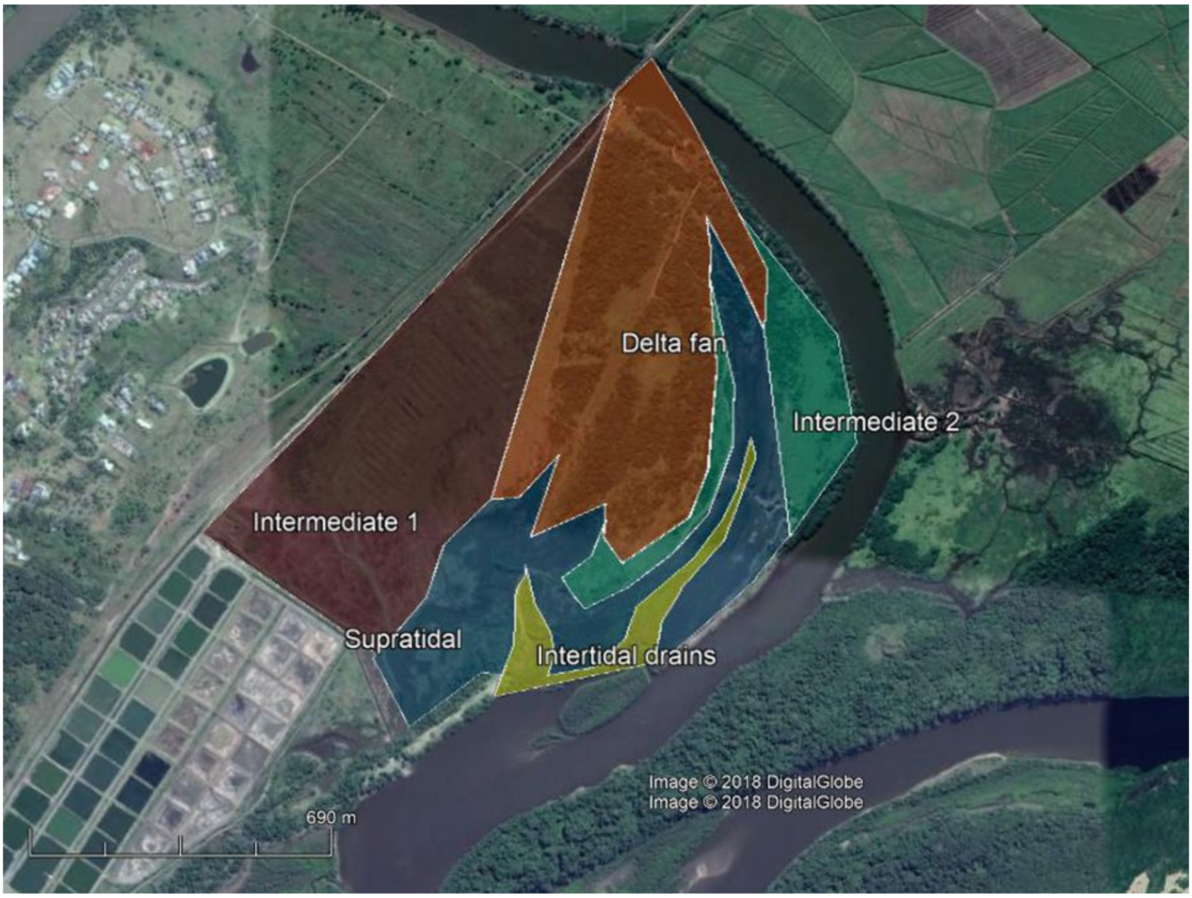


Figure 7-7: Geomorphological units – based on topography, geomorphological processes and resultant expression of the vegetation. (See description of the units in the text above).

7.2.6 Vegetation in the full floodplain

The vegetation of the floodplain has been mapped by Taylor (2015) (Figure 7-8). For the resolution required by of the mapping exercise, and due to complexity of the drivers and the small-scale patterns, one of the categories used is 'floodplain vegetation'. This is a catch-all category to include a variety of plant communities. No studies with further detail have been done in the full floodplain.

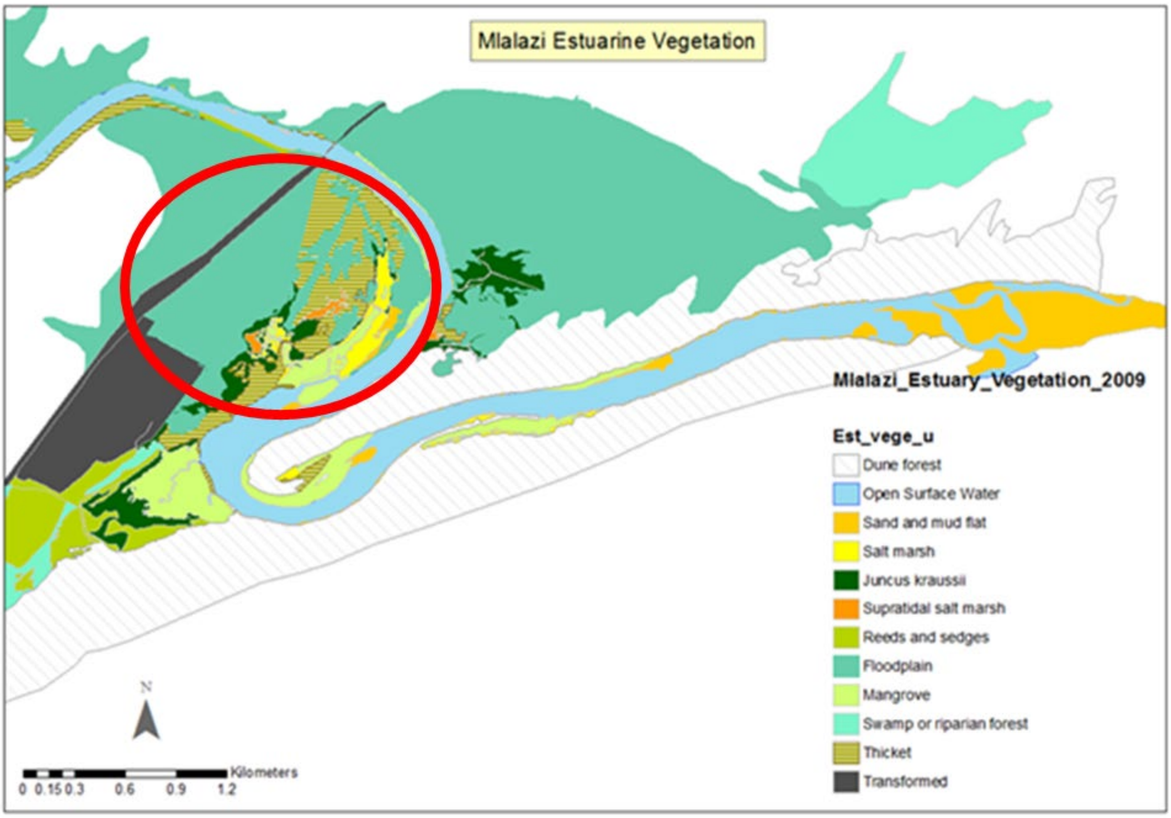


Figure 7-8: Present day vegetation of the Mlalazi Estuary and Floodplain, mapped from 2009 images (Taylor, 2015). The red circle demarcates the detailed study site.

7.2.7 Vegetation in the detailed study site

Detailed surveys were done in in a study site within the Mlalazi Nature Reserve downstream of the Railway Bridge (Figure 7-9).

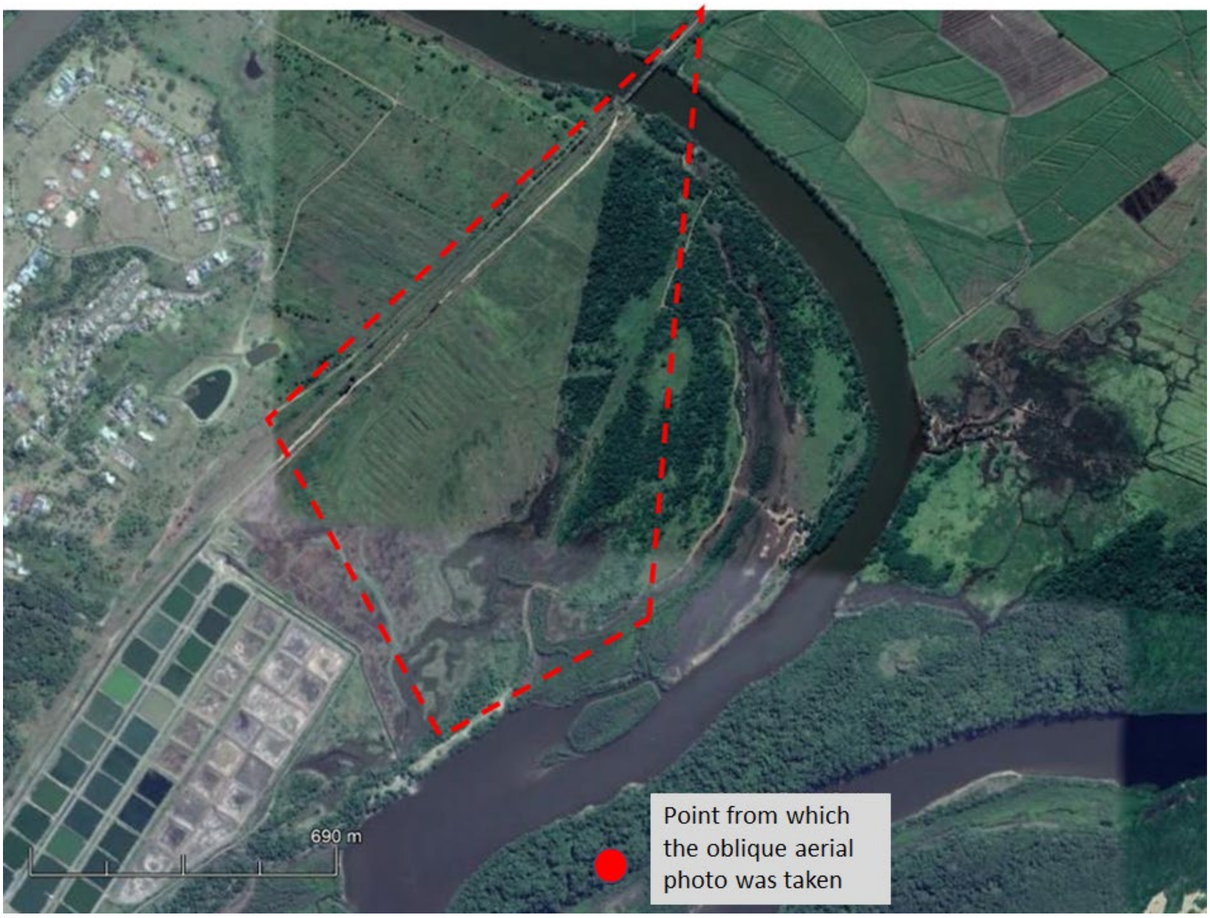


Figure 7-9: Detailed study area. The red dashed lines show the coverage of the oblique aerial photo shown in Figures 7-11 and 7-12. The locality of the detailed study site is shown in Figure 7-8.

Within the study site the vegetation was classified in habitat categories (Table 7-2). These vegetation types only partially reflect the flooding regimes of the different types of floods they are exposed to. There are a number of other variables that influence them. These include geomorphological setting in the landscape, elevation above sea level, distance from the margin of the estuary, distance from the mouth, exposure to salinity when being flooded, proximity of the groundwater to the surface, salinity of the groundwater, sediment grain size, presence of salt capping. What is most important in some of the vegetation types is the degree of human impact. It is also important to realise that the vegetation may be in different stages in succession pathways and may also be affected by competition with other vegetation as well as grazing by crabs or large herbivores. In an estuarine floodplain there are many permutations of a number of drivers. A key task of this study has been to simplify this – which is shown conceptually in Figure 7-10.

Table 7-2: The features and main species of the floodplain habitats recognised in the detailed study area.

Primary habitat	Secondary habitat	Features and main species
Riparian		
	Woody thicket	Slightly raised levee formed by river floods. *Apodytes dimidiata, Vachellia robusta, Rhus nebulosi, Scutia myrtina, Setaria megaphylla.*
	Saline grass	*Stenotaphrum secundatum, Sporobolus virginicus, Paspalum vaginatum, Cyanodon nlemfuensis*
Reed beds		
		Phragmites australis, Phragmites mauritianus
Old fields		
		Cyperus thunbergii, Phragmites australis
Supratidal Salt marsh		
	Ncema	Flooded by extreme marine tides. *Juncus kraussii*, *Acrostichum aureum*
	Bare mud flats	Flooded by extreme marine tides. Soil capping due to capillarity from saline groundwater
	Succulent salt marsh	Flooded by extreme marine tides. Soil capping due to capillarity from saline groundwater. *Sarcocornia natalensis*
Intertidal		
	Mangrove	Tidal inundation. *Rhizophora mucronata, Bruguiera gymnorrhiza, Avicennia marina*, *Triglochin striata*
Dry land		
	Dune formation	Palaeo-dune or wave margin. Trees typical of dune forest
	Dredger spoil	Deposited in the 1960s. Grasses that can withstand low salinity such as *Cynodon dactylon, Stenotaphrum secundatum*. Also, woody plants such as Hibiscus tileaceous.

Figure 7-10: Map of the vegetation categories in the sample study site. (See table 7-2 for the categories)

7.3 Towards a synthesis and conceptual model

The floodplain is a complex of primary and secondary habitat units. And to complicate it further the vegetation may be at different stages of recovery after being impacted by flood events and by human disturbances. Table 7-3 provides a summary of the flood zones and the main drivers and vegetation. From this a simple spatial conceptual model was developed. This shows the different intensities of the main controls: river floods coming in via the Railway Bridge form a flood delta, saline water entering the supratidal areas via the tidal channels from the estuary and groundwater seepage coming from the Eemian dunes to the west (Zini Estates). These controls overlap in a central low-salinity wetland. This is all depicted in Figure 7-11.

A conceptual model of the main drivers affecting the floodplain is shown in Figure 7-13.

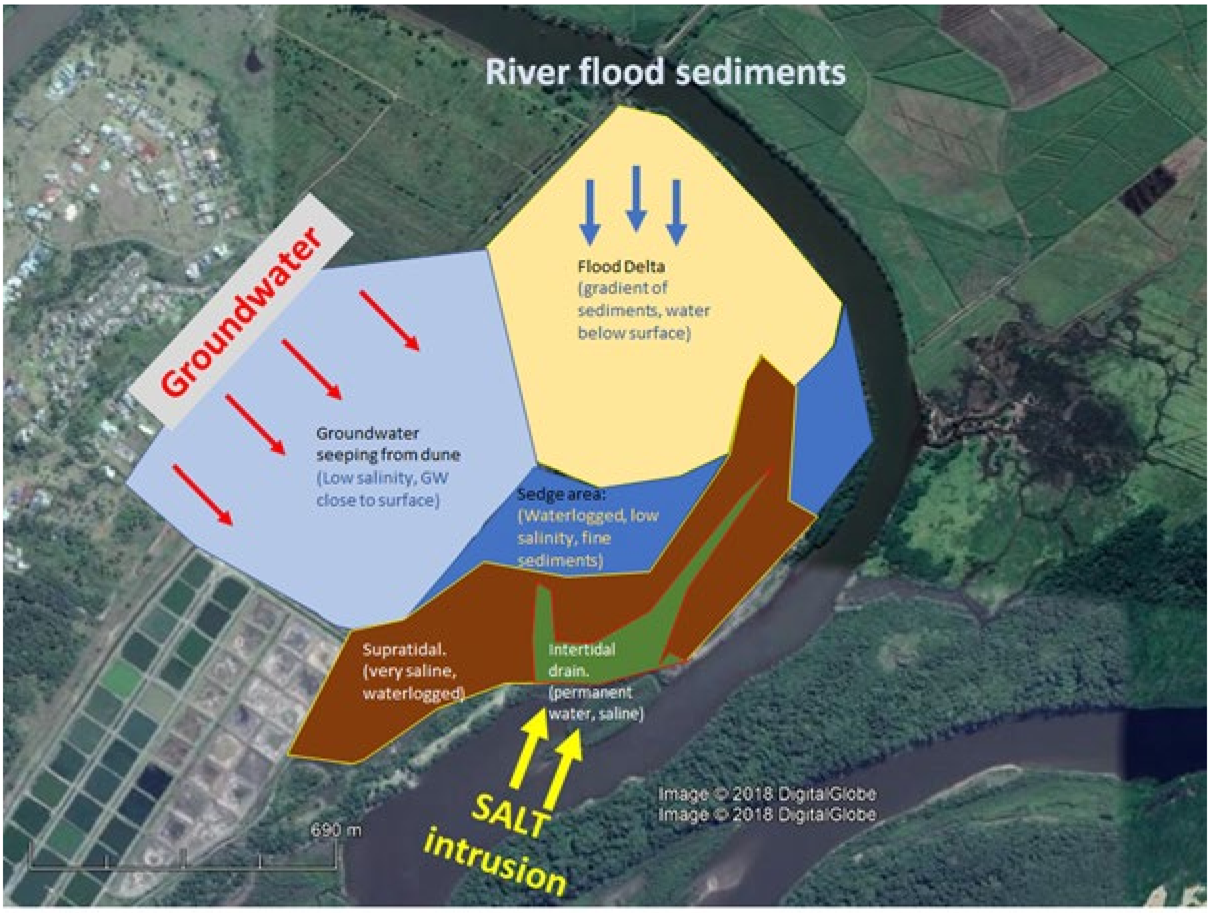


Figure 7-11: Conceptual model of the dominant drivers of the floodplain

Using the above information, the part of the detailed study area shown in an oblique photo (Figure 7-12) is classified into units that can be used for management purposes.

Figure 7-12 shows a representative portion of the floodplain characterised into a few simplified ecological units (Figure 7-13) based on our overall understanding.

Table 7-3: Summary of characteristics and features of the different flood zones

Type of flooding	Flood range (m)	Comment	Frequency	Inundation duration	Saline water	Energy	Geomorphology and sediment impacts	Sediments	Topography	Vegetation	Depth to groundwater
Normal marine tides	-0.5 to + 0.5	Progressive reduction away from mouth	Diurnal	Few hours	yes	Moderate	Tides and waves suspend fine sediments which settle where there is still water – such as in mangroves	Sand or mud deposits	Moderate slope, flattened in places where there are mangroves	Mangroves (3 species) *Triglochin*	Flooded during high tides, groundwater close to surface at low tides (affects crabs)
Supratidal (storm-surges)	Up to 1 m	Extreme tides plus storm surge Progressive reduction away from mouth	Random – but may have some seasonality	Few days	yes	Moderate to high	Inundate dry soils with saline water. This water evaporates creating salt flats and areas with very saline soils. In addition, capillarity brings groundwater to the surface when it is not too deep. This evaporates leaving a capping of precipitated salt	Mud accumulates	Relatively flat	Ncema, succulent salt marsh, *Acrostichum* fern Saline grass lawns	Flooded or within capillary range (usually within 20 cm of surface)
Back-flooding when the mouth closes	Up to 3-4 m	Level elevation – affected by winds (?)	Random – but more likely during a series of dry years	Months or years	yes	Very low, but there may be strong flows when the mouth breaches resulting in a rapid outflow of water.	This is a slow process not associated with strong flows or erosion. It may result in the settlement of fine particles – especially if there is growth of submerged or emergent macrophytes. Decaying vegetation may result in high biological oxygen demand	Mud deposition	Slope	Reeds, sedges Dependent on groundwater. Saline grass lawns Submerged macrophytes	Variable. May be influencing by groundwater fluxes from beyond the catchment
River floods	Almost up to 10 m (1987 flood, Badenhorst *et al.*, 1989)	Highest where channel narrow or where there is some constriction	Random	Few days	no	High at the peak of the flood	Associated with high flows and high sediment loads – as suspended sediments as well as high bed-loads of coarse sand	Variable – sand where there are deposits related channel avulsion. Fines in backwaters or where riparian lawns settle silt and clay	Flat to gentle slope. May be scour channels	Riparian lawn grasses. Riparian trees and shrubs	Beyond the range of roots most of the time – but recharges to be at the surface during or after a flood

Type of flooding	Flood range (m)	Comment	Frequency	Inundation duration	Saline water	Energy	Geomorphology and sediment impacts	Sediments	Topography	Vegetation	Depth to groundwater
Freshwater streams and seeps from beyond the floodplain boundary	Perennial seepage from groundwater discharge or low stream flows.	Little estuarine influence – but transects the floodplain May act as a refuge between flood events	Perennial	Permanent	No	Very low	May be small-scale scouring by the stream. May accumulate organics.	Highly organic (peat)	On slope or at toe of slope – where groundwater emerges	Swamp forest or sedge swamp	Fully saturated soils – all the time

Figure 7-12: A photograph of the part of the floodplain shown in Figure 7-12.

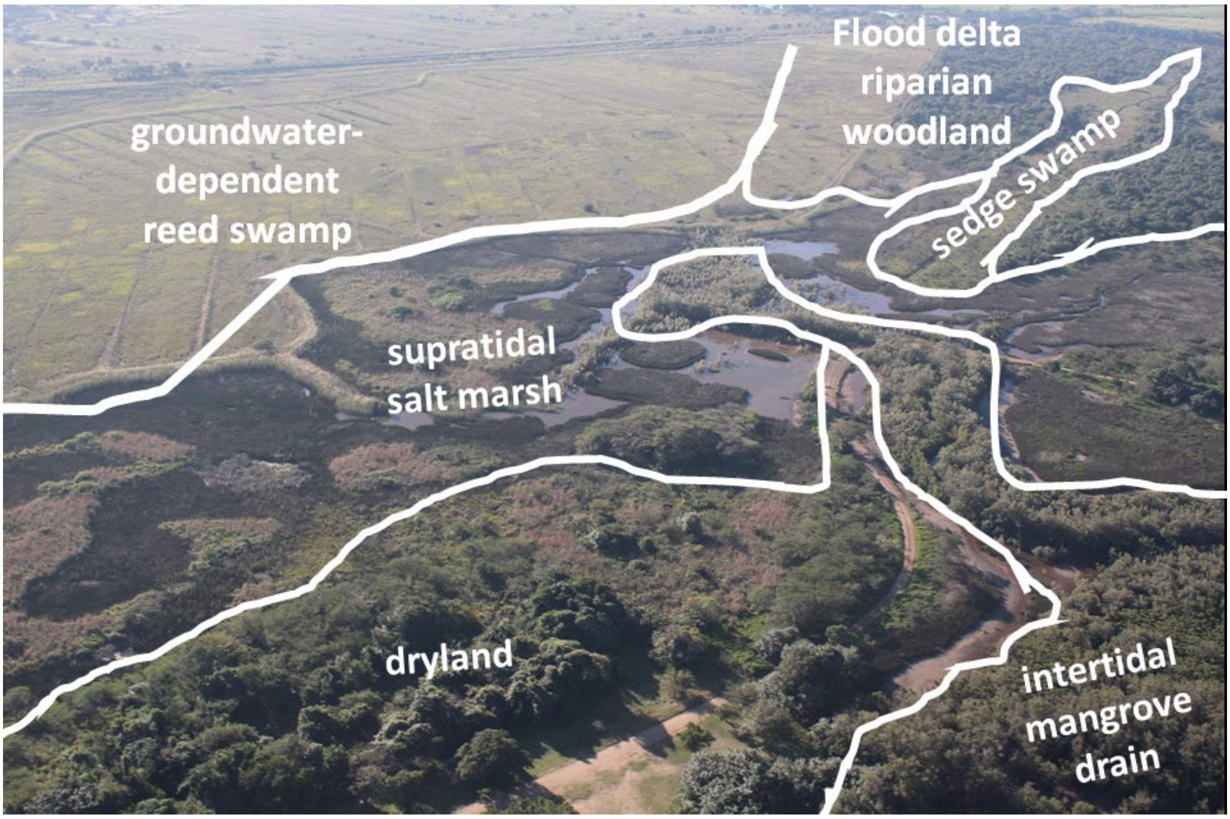


Figure 7-13: The classification of the floodplain ecological units

7.4 Discussion

At any point in the floodplain the overall probability of being flooded is the cumulative probability of being flooded by each type of flood event. However, it is not just probability of flooding that is important – it also is the duration of being flooded and whether the water is saline or not. The time needed for recovery between flood events will determine how far the vegetation is along a succession initiated after flood waters recede.

Most times, the flooding is a short duration event. In the estuary its ecological impact on submerged biota is mainly in the form of flushing out the system. It is only during the long-duration back-flooding that a submerged plant community will develop within the floodplain – as described in Section 6.

Inundation with saline water leads to salinization of soils. This is one of the key differences between an estuary floodplain and a river floodplain. Where the groundwater is close to the surface capillarity will raise the water to the surface (especially so in fine-grained sediments). If the water is saline, then as the water evaporates it leaves a capping of salt on the surface of the soil. This affects plant germination and growth.

Generally, the processes operating in an estuarine floodplain, and how they interact with each other, are poorly understood. There is much scope for further investigations.

8. STATISTICAL MODELS of MOUTH DYNAMICS

The dynamic processes and system responses in the Mlalazi Estuary are driven by many factors that operate through complex interactive processes that are not fully understood. Information on the different driving forces is sparse and limited for a comprehensive assessment. Consequently, the model approach in this project has been to identify the characteristic scales of the main driving forces and their controlling features and develop basic conceptual models that can direct the development of mathematical models of the main processes.

While physically based numerical model have been applied to derive specific information of some driving forces in estuaries, they have not provided details of the mouth and ecological systems required in this project. Consequently, this section presents the initial development of statistically based models of the estuary mouth.

Statistical models take on various forms that include but are not limited to time-series models, multivariate models and stochastic models. The choice depends on the purpose of the model application(s) and these can include:

- Descriptive & inferential understanding of the system, and
- Predictions of future conditions.

In the mouth dynamic model, the main purpose is to establish descriptive and inferential knowledge of the driving forces that affect the mouth conditions that lead to the closure and breaching under natural conditions. No attempt to develop extended forecast of conditions under mouth closure have been attempted as these inevitably depend on anthropogenic forces.

8.1 Conceptual Model of the Mouth Dynamics

The analysis of the estuary and mouth conditions presented in the preceding sections indicate that the mouth hydraulic properties are highly dynamic and have a direct influence on the estuary response to both fluvial and marine interactions.

The marine state is considered to be stationary within the context of this study and represents a regular cyclic tidal influence on the estuary through the controlling hydraulic features of the mouth. Consequently, the estuary tidal response is an indicator of the hydraulic controls of the mouth and can be used as a surrogate indicator of the changing hydraulic conditions of the mouth.

The fluvial state is considered to be a highly dynamic and stochastic system that promotes scouring and deposition within the estuary that further influence the hydraulic conditions of the mouth.

Both these systems represent opposing processes that have different characteristics temporal scales. The fluvial state represents extended periods of drought with no inflow to extreme events that can create a wave in the estuary of over 9 m that is nearly an order of magnitude greater than the tidal range of 0-2 m. The extreme of both these conditions (drought and floods) have low probabilities of occurrence) and require extreme value probability distribution for their simulations.

While there are perceived to be other controlling forces/factors that play a significant role in the mouth dynamics, the analysis presented above indicate that the two main driving processes are the random fluvial processes and the regular tidal interaction within the estuary. These may be influenced under certain conditions by extreme weather conditions when the mouth has reached critical states.

For the purpose of this study; namely to develop a probabilistic model of the mouth state for inferential purposes, the basic fluvial and marine states have been used as the basis of the conceptual model. To apply this simplistic conceptual model to a predictive process using stochastic principles the following investigative mathematical models have been considered for application:

- Acyclic Bayesian Network (ABN), provide a snap shot of a system at any given time,
- Dynamic Bayesian Network (DBN), extended network capable of modelling influences of an underlying process that is stationary over time.
- Spreadsheet programs.

8.2 NUMERICAL MODELS

There are several software packages that enable the development of Numerical Models. Three packages have been investigated in this project, namely

- Netica by Norsys Software Corporation.
- GeNie (Graphical Network Interface for SMILE), BayesFusion, LLC (Univ of Pittsburgh)
- Spreadsheets (Calc in Open Office).

8.2.1 Graphical Models

Common Bayesian networks use directed graphs to represent factorisation of joint probability distributions. For example, the Probability of the mouth closure Pr[C] that is conditional on the Probabilities of fluvial events Pr[F], tidal range Pr[T] and wind conditions P[W] can be expressed as
Pr[C,F,T,W] = Pr (M|F,T,W) Pr(F|T,W] Pr(T|W Pr(W). These joint probabilities Pr() can be represented by graphical model of the form shown in Figure 8-1. Each factor (variable) is linked in the graphical representation by arrows to dependent factor through the joint or conditional probability distribution. Factors without a link are assumed to be independent (P[F|T]=0). This simplistic model could be expanded to include seasonality that would include joint probability functions with fluvial and weather events.

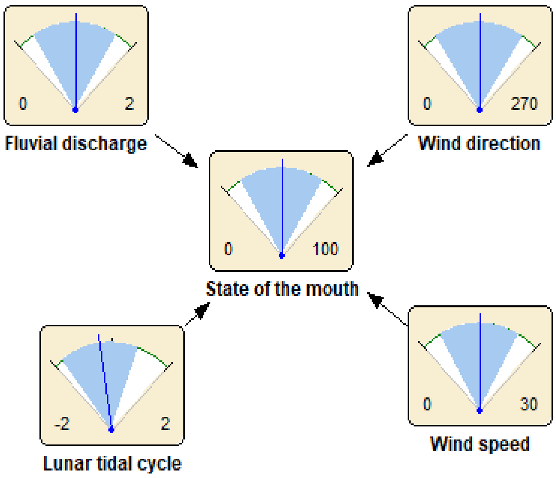


Figure 8-1: Simplistic graphical representation (using Netica) of joint probabilistic model of the main conceptualised factors controlling the mouth state. Arrows indicate the joint probabilities.

8.2.2 NETICA

Netica 6, developed by Norsys Software Corp was purchased by the University of Zululand for Windows 10 operating system and has been examined as a suitable program for this project. This software enables the development of both Acyclic (Figure 8-1) and Dynamic Bayesian Network (Figure 8-2) models. Since the changing mouth conditions are transient and highly dynamic, a model of the state of the mouth at any one instant in time must incorporate the prior changing conditions that lead to the current state. Consequently, the Dynamic Bayesian Network (DBN) is considered to be more relevant for the development of the mouth state than the Acyclic Bayesian Network in the current study.

An illustration of the creation of a simplistic transient model of the mouth elevation in Netica is shown in Figure 8-2 based on the conditional probability of the tidal range. The development of the model over extended time periods with additional probabilistic components required excessive parameterisation and other alternatives were examined due to the lack of sufficient information on the joint probabilities.

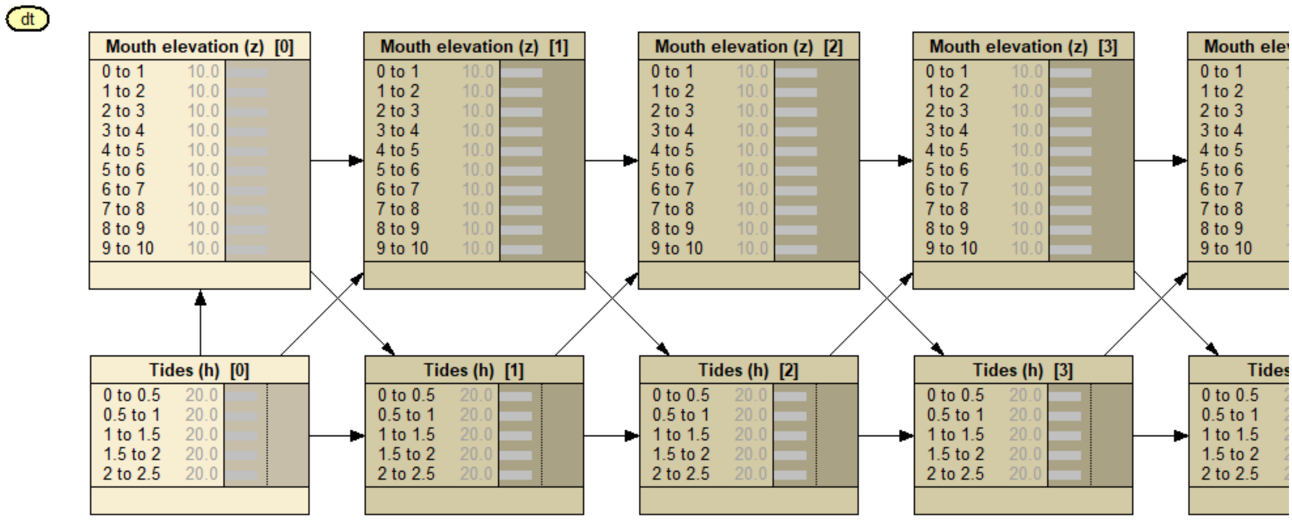


Figure 8-2: **A simplistic model of the changing mouth conditions in incremental time steps in Netica.**

8.2.3 GeNIe by BayesFusion, LLC

GeNIe is a development environment for building graphical decision-theoretical models. The models described in this section were created using the GeNIe Modeler that is available free of charge for academic research and teaching use from BayesFusion, LLC, http://www.bayesfusion.com/. The core of the GeNIe implementation is based on the SMILE reasoning engine for graphical probabilistic models, available free of charge for academic research and teaching use that is also available from BayesFusion, LLC, http://www.bayesfusion.com/.

Influence diagrams are used to show the structure of the system and contain several types of nodes (Decision, Chance, Deterministic and Utility) and the interlinking influence arcs. GeNIe also has a number of variants of these nodes that include two types of Utility nodes;

- Multi Attribute Utility (MAU) that
- Additive Linear Utility (ALU) that,

and two types of chance nodes;

- Chance-MopiyMax , and
- Chance NoisyAdder that both allow specification of deterministic functions and operators but does not include probabilistic functions.
- Equation nodes that are a bridge between Bayesian network and system of simultaneous structural equations

- While the DBN enables nodes to represent random variable there is no Random Number Generator to facilitate the interaction between stochastic events on a temporal series in the Temporal Plate.

Since the conceptual model identified the main controlling factors as cyclic tidal action and stochastic fluvial conditions, only the dynamic model was considered in this study. Considering the temporal characteristics of the mouth dynamics and model constraints, the initial modelling process was confined to 12 hourly time steps operating over at least one 14-day cycle (28 time steps) although this could be increased if the computer constraints were permitting.

DBN in GeNIe enables variable cyclic factors to be linked through joint probability distributions as illustrated in Figure 8-3. All nodes outside the Temporal Plate are static and modelled as acyclic components. Because of the cyclic process involving conditional joint probabilities, there is a danger of extremely large joint probability tables as multiple factors are linked. It is necessary to carefully manage the linkages with the available information and within computer constraints.

The initial attempt to model the mouth using a deterministic node was configured with the three linked nodes shown in Figure 8-3. The deterministic temporal node representing the change in the elevation of the mouth every second step was simulated over 28 cycles with the initial conditions drawn from the tidal range and storm probability distributions represented by the graphs in Figure 8-3. The progressive reduction in the tidal range should have culminated in the "Mouth State" closing after 10 steps. However, this model does not include the random sequence of storm events, only the initial state.

Unfortunately, the attempt to get the random storm event to operate in the temporal plate (Figure 8-4) was not successful and the initial storm conditions would not have affected the transient model any further. While this model has considerable potential, it was considered more pragmatic for this project to pursue the spreadsheet model described in the next section.

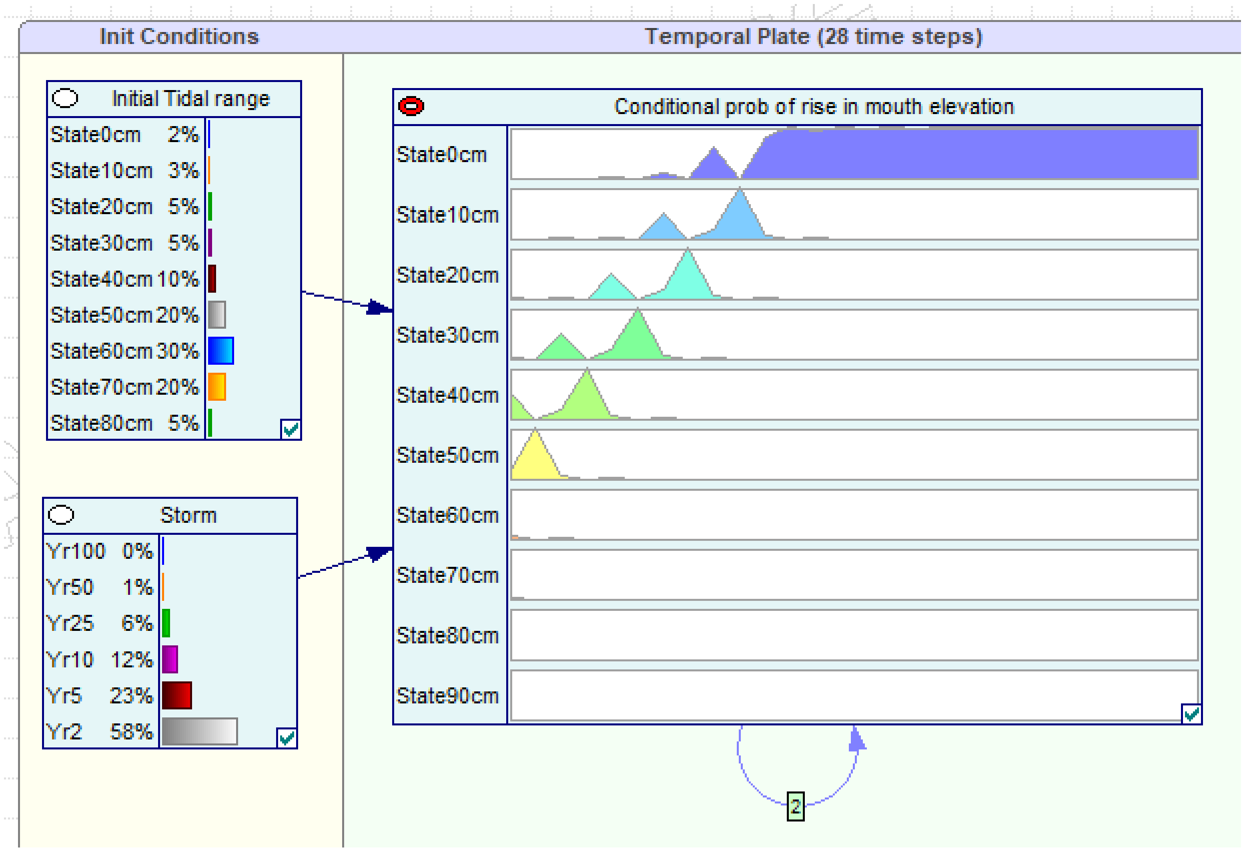


Figure 8-3: **The model configuration in GeNIe for the state of the mouth during the 28 step sequence starting with initial conditions of tidal range and storm event.**

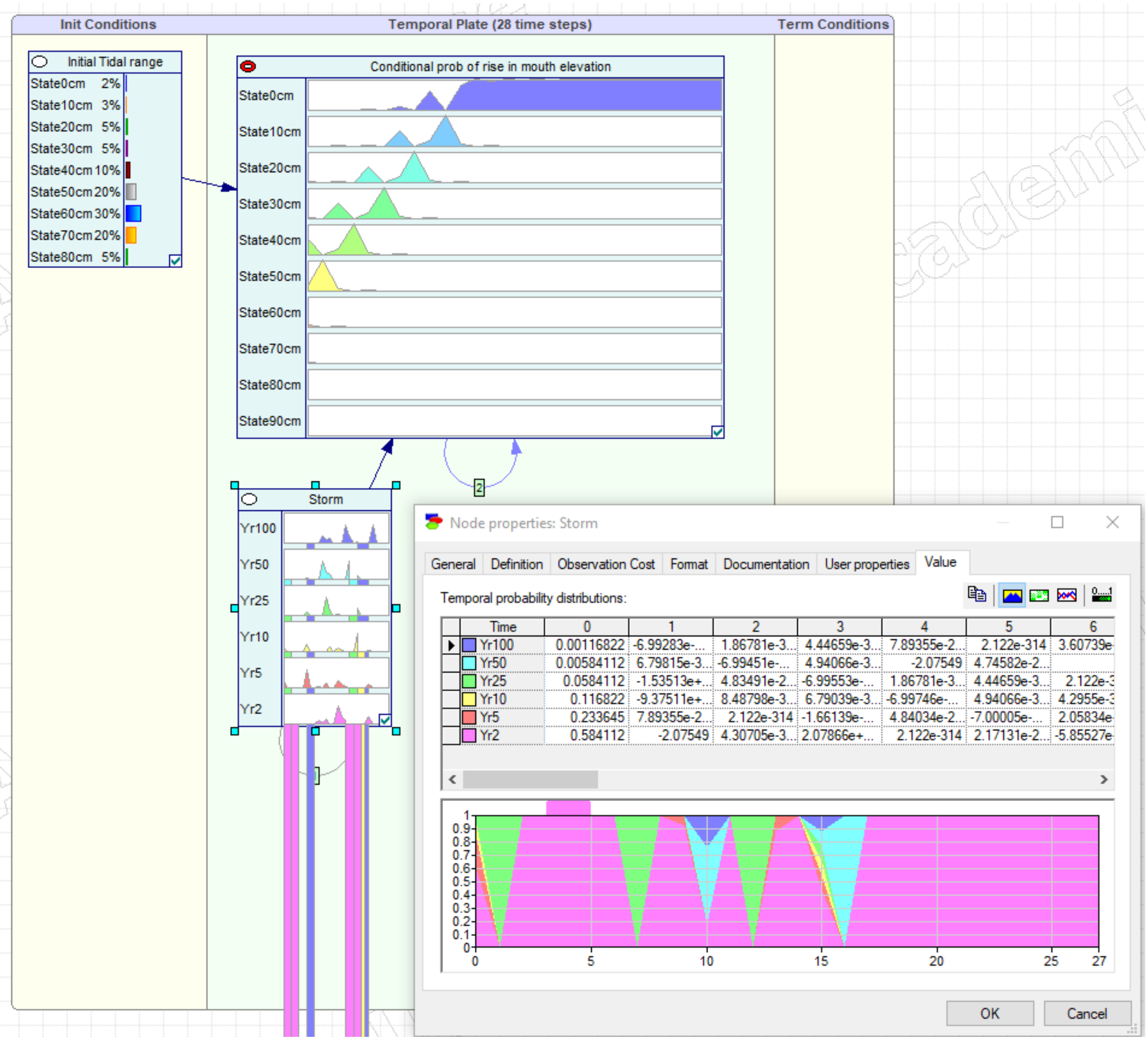


Figure 8-4: **The DBN in GeNIe showing the attempt to include a stochastic storm sequence linked to the mouth state. Also shown is the conditional probability table for the time steps in the storm node.**

8.2.4 SPREADSHEET MODEL

The open source Office suite of programs with the Calc spreadsheet were used to investigate the use of spreadsheets to develop probabilistic models of the dynamic processes driving the mouth and ecological processes that affect the desired states.

In the analysis above it was established that there was a reasonable correlation between the low tide and high tide in the estuary.

The extreme storm events in the estuary catchment and the drought periods have been shown to have a significant impact on the mouth state. These are assumed to be stochastic events that can be described by a simple statistical model. For the purpose of this study, it is assumed that a Log Normal probability model represents the magnitude of a storm event and that these occur as random events. The storm events are assumed to have a duration of 1 day but can induce a response over two three-four tidal cycles.

The marine tide is simulated as two cyclic components with a 12-hour and 14-day periods. The basic estuary tidal component is derived directly from the marine tides assuming the following conditions that have been derived from the analysis in earlier Sections.

- Wave attenuation through the estuary mouth,
- Minimum tidal elevation related to the mouth state and estuary storage, and
- Wave lag of 1 hour,

The current model is insensitive to the lag.

The regular tidal motion in the estuary that is interrupted by the storm events, is represented as a summation of the two events.

The tidal motion is also affected by the residual storage during flood and ebb tides that can induce a rise in the low tide conditions. The storage imbalance increases from zero at low neap tides to a maximum during high spring tides. This imbalance can accumulate of several cycles until the tidal range is reduced to zero and the mouth is closed to all tidal action or the mouth conditions change and the tidal interaction is increased. It is assumed that the storage has a strong cyclic component driven by the tides. However, the conditions that promote the accumulation of the storage imbalance are not well defined. It is assumed that any significant fluvial event will interrupt accumulated storage and low tide will revert back to a lower state limited by the mouth elevation.

The model was configured in the spreadsheet using hourly time steps for an arbitrary period. The assumed regular marine tidal cycle was attenuated to represent the estuary tidal motion above an arbitrary mouth elevation that remained constant for the simulation period. The regular cyclic motion was adjusted for an arbitrary storage between flood and ebb tides in the estuary assuming a direct correlation between low and high tides. The estuary tide with cumulative storage was further adjusted to allow storage accumulation between lunar cycles creating a trend on the low tide sequence as shown in Figure 8-5.

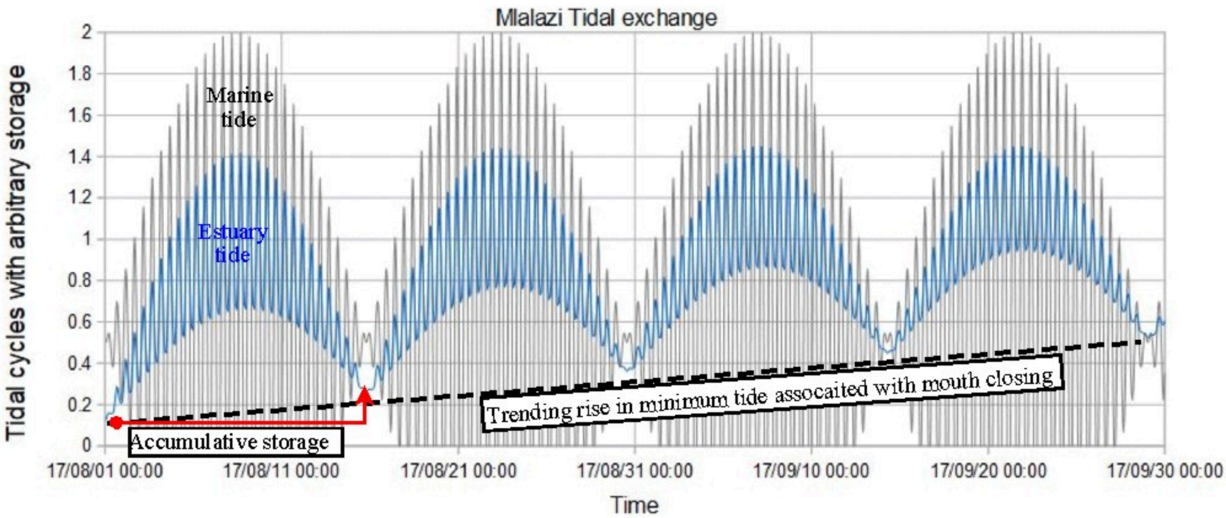


Figure 8-5: A model simulation of the marine tide (grey) and estuary tide (blue) assuming the indicated level of storage within the estuary between flood and ebb tides leading to the systematic reduction in the tidal range associated with the rising mouth elevation without fluvial interruptions.

The model results were compared to several examples of the measured tidal motion at the estuary mouth for several months in 2014. During this period there were several small fluvial events that interrupted the basic tidal pattern as illustrated in Figure 8-7 that were not incorporated into the initial model shown in Figure 8-5.

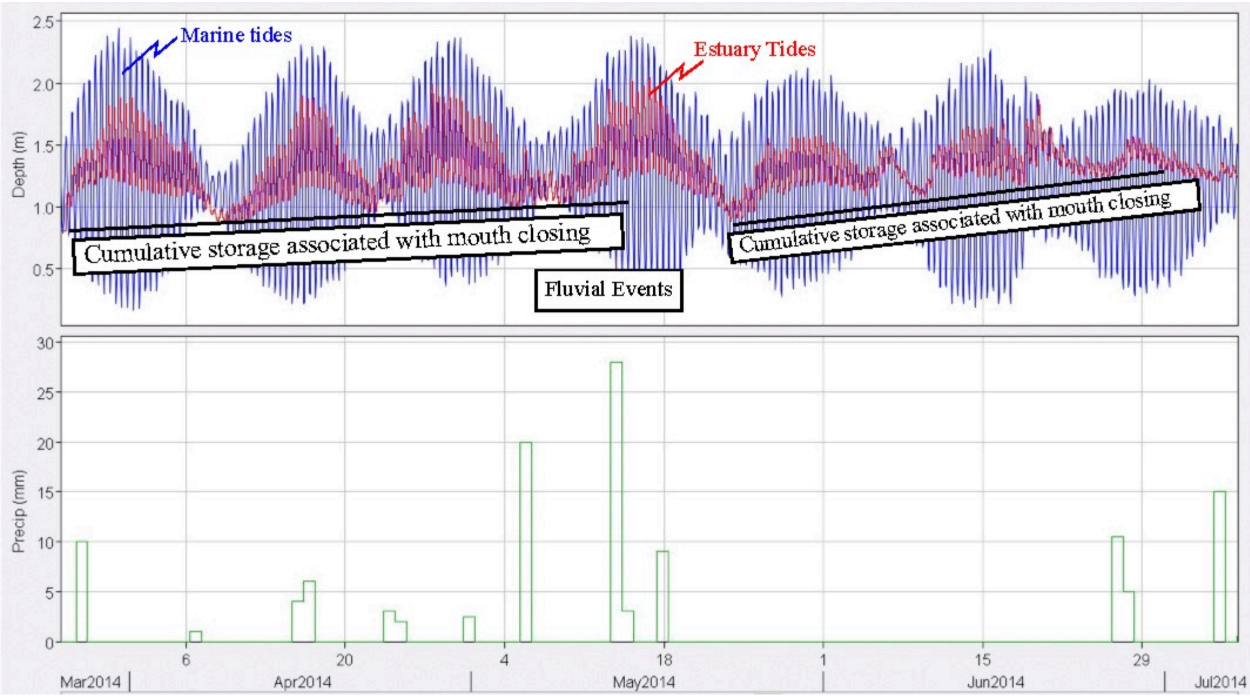


Figure 8-6: Observations of the marine (blue) and Estuary (red) tidal interaction during 2014 showing the trends in estuary storage resulting in rising levels of the minimum low tide that is assumed to be associated with the mouth elevation. The rising trend in storage (mouth elevation) is interrupted by fluvial events shown by the rainfall record in the lower graph.

The basic spreadsheet model (Figure 8-5) was modified to include stochastic fluvial events based on a simple exponential probability distribution. The fluvial event is assumed to raise the estuary high and low tides as shown in Figure 8-6. It is also assumed that the larger fluvial events may change the mouth through sediment scour causing a lowering of the minimum neap tides. The initial attempt to simulate these fluvial events in the spreadsheet model is shown in Figure 8-6. The fluvial events shown by the superimposed red graph causes a rise in the estuary tides that can influence the trend in the cumulative storage over several lunar cycles.

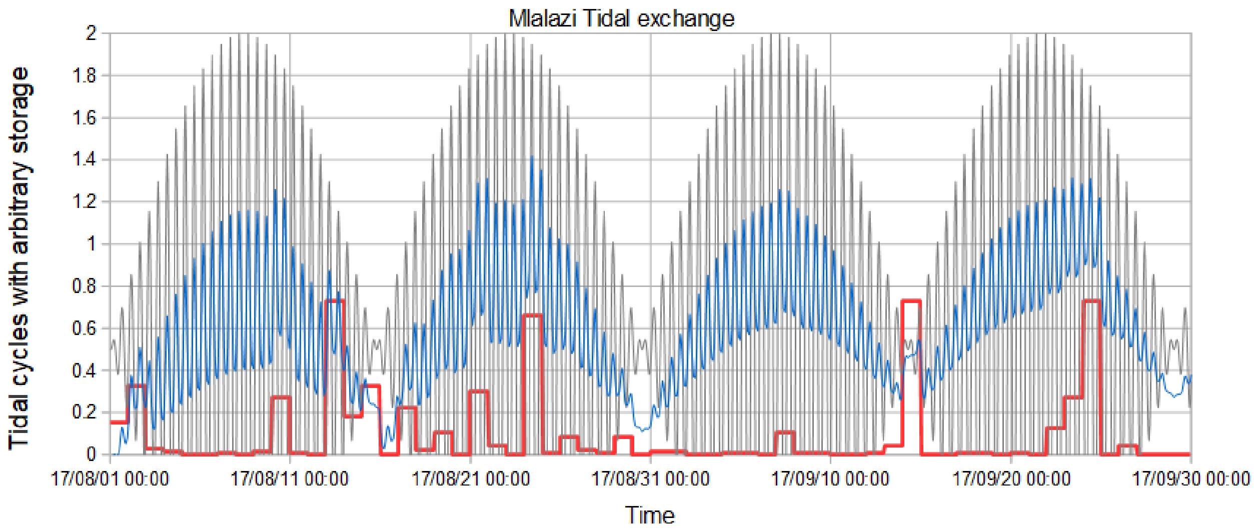


Figure 8-7: The simulated marine-estuary tidal interaction with random occurrences of fluvial events (Red graphs).

The basic spreadsheet model illustrates that the main controlling forces on the mouth state are both deterministic and stochastic that can be combined to derive a sequence of mouth closures using a simple spreadsheet model. Further development of the model is required to refine the stochastic model of rainfall and to include other potential controlling forces such as deterministic and stochastic marine conditions leading to the irregular marine tides shown in Figure 8-6.

9. SUMMARY AND CONCLUSION

The recent Water Reserve Determination study (DWS, 2015) highlighted the fact that little is known about the Mlalazi Estuary from an ecological and hydrological perspective. Although generations of students from the University of Zululand and University of KwaZulu-Natal have done field trips to the estuary and there have been many specialist studies (mainly zoological), there is relatively little published knowledge and information on the system to support a comprehensive study of the mouth state.

There are various temporal and spatial scales that affect the estuary. It is necessary to start with the understanding that, geologically, the current system is in a stage along an evolutionary trajectory. Over time it is progressing from a marine bay through various phases of an estuary which have less and less connectivity with the sea. It progressively becomes a system that closes at times. This is where it is at present. The long-term geological evolution will continue. This is not always in a steady linear manner (for instance this process could be temporarily reversed by sea level rise), but the end point may eventually be either a narrow channel to the sea set in a wide floodplain or else a coastal lake with no direct linkage with the sea.

At present, the Mlalazi Estuary is at the stage where it is connected with the sea most of the time – albeit in a constricted manner. However, it does close periodically, to the extent that water backs up behind the closed mouth, and then there is no biotic linkage with the sea.

The conceptual models of the estuary dynamics has involved the analysis of a limited period of water level monitoring data and satellite imagery. The main driving variables have been established through the development of a catchment model has been essential to derive the magnitude and frequency of flows and sediment movement into the estuary from a range of stochastic rainfall events that include several extreme cases. The temporal and spatial propagation of these stochastic events through the estuary is also being derived from numerical studies of the estuary dynamics. Further studies are required using emerging models to understand the interaction between the stochastic fluvial events and the marine tidal system.

Observational records indicate that Mlalazi estuary was closed to all marine tidal interaction on average every few years. Under these conditions, if the water rises above a specific level, the estuary is breached artificially to protect ecological systems and anthropogenic activities in the estuary and its floodplain. This unnatural process has constrained the scope of the study to artificial controls of the hydrodynamics.

The short period of water level monitoring in the estuary has established the period of the tidal wave propagation up the estuary, the extent of the attenuation and lag of the tidal interaction through the mouth and an estimate of the tidal prism that are important factors in the estuary response to the marine tides. The monitoring record also indicates that there is a significant difference in the flood and ebb tidal period in the estuary due to the different lag and head gradients across the mouth during the tidal cycles caused by the hydraulic nature of the mouth basin and channel. This creates a consequential difference in the velocity profile through the mouth that leads to the temporary water storage in the estuary, particularly during the rising spring tides. The difference in the velocity profile during flood and ebb tides can also induce different erosion and deposition patterns in the mouth over successive tidal cycles. This suggests that there is an influx of sediments under a higher flow velocity during the flood tide relative to a reduced sediment transport associated with the lower ebb tide velocities. This would result in a slow accumulation of sediment in the mouth basin that would eventually lead to the mouth closure. However, this progressive accumulation of sediment is interrupted by the stochastic fluvial events of varying magnitude that mobilise the mouth sediments leading to increased tidal interaction. The concurrent occurrence of storm events and marine spring tides is likely to have a bigger impact on the mobilisation of the mouth sediments and suppression of the mouth closure trajectory. Consequently, during extended drought periods when there are generally fewer storm events, there would be a tendency for the mouth to close more frequently.

The low tide elevation in the estuary must represent the elevation of the mouth sediments when there is no outflow of water from the estuary during periods of marine low tide. However, the temporary storage of water in the estuary between flood and ebb tides will maintain the estuary water level above the mouth elevation. Consequently, the low tide elevation during periods of temporary storage cannot be used as a surrogate indicator of the mouth elevation. Hence, the estuary low tide is a potential indicator of the mouth elevation when there is little or no storage in the estuary. Since the mouth elevation is the main indicator of the marine-estuary interaction and the state of the mouth closure, it would be the primary parameter in a model of the mouth state during neap tides.

The systematic increase in sediments and inferred consequential rise in mouth sill elevation process is altered if there is a fluvial event. Such stochastic events create the addition of river water into the estuary that will increase the head of water in the estuary and hence the velocity of outflow with the accompanying scour of the mouth sediments and subsequent increase in tidal interaction. The magnitude and frequency of these stochastic events will influence the regular estuary-marine interaction that will directly influence the frequency of the mouth closure.

While the discharge rates through the mouth can be established from the bathymetry of the estuary and the changing water level, it has not been possible to establish the magnitude of the flow velocities through the mouth due to the rapidly changing nature of the basin and channel. Attempts to measure the flood and ebb tidal flow velocity ranges were not successful. Since the hydraulic control can be related to the sand banks in the mouth basin or the open water channel through the beach berm, these would need to be mapped for future studies to enhance the knowledge of the mouth dynamics.

It is possible to gain an understanding of residence times of water within the estuary by having a better knowledge of salinity patterns.

The main variables needed to understand the estuary dynamics are water levels in the estuary channel and river inflows. These need to be monitored reliably and consistently at various time scales. To go forward it is necessary to have data relating to the regular changes as well as the events that impact on the estuary

For continuous monitoring of water elevations in the estuary (in order of importance) the following is needed:

1) A logger close to the mouth to give changes in water levels as seawater flows in and as there are outflows from the estuary. DWS have established a monitoring station within the mouth basin.
2) A logger in the upper reaches of the estuary will give information relating to river inflows and the maximum stage in the estuary.
3) A logger in the middle of the estuary will give information about tidal rise and fall within the estuary. If this logger also is connected to a salinity sensor it will give information about the tidal movements of the salt wedge. To be most effective this logger should be about ¼ of the way up the estuary – but the Railway Bridge site would be suitable.

Security is important for loggers.

The catchment runoff and sediment study highlighted the significant errors in both the flow monitoring record and the rainfall coverage for the catchment. Any improvement of the catchment runoff and sediment discharge would require improved rainfall coverage, flow and sediment monitoring.

An issue that needs resolution is what is meant by the terms ‘open’ or ‘closed’ when referring to the mouth. Hydrologically and ecologically there are differences in meaning. When considering hydraulics, a fully open mouth is one where the movements of water between the estuary and the sea are unimpeded. This would only occur when the estuary is in its geological state as a bay. From the hydraulics perspective the mouth is never fully open now as it never reaches the dimensions where there are unimpeded tidal flows. Ecologically, the mouth is open when there is free biological connectivity allowing the unimpeded movement of biota between the estuary and the sea.

The biota of the estuary are controlled to a very large degree by the long history of anthropogenic mouth breaching. It is this breaching that has enabled 40 ha of mangroves to establish, and also the periodic growth of *Zostera capensis*. The vegetation studies of the estuary have considered the present patterns of vegetation growth as well as possible plant responses to prolonged mouth closures.

The dynamics of the estuarine floodplain would be controlled to a large extent by the prolonged flooding associated with an extended mouth closure event. The key points relating to the estuarine and floodplain vegetation are:

1) The trajectory of the estuary is to evolve from a deep bay to a floodplain reed swamp or a coastal lake not linked with the sea.
2) The estuary, at present, is in the ecologically defined TOCE stage. It does close naturally.
3) Artificial breaching has been carried out every time the mouth has been closed for more than a few weeks at a time ever since the late 1800s. This has allowed the estuary to have characteristics more typical of a POE than TOCE. For instance, this has allowed 40 ha of mangroves to colonise the Mlalazi Estuary.
4) At present there are few submerged macrophytes – only small patches of *Zostera capensis* near the mouth when conditions are suitable for its growth. These conditions relate to an open mouth through which there is regular seawater influx. However, if the mouth closes and is <u>not</u> artificially breached, it could remain closed for several months or even years at a time. Should this occur, then the inundated floodplain could develop into an ecosystem similar to some of the nearby coastal systems – with low salinity and an abundance of submerged macrophytes.
5) The floodplain is subjected to different types of flooding:
    a. River floods – freshwater, short-term high-energy events.
    b. Backing up floods of long duration which may have some salinity.
    c. Storm-surge flooding of the estuary with sea water.
    d. Supratidal flooding due to extreme tides which occur only a few times each year.
    e. Intertidal flooding due to the normal twice-daily marine tides.
    f. Freshwater groundwater from beyond the boundary of the floodplain; manifested as small streams or seeps.

Each of these has its own characteristics such as duration of flooding, saline or fresh, water elevation, energy and frequency of occurrence. Each part of the floodplain is affected to a different degree by these types of flooding/inundation.

Artificial breaching of the mouth is the most important human intervention that affects the estuary.

Universally, the guiding principle for estuarine management should be to maintain or restore natural processes where possible. If this is applied to the Mlalazi Estuary, artificial breaching should not be permitted. But, without artificial breaching the Mlalazi Estuary mangroves would be exterminated. Associated with this would be the loss of all the species relying on mangrove habitat. Artificial breaching should be viewed in the context of the cumulative effect of all the anthropogenic impacts in the catchment as well as in the estuary that affect the system. The catchment area has been heavily impacted by agriculture and associated farm dams, by forestry, by high-density subsistence agriculture and associated land degradation, and by urban development. So, breaching alone will not restore the estuary to pristine conditions.

It can be argued that the current policy to breach the mouth artificially does maintain the mangroves which are an important asset. It is of benefit to society to continue with this intervention. A century of development of the mangroves will be destroyed by allowing a prolonged mouth closure. Any decision to cease artificial breaching in this case should not be taken lightly and not without full understanding of the consequences of the action.

Ecologically, the mouth can be classified as an open or closed system. However, the mouth is in a constant state of flux and, hydrologically, it cannot be classified as an open or closed system. Consequently, hydrological models of the mouth must incorporate the transient nature of the system with a variable level of tidal interaction. Attempts to develop statistical models of the hydraulic state of the mouth using Bayesian principles rejected all acyclic models and had limited success with the Dynamic Bayesian Network models. Spreadsheet models showed greater potential for statistical simulation of the mouth dynamics.

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