Genesis and hydrological function of an African mire: understanding the role of peatlands in providing ecosystem services in semi-arid climates

by

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AUTHOR’S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Piet-Louis Grundling
University of Waterloo
November 2014

STATEMENT OF CONTRIBUTIONS

Exceptions to sole authorship:

I hereby declare that I was responsible to write the proposal for this research project (WRC K5/1857: 2007-2012) and was the project leader/main investigator for the research project that formed the basis of this PhD thesis. The research project was funded by both the South African Water Research Commission and in kind contributions from the Council for Geoscience, Council for Scientific and Industrial Research, Department of Water Affairs Maccaferri (Pty) Ltd., the Stichting Ecological Restoration Advice, The Netherlands and University of Waterloo. Canada. Because of the multidisciplinary nature of the research, expert input was received for isotope and geochemical tracers from Prof A.P. Grootjans, and for the evapotranspiration measurements and calculations from Prof C.E. Everson and Mr. A. Clulow.

This thesis is written in manuscript format. Some minor editorial differences may exist between the published version and the version that appears in Chapter 2 of the thesis.

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I was the lead author on this paper and did the main work of conceptualizing, analysing, writing, submitting, editing and addressing comments from the reviewers. The co-authors contributed to the published manuscript: Prof. A.P. Grootjans helped with conceptual interpretations and peat classification; Prof. J.S. Price help with infield observations and acted as advisor, offering suggestions as well as editorial changes, and Prof. W.N. Ellery with geomorphological interpretation. C^{14} results utilised were from South African Council for Geoscience Research Report no: 2000-0132 (Grundling *et al*., 2000).

Chapter 3 to be submitted as:
Grundling, P., and Price, J.S. Hydrological function of a subtropical African mire: Contributing flow to adjacent and downstream ecosystems

I did the main work of conceptualizing, field site assessments and instrumentation, analysing, and writing; Prof. J.S. Price gave help and suggestions with the study site selection, instrumentation and editorial changes. Prof. A.P. Grootjans helped with the conceptual illustration. Most of the laboratory analyses were done by undergraduate students of the University of Zululand under the guidance of Prof B.E. Kelbe.

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I did the main work of conceptualizing, field site assessments and instrumentation, analysing, and writing; Prof. J.S. Price gave help and suggestions with the study site selection, instrumentation and editorial changes. Prof. A.P. Grootjans assisted with the geochemical and temperature analysis.

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I did the main work of conceptualizing, field site assessments and instrumentation, analysing, and writing; Mr A. Clulow did all the evapotranspiration related field work, analyses and writing. Prof. J.S. Price gave help and suggestions with the study site selection, instrumentation and editorial changes.

ABSTRACT

The effects of changes in climate or landscape on wetland ecosystems in drier regions need to be considered within the context of natural processes. Hydrological processes are a key component in the development and maintenance of wetlands. The source of water, for instance, can determine a wetland's vulnerability to a changing landscape and environment. To understand these integrated processes and functions, the genesis and hydrology of a large natural mire (1 462 ha), located in the subtropical eastern part of South Africa has been studied, with a focus on peat development, surface and groundwater exchanges and the water balance of the mire

Mfabeni Mire is a groundwater dependant ecosystem that was formed in the Late Pleistocene and continued to develop during the Holocene. The basal peat of the mire was dated at ca 44 000 cal years Before Present at a depth of 9.9 m. The average accumulation rate during the Late Pleistocene was 0.15 mm/year and during the Holocene it was higher at 0.3 mm/year. Despite climate change over this period, peat formation has hardly been interrupted, suggesting that the system has been able to almost continuously sustain peat formation processes. The infilling of a north-south paleo-valley with peat (11 m) resulted in a reduction in permeability for eastward-flowing groundwater, which forces a rise of the groundwater as peat accumulated. This set of circumstances created a consistent and permanent discharge of groundwater into the peatland, allowing for the uninterrupted formation of peat over an extended period. Wetlands with inputs from regional groundwater sources are buffered against climatic variability, and are therefore less vulnerable to changes in climate. Mfabeni Mire is an example of such a dynamic ecosystem that is presently adapting, as in the past, to a changing environment.

Wetlands are an integral part of the hydrological cycle and their position in the landscape determines their contribution in regulating flow to downstream ecosystems. The average rainfall for the Mfabeni peatland was determined over a period of 48 months and was 942 mm/year compared to the long term annual average of 1 364 mm/year (1961 to 1989) at the coast (Wejden, 2003). The stream outflow of Mfabeni responds rapidly to larger rainfall events (≥40mm) and low flow periods coincide with drier periods with a relatively low baseflow (360 m^3/day) sustained by groundwater inputs from the western inland dunes. The annual flow is more than 2 orders of magnitude less than the long term annual average rainfall indicating the importance of evapotranspiration and groundwater losses in the system.

Direct rainfall on the fen due to its relatively large size is important and together with groundwater inflows these water inputs maintain a high water level in the fen (80% of the time less than 0.4 m below surface), with the surface inundated 10 - 20 % of time. Groundwater efflux from the western inland dunes provides substantial recharge towards Mfabeni at the swamp forest on its western boundary, while coastward hydraulic gradients from the dune complex through the wetland are evident. At the swamp forest the discharging water has a similar δ^2H - $\delta^{18}O$ ratio than the groundwater from the western inland dunes. However, only a small portion of groundwater from the inland dunes is flowing through the mire towards the coast in the east. However, a more likely alternative is that rainwater (the dominating influx into the system) from the sedge fen recharge at the eastern margin of the fen to the eastern dunes. In these dunes the δ^2H - $\delta^{18}O$ line follows similar slopes (i.e. having an evaporation signature) to fen waters, suggesting that evaporatively enriched water from the fen enters the eastern dune at the margin. The major portion of groundwater from the inland dunes is forced to discharge southwards into Lake St. Lucia due to the plug effect of the lesser permeable peat in Mfabeni Mire as the hydraulic conductivity of the peat (10^{-4} to 10^{-5} cm/s) is more than an order of magnitude less than in the dunes (10^{-2} to 10^{-3} cm/s). The surface flow and subsurface flow along the surface gradient are more critical in keeping the peatland wet and maintaining its functions as the groundwater contribution through the peat are limited due to the very low hydraulic conductivity of the deeper more decomposed peat.

Based on its water balance, Mfabeni Mire is, primarily functioning as a control mechanism of the regional water table in order to maintain wetness of the accumulated peat within the mire. Groundwater inflow (at 14 mm [< 2%] of the yearly water balance) is therefore an important component, not only in developing, but also in maintaining peatland integrity by ensuring waterlogged and anaerobic conditions in drier periods. The groundwater outflow is an insignificant component (0.3 mm/year) compared to the other water balance components. The annual outflow through the Nkazana stream was 9 mm/year with storage accounting for 3 mm/year. Evapotranspiration losses from the system are the largest component of the Mfabeni Mire water balance (1053 mm/year) and have exceeded rainfall (1031 mm/year) during the period of monitoring by 22 mm (2.1% of the rainfall). The swamp forest evapotranspiration rates were higher than the sedge/reed fen contributing 34% of evapotranspiration whilst only covering 28% of Mfabeni Mire's surface.

In conclusion, the majority of the groundwater discharged into Mfabeni Mire was lost to evapotranspiration, and the Nkazana stream, although perennial, is characterised with persistently low flows during dry periods, providing a freshwater refugia for plant and animals at the inflow to Lake St. Lucia . However, the value of Mfabeni Mire is more likely in dampening climate turbations, thereby contributing to steadier groundwater conditions in a landscape where seasonal change and long-term drier periods are major ecological drivers. This creates also a more stable environment for adjacent ecosystems. Consequently peatlands in semi-arid climates should be recognised as an asset in natural resource management and their potential to support adjacent ecosystems should be protected through proper planning and conservation practices supported by appropriate research.

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For Renée and Amy

“*God saw all that he had made, and it was very good*”

Genesis: 1: 31

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1. INTRODUCTION

Wetlands are not only one of the most important ecosystem types in the world, providing various goods and services to both humans and the environment but are also of the most threatened with about 50% of the world's wetlands reported to be degraded or destroyed (Mitsch and Gosselink, 2000; Russi *et al*., 2013). Wetlands are maintained by hydrological processes and their position in the landscape determines their character and response to change (Mitsch and Gosselink, 2000, Lapen *et al.*, 2005). Of the world's wetlands, 50% are peatlands contributing greatly to biodiversity, regulating hydrological functions, and hosting a third of the earth's terrestrial carbon (Joosten and Clarke, 2002). Most peatlands occur in temperate climates where precipitation exceeds evapotranspiration; a significant proportion do occur in subtropical climates with a water deficit, with less than 5% of the world's peatlands occurring in Africa (Lappalainen, 1996).

Southern Africa is a semi-arid region with an average rainfall of 497 mm/year, which is well below the world average of 860 mm/year (DWAF, 1986) where wetlands are characterized by strong seasonal variations of water table and stream flow patterns reflecting the variability in precipitation and evapotranspiration. Wetlands in South Africa are therefore mostly seasonal and temporarily wet and comprise less than 15% of the land surface with only as much as 10% of those being peatlands (SANBI, 2006). The Maputaland Coastal Plain on the eastern seaboard, in the KwaZulu-Natal Province, South Africa hosts approximately 50% of the country's peatlands, including Mfabeni Mire, one of the largest (1 462 ha) and deepest (11 m) peatlands in South Africa. These peatlands are often groundwater dependant and land-cover change such as plantation activity and agricultural encroachment onto peatlands can alter water available to both terrestrial and aquatic ecosystems (Grundling, 2014). It is important to determine the nature and importance of surface-groundwater interactions in landscapes where rainfall is seasonal and there is high inter-annual variability as the dependency of these systems on groundwater leaves them vulnerable to catchment changes and groundwater exploitation. Inadequate knowledge of these processes and their linkages compromise our ability to make sound management decisions in the conservation of wetlands in semi-arid regions.

1.1 STUDY AREA

Mfabeni Mire is located on the Eastern Shores of Lake St. Lucia, an area between the Indian Ocean in the east and Lake St. Lucia to the west, within the catchment of the Mkuze River (Figure. 1.1). The region of the entire coastal plain in northern KwaZulu-Natal is known as Maputaland and has a subtropical climate with hot and humid summers and mild, drier winters where frost rarely occurs (Taylor, 1991). Sixty percent of the annual precipitation occurs in summer; the mean annual temperature is 21ºC with the mean maximum monthly temperature 35ºC for January and the mean minimum monthly temperature 5.5 ºC for June (Mucina and Rutherford, 2006).

The mean annual precipitation is 1 364 mm/year (1961 to 1989) at the coast and is 950 mm/year (1957 to 1989) at Charters Creek, 10 km inland (Wejden, 2003). However, rainfall records over the past 100 years indicate distinct cyclical drier and wetter episodes with a marked reduction (up to 50%) in annual precipitation for prolonged periods (Baker *et al.*, 2014).

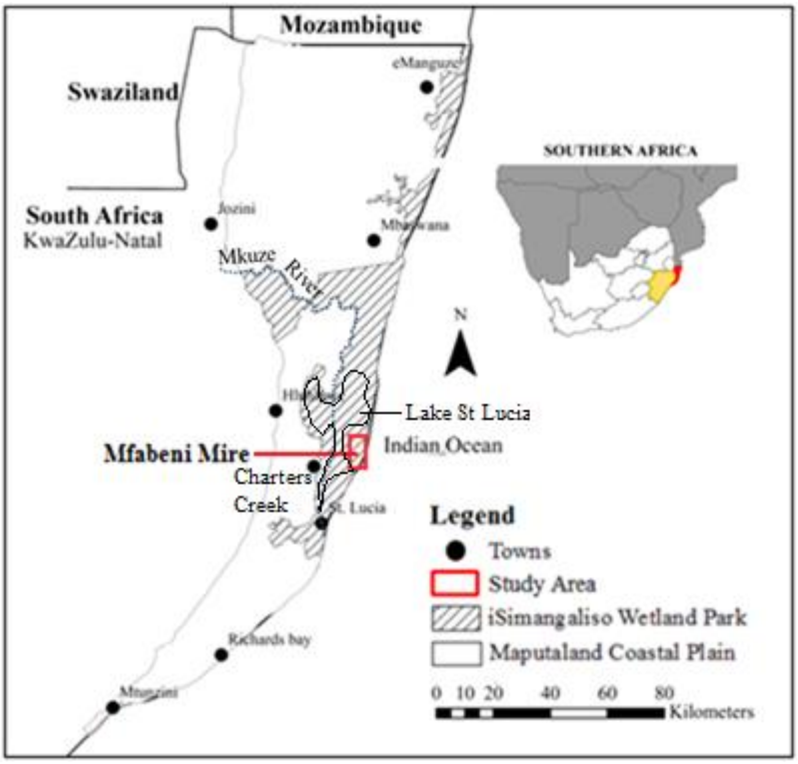

Figure 1.1: Location of the study area: Mfabeni Mire on the Maputaland Coastal Plain, KwaZulu-Natal Province, South Africa.

Wetlands, ranging from seasonally inundated depressions to permanently wet mires and swamp forests are common on the Eastern Shores (Figure 1.2), whilst coastal dune forest and wooded grassland dominate terrestrial areas (Grundling *et al*., 1998; Goge, 2003; Venter, 2003). The land-cover within the catchment comprises bare sand, wetland, grassland, thicket, dune forest and open water (Figure 1.2). Wetlands occurring in the central part of the catchment (excluding Lake Bangazi) form in total 57% of the landcover: Mfabeni Mire 44% (Nkazana swamp forest 12%, and the sedge fen 32%) and the smaller ephemeral systems 13%. The dune forest and most of the thicket occur across large parts of the eastern dune complex with the bare sand areas restricted to the western dunes (Figure 1.2). Grasslands, dominant on the western dune cover the remainder of the catchment.

The Eastern Shores comprises high coastal sand dunes and low-lying plains located on the Maputaland primary aquifer, which hosts one of the highest concentrations of wetlands in South Africa and the greatest extent of swamp forests, which are common in the region but rare in South Africa (Grundling *et al*., 1998). Within the low-lying plain occurs Mfabeni Mire, bordered in the east by an 80 – 100 m high coastal vegetated dune cordon and in the west by the older 15 – 70 m high Embomveni (Western) dune ridge (Davies *et al*., 1992). The peatland is ca. 10 km long, 3 km wide in places and comprises 1 462 ha (31% of the 4 636 ha of the topographically defined catchment). It is triangular with the main surface drainage within the swamp forest on its western edge, flowing southwards to Lake St. Lucia, and is bound by beach ridges in the north and south separating it from Lake Bangazi and Lake St. Lucia, respectively. Minor intermittent water exchanges to or from Lake Bangazi occur depending on lake levels, which vary depending on wet and dry climate cycles. It is covered in the north and the east with sedge/reed communities, with swamp forest in the south and west (Grundling *et al*., 2000). The swamp forest achieves its maximum extent across the peatland towards the centre of the system. On the Eastern Shores land-use in the past focused on *Pinus* plantations established on terrestrial areas and in wetlands. These plantations were cleared in the early 2000’s to make way for wildlife conservation and tourism, now the primary designated land-use activities. It is worth mentioning that substantial economic mineral resources of heavy minerals (e.g. titanium and zircon) occurs in the dune sands in the eastern dunes (Davies *et al.,* 1992), but these will not be exploited due to the conservation status of iSimangaliso Wetland Park.

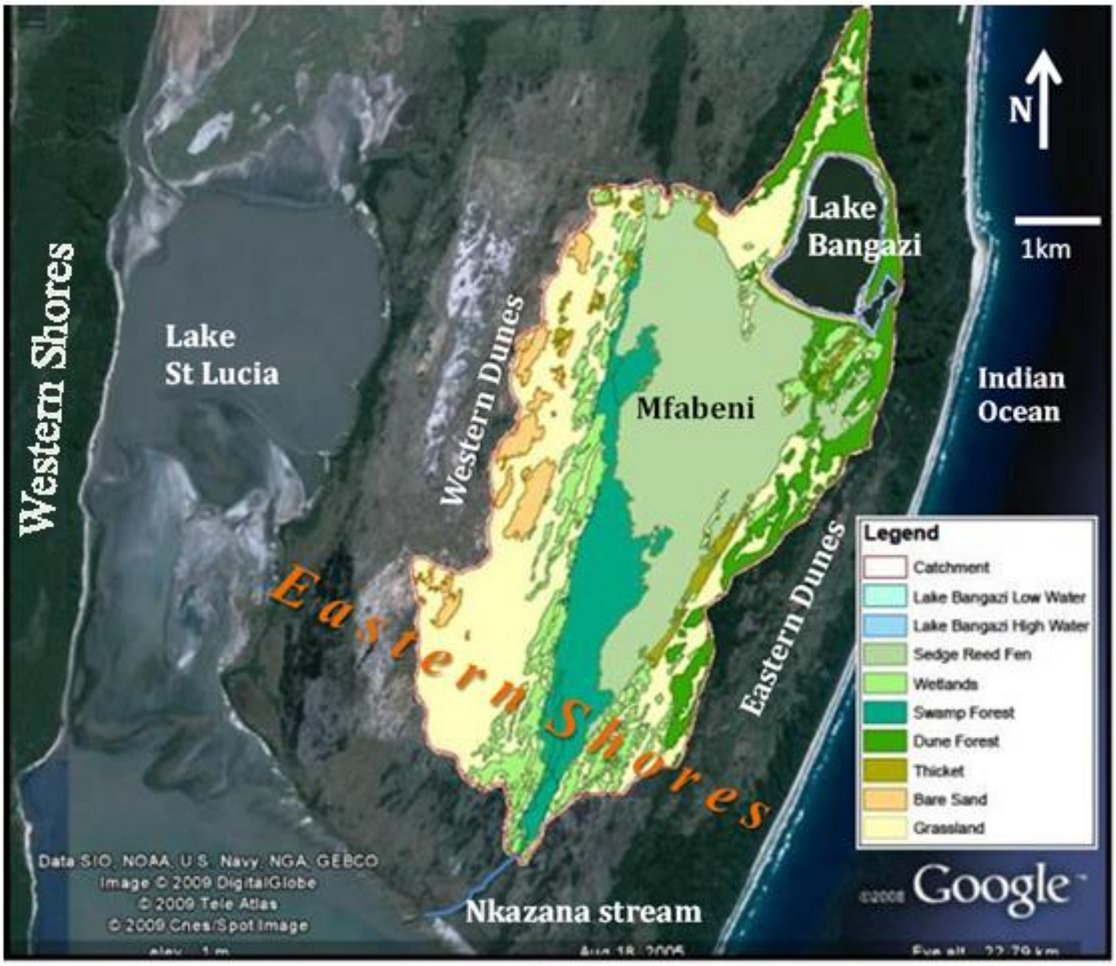

Figure 1.2: The catchment and landscape setting of Mfabeni Mire within the Eastern Shores of the iSimanagaliso Wetland Park, located between Lake St. Lucia in the west and the Indian Ocean in the east (Google Earth, 2010; Image date: 18/08/2005)

The idealised geology of the Eastern Shores (Table 1.1), as derived from Davies *et al*. (1992), Johnson and Anhauesser (2006), Botha and Porat (2007), and Porat and Botha (2008), consists of Jurassic rhyolites and basalts of the Lebombo range, which are overlain by Cretaceous siltstones of the Zululand Group. An unconformity (a break in a stratigraphic sequence) exists between the Zululand Group and the younger Port Durnford Formation of Middle Pleistocene age consisting of lacustrine mud and clayey carbonaceous sand. The overlying Pleistocene sands and sandstones (Kosi Bay, Isipingo and KwaMbonambi Formations) and Holocene sands (Sibayi Formation) are well sorted, highly porous and permeable. The older KwaMbonambi Formation forms the lower Embomveni (Western) dune ridge, whilst the younger Sibayi Formation covers the Kosi Bay formation to form the higher coastal dune in the east. The Mfabeni peat has accumulated in the valley between these two dune ridges. Thin dense organic and/or clay rich layers of low permeability have been encountered at depth adjacent to the eastern boundary of the mire. These buried layers in the sand are not uncommon in the region (*c.f.* Grundling, 2014).

Table 1.1***:*** The idealised geology of the Eastern Shores

Western dune cordon	**Low Lying Plain (Including Mfabeni Mire)**	**Eastern dune cordon**	
KwaMbonambi Formation: Remobilised underlying dune sand *(Late Pleistocene-Holocene 20 – 8 ka)*		**Sibayi Formation:** Brown and orange-brown aeolian sands (cover sands); Coastal Barrier Dune Cordon *(Holocene<10 ka)*	
Kosi Bay Formation: Orange to Yellowish brown silty sands (Older Aeolian Sands). Inland dune system *(Middle to Late Pleistocene, >300 ka)*	**KwaMbonambi Formation:** Alluvium and Inter dune peat *(Holocene<10 ka)* **Mfabeni Peat** *(Pleistocene/Holocene)*	**Kosi Bay Formation:** Orange to Yellowish brown silty sands (Older Aeolian Sands). Forms core of coastal dune. *(Middle to Late Pleistocene, >300 ka)*	
			Isipingo Formation (Upper): Interlayered Calcareous Sandstones and Uncemented Sands *(Eemian* beach deposits~*125 ka)*
			Isipingo Formation (Upper): Carbonate cemented sandstones *(Pleistocene* aeolianite~ *200 ka)*
Port Durnford Formation: Lacustrine mud and clayey carbonaceous sand (Early to Middle Pleistocene)			
Unconformity			
Zululand Group: Siltstone *(Upper Cretaceous)*			
Lebombo Group lavas: basalts and rhyolites *(Jurassic)*			

1.2 RESEARCH GAPS

Mfabeni Mire occupies an inter dune valley bordered by dune cordons, across which is a substantial rainfall gradient (Taylor *et al.*, 2006). Water efflux from the dunes may provide substantial recharge towards Mfabeni, while coastward hydraulic gradients from more inland locales are probably small or absent. The water budget of Mfabeni Mire is unknown, as is its regulatory function on discharge water. Consequently, the linkages between the coastal dune system and Mfabeni Mire, and its water regulation function, which might dictate the nature and magnitude of the local freshwater discharge to the St. Lucia estuary, need to be understood.

The freshwater discharge from Mfabeni Mire to the St. Lucia estuary, which has provided refuge for aquatic species during periods of drought, may become crucial under a more erratic climate. It is necessary to understand the peatland's ecological function and quantify the capability of this system to respond to climatic and land-use stresses, and its role in sustaining discharge to downstream aquatic and adjacent swamp forest ecosystems.

Climate change, exotic forest plantation activity and agricultural encroachment onto coastal peatland are significant stressors that threaten to alter the water available to both terrestrial and aquatic ecosystems. Inadequate knowledge of the processes and their linkages compromise our ability to make management decisions. We will only be able to manage these valuable resources to the long-term benefit of society if we understand the mechanisms involved in their functioning.

1.3 PROBLEM STATEMENT

South Africa is in reality a dry and arid land with and average rainfall of 497 mm, compared to a world average of more than 860 mm per annum. Our society depends on a national level on our water resources. Peatlands, as are all wetlands, are part of this water resource. These water resources are not only being exploited but must adapt to external factors such as a land use change and global climate change. The role these systems play in supplying water to downstream ecosystems and estuaries affect fisheries, agriculture, domestic water supply as well as tourism. The economic impact of this is difficult to quantify but is substantial.

There is currently a dearth of knowledge about South African peatland hydrology. Hydrological processes are a key component in the development and maintenance of wetlands and the source of water determine a wetland's vulnerability to a changing landscape and environment. The effects of changes in climate or landscape on wetland ecosystems need to be considered within the context of natural processes.

This study will attempt to quantify the hydrological processes involved when peatlands adjust to eternal stressors, and a range of processes including, surface-groundwater interaction, runoff responses and ecosystem services issues.

1.4 RESEARCH OBJECTIVES

The overall objective of the proposed research is to investigate the ecosystem processes that regulate water supply in the St. Lucia wetland complex, with specific reference to Mfabeni Mire:

1) *Development and persistence of an African mire: how the oldest South African fen has survived in a marginal climate*

This chapter focuses on the development of Mfabeni Mire with the specific objectives to:

a) assess the development of this mire system in relation to the landscape position and

b) understand the hydrological conditions in which the mire could survive in spite of a large regional water deficit.

2) *Hydrological function of a subtropical African mire: Contributing flow to adjacent and downstream ecosystems*

The aim of this chapter is to characterize the groundwater exchanges through the system with specific objectives being

a) to understand the feedbacks between regional and local flow systems that contribute flow to downstream ecosystems, and

b) to develop a conceptual model of the system's hydrological function.

3) *Using stable isotope and geochemical tracers to gain insights into the groundwater flow of Mfabeni Mire*

The aim of this chapter is to improve the interpretation and verification of the feedbacks between rainfall, evaporation, groundwater and surface flow through the Mfabeni Mire using isotopic, geochemical and thermal techniques. The specific objectives of this study are to

a) establish the source area of the stream flow of Mfabeni

b) determine the area where groundwater recharge occurs for Mfabeni Mire, and

c) investigate the mechanism of maintaining the wetness of the mire's peat (surface or groundwater throughflow).

4) *The water balance of an African mire: perceptions, reality and the implications for wetland ecosystem service interpretation*

The specific objective of this chapter is to quantify the water balance of Mfabeni Mire and thereby define its contribution to downstream and adjacent ecosystems.

5) *Synthesis, management guidelines and research recommendations*

The objective of this synthesis chapter is to provide management guidelines and research recommendations as well.

1.5 RESEARCH APPROACH

Most of the work entailed the gathering of hydrological data including climate, surface and groundwater characteristics. Most sampling points, except for installing water well points in the dunes, were done by hand to minimize impact on the peatland. In the dunes existing/old plantation service roads were used wherever possible to minimize impacts.

The water budget was evaluated. Discharge was measured continuously at a weir on the Nkazana stream. Rainfall was measured with tipping bucket rain gauges at two locations and manual rain gauges spread across the mire. Evapotranspiration for the sedge fen in Mfabeni Mire was modelled using meteorological data from a meteorological station located near the centre of the fen. The swamp forest evapotranspiration was measured and modelled by using a combination of eddy covariance and sapflow equipment. Storage changes were determined from changes in water table measured in PVC wells fitted with pressure transducers.

The groundwater monitoring network was expanded upon the existing infrastructure by adding multi-level piezometer nests at strategic locations especially in the dune-slacks and peatland complex. Piezometer nests in dune areas were installed by using mechanical equipment mounted on a truck along old management tracks. In peatland areas all piezometers nests were installed by hand to minimize damage to the peat, using a hand-auger and PVC tubes in the peatland and stainless steel drivepoint piezometers in sand materials.

The longer-term behaviour of the hydrological system was evaluated using geochemical methods. Water isotopes ^{2}H and ^{18}O and major ion chemistry were sampled to characterize the spatial distribution of groundwater recharge and discharge, and water flow pathways within and between systems.

1.6 RESEARCH ORGANISATION

The different chapters address specific objectives in order to cover the identified research gaps but are closely linked to one another as indicated in Figure 1.3. The thesis is written in manuscript format hence there is some unavoidable repetition mainly in the description of the study area and sometimes the methods.

- In Chapter 2 the geological setting and stratigraphic characteristics of a peatland and the surrounding landscape are investigated, as these factors affect groundwater flow into and within the wetland. Sustained groundwater flow is vital for survival of obligate species and the maintenance of anaerobic conditions necessary for peat accumulation in regions with large water deficits as in marginal climates. Therefore, this chapter focused on the development and hydrological conditions of the Mfabeni Mire.
- Chapter 3 focuses on the landscape hydrological setting of Mfabeni and small isolated perched wetlands occurring in depressions between dune ridges. The surface and groundwater exchanges of Mfabeni Mire were studied to understand the role of this large wetland complex in maintaining adjacent wetlands and downstream water flows in a changing environment.
- Chapter 4 deals with the isotopes and geochemistry to establish the source area of the stream flow and to determine the groundwater recharge area of the Mfabeni Mire.
- In Chapter 5, the water balance of the Mfabeni Mire is accounted for in order to evaluate its function and to define its contribution to downstream and adjacent ecosystems.
- In Chapter 6, the synthesis provides a brief synopsis and conclusion of findings and proposes management guidelines and research recommendations based on the research outcomes.

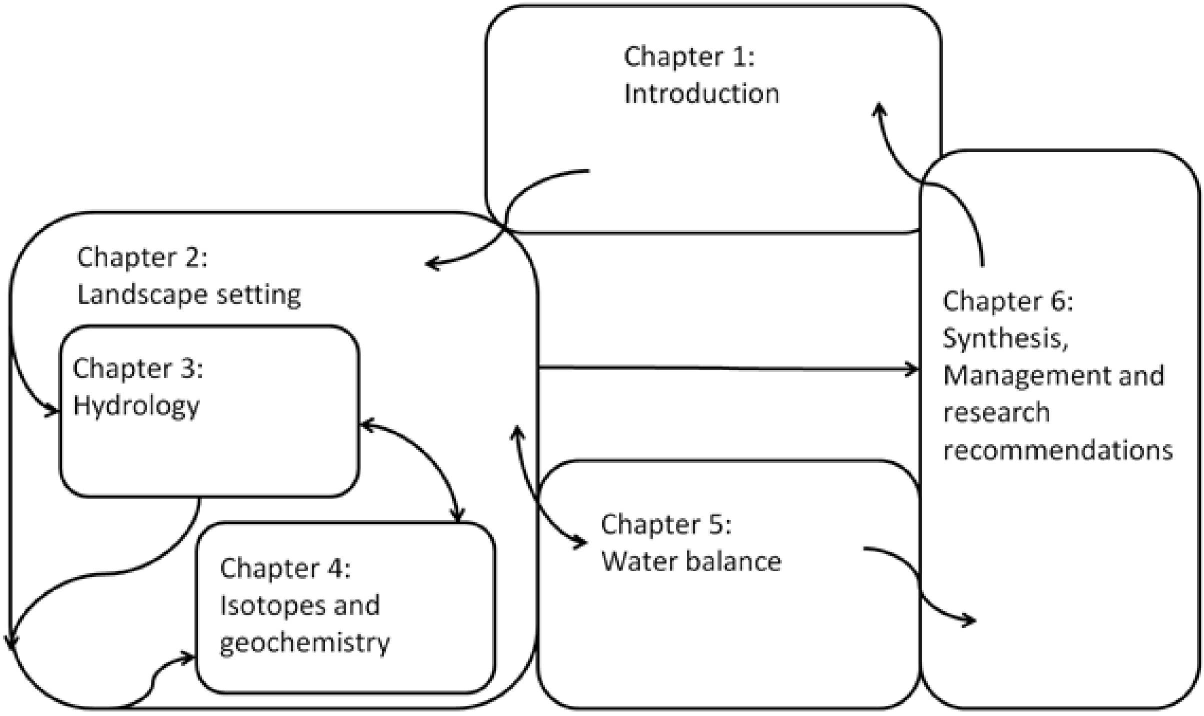

Figure 1.3: The organisation of the thesis and the linkages between chapters

2. LANDSCAPE SETTING

Development and persistence of an African mire: how the oldest South African fen has survived in a marginal climate

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Abstract

Hydrological processes maintain wetlands, whose position in the landscape determines their character and possible response to climate change. Such responses to long periods of climate change were studied in a large groundwater fed fen (Mfabeni Mire), which is one of the oldest fen systems in South Africa. The geological and geomorphological setting of the mire was studied as well as its stratigraphy and chronology. The basal peat of the mire was at a depth of 9.9 m dated at ca 44 000 cal years Before Present (BP). The average accumulation rate during the Late Pleistocene was 0.15 mm/year. During the Holocene it was higher (0.3 mm/year). Despite climate change over this period, peat formation has hardly been interrupted, suggesting that the system has been able to almost continuously sustain peat formation processes. This is possible because the peatland is situated in a valley that is bordered by a highly permeable sand dune cordon with an elevated groundwater table that directs groundwater towards the mire. The infilling of the valley by peat has resulted in a basin with lower permeability than in the surrounding dunes, forcing the water table in the adjacent aquifer to rise, thus ensuring the mire system a supply of groundwater that is large enough to dampen the effects of climatic variation.

Keywords: *coastal dunes, geology, hydrology, mire, peat, radio carbon dating.*

2.1 INTRODUCTION

Peatlands, which comprise about 50% of the world's wetlands (Mitsch and Gosslink 2000, Joosten and Clark, 2002), are rare in semi-arid and arid areas such as southern Africa (Scott 1982, Grundling and Grobler 2005), and are often threatened by human development, mainly for agriculture (Cowan and Van Riet, 1998; Grobler *et al.*, 2004). Consequently they are of high regional importance, and require good management, which is challenged by the poor understanding of their ecological and hydrological functions. Peatlands are ecohydrological systems where there are strong feedbacks between vegetation and local precipitation, evapotranspiration, surface and groundwater flows (Ingram, 1983; Emili and Price, 2006), in which the peat substrate comprises the incompletely decomposed vegetation that grows there. Both the magnitude and source of water fluxes, the associated supply of dissolved minerals and nutrients influence the vegetation response and determine the peatland form and function (Ivanov, 1981; Rydin and Jeglum, 2006). Many peatlands in semi-arid areas are fens, which are peatlands mostly located in valley bottoms (topogenous), but sometimes on slopes (soligenous), that receive their water input from precipitation, surface inflow and especially groundwater inflow (Joosten and Clark, 2002). Consequently, they are minerotophic and often nutrient-rich reflecting predominant surface and groundwater sources (Clymo, 1983; Rydin and Jeglum, 2006).

Most peatlands in the northern hemisphere developed during the Holocene since the last glaciation, and in that climate accumulated peat at 0.3-0.55 mm/year (Borren *et al.*, 2004, Gorham *et al.* 2003). In non-glaciated areas, peatlands of Late Pleistocene age have been reported (Irving and Meadows, 1997; Wüst *et al.*, 2008) with accumulation rates ranging from 0.5-2 mm/year (Hope *et al.*, 2005; Dommain *et al.*, 2011). Differences in peat accumulation result from variations in climate, duration and level of inundation and dominant vegetation type. The most rapid accumulation is often in *Sphagnum* dominated systems, because of its resistance to decay. However, there is also substantial peat accumulation in sedge- (Chimner and Carberg, 2008) or tree dominated systems (Dommain *et al.*, 2011), including semi-arid or tropical peatlands (Lappalainen, 1996).

Many northern peatlands have a predictable succession from sedge to moss-dominated vegetation arising because peat accumulation, and the resulting rise in water table, changes the strength and source of water inputs (Ivanov, 1981; Lapen *et al.*, 2005). In semi-arid peatlands the accumulation of peat can also affect the hydrology (Norström *et al.*, 2009) but the elevation to which peat can accumulate relies more strongly on the availability of water from surface or groundwater sources. Kulczyñski (1949) indicated in a study of Polesian peatlands that the accumulation of peat in lowlands could result in a rise of regional groundwater levels, whilst Emili and Price (2006) noted that a higher regional water table will favour peatland expansion in a hypermaritime forest–peatland complex, western Canada. In a study of peatlands on the Ruoergai Plateau, in China, Schumann and Joosten (2007) established that the accumulation of peat in lowlands impeded water flow and caused a rise of the water table in the mires, which caused a rise of the groundwater in the adjacent upland, thereby facilitating continuous peat accumulation during the Holocene. However, Grundling *et al*. (2000) and Ellery *et al*. (2012) concluded that peatland formation in floodplains in tropical and subtropical regions such as Maputaland, South Africa, is part of backwater and aggradational (the accumulation of sediment sequences) floodplain processes.

The development of peatlands is strongly linked to hydrological processes from the pore-space to landscape level (Price, 2003). The persistence of peat-accumulating wetlands (mires) in semi-arid settings and/or environments with strongly seasonal rainfall, which is common throughout southern Africa, requires water inputs from large catchments or sustained local groundwater input (Meadows, 1988; Colvin *et al*., 2007; Ellery *et al.*, 2009). Groundwater inflow, being less temporally variable than precipitation in marginal climatic settings where rainfall is strongly seasonal and evapotranspiration exceeds precipitation, provides a relatively constant water source that is likely to sustain permanently wet conditions (Kurtz *et al*., 2007). It is therefore important to determine the nature and importance of surface-groundwater interactions in landscapes where rainfall is seasonal and exhibits high inter-annual variability. Furthermore, given the wide interest in climate change and its expected impact on wetlands (Joosten, 2009; Crooks *et al*., 2011), it is necessary that management guidelines are based on a sound understanding of the development and functioning of these systems.

Groundwater flow to peatlands is governed by its catchment's topography, geology and the storage and transmission properties of the geologic materials and soils (Freeze and Cherry, 1979; Dingman, 2002). Topography can contribute to complex patterns of groundwater flow into peatlands (Winter, 2001; Lapen *et al.*, 2005) where a landscape with prominent or high relief will develop local flow systems compared to relatively simpler regional flow systems in a flatter landscape (Winter, 1999). Geologic controls on groundwater movement include stratigraphic variability in the case of unconsolidated lithologies, or structural and lithological controls in the case of consolidated sediments (Le Maitre and Colvin, 2008). Preferential flow will typically take place in or along permeable layers, contact, faulting and folding zones (Freeze and Cherry, 1979; Dingman, 2002). It is therefore important to understand the geological setting and stratigraphic characteristics of a peatland and the surrounding landscape, as these factors affect groundwater flow into and within the wetland (Winter, 1999). Sustained groundwater flow is vital for survival of obligate species and the maintenance of anaerobic conditions necessary for peat accumulation in regions with large water deficits as in marginal climates. This study focuses on the development of Mfabeni Mire, an 11 m thick peat deposit in a valley-bottom setting in South Africa. The objectives of this study are to 1) assess the development of this mire system in relation to the landscape position and 2) understand the hydrological conditions in which the mire could survive in spite of a large regional water deficit.

2.2 STUDY AREA

Mfabeni Mire is located on the Eastern Shores of Lake St. Lucia, an area between the Indian Ocean in the east and Lake St. Lucia to the west, within the catchment of the Mkuze River (Figure. 2.1). The region of the entire coastal plain in northern KwaZulu-Natal is known as Maputaland and has a subtropical climate with hot and humid summers and mild, drier winters where frost rarely occurs (Taylor, 1991). The mean summer temperature (November to March) exceeds 21ºC with 60% of the annual rainfall occurring in summer (Mucina and Rutherford, 2006). The mean annual precipitation of the Eastern Shores decreases from 1 200 mm/annum in the east on the coast to 900 mm 10 km westwards across Lake St. Lucia (Taylor *et al*., 2006).

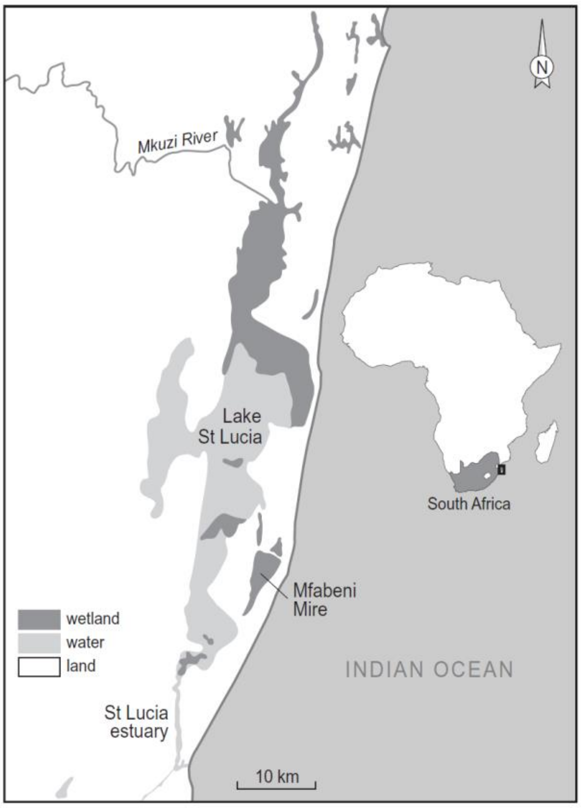

Figure 2.1: The location of Mfabeni Mire in South Africa.

Wetlands, ranging from seasonally inundated depressions to permanently wet mires and swamp forests are common (Figure 2.1), whilst coastal dune forest and wooded grassland dominate terrestrial areas (Grundling *et al*., 1998; Goge, 2003; Venter, 2003). In the recent past the dunes surrounding Mfabeni Mire supported exotic *Pinus* plantations that were planted for commercial timber production, but these trees were removed in the early 2000's. Wildlife conservation and tourism are now the primary designated land use activities. The Eastern Shores comprises high coastal sand dunes and low-lying plains located on the Maputaland primary aquifer, which hosts one of the highest concentrations of wetlands in South Africa and the greatest extent of swamp forests, which are common in the region but rare in South Africa (Grundling *et al*., 1998). Within the low-lying plain occurs Mfabeni Mire, bordered in the east by an 80 – 100 m high coastal vegetated dune cordon and in the west by the older 15 – 70 m high Embomveni (Western) dune ridge (Davies *et al*., 1992). The peatland is ca. 10 km long, 3 km wide in places and comprises 1 462 ha (31 % of the 4636 ha of the topographically defined catchment). It is triangular with the main surface drainage within the swamp forest on its western edge, flowing southwards to Lake St. Lucia, and is bound by beach ridges in the north and south separating it from Lake Bangazi and Lake St. Lucia, respectively. Minor intermittent water exchanges to or from Lake Bangazi occur depending on lake levels, which vary depending on wet and dry climate cycles. Mfabeni Mire is dominated in the north and east by reed/sedge vegetation communities with sparse occurrence of *Sphagnum* (less than 10% of the peatland), and in the south and west by swamp forest (Grundling *et al*., 1998) that achieves its maximum extent across the peatland towards the centre of the system.

The idealised geology of the Eastern Shores, as derived from Davies *et al*. (1992), Johnson and Anhauesser (2006), Botha and Porat (2007), and Porat and Botha (2008), consists of Jurassic rhyolites and basalts of the Lebombo range, which are overlain by Cretaceous siltstones of the Zululand Group. An unconformity (a break in a stratigraphic sequence) exists between the Zululand Group and the younger Port Durnford Formation of Middle Pleistocene age consisting of lacustrine mud and clayey carbonaceous sand. The overlying Pleistocene sands and sandstones (Kosi Bay, Isipingo and KwaMbonambi Formations) and Holocene sands (Sibayi Formation) are well sorted, highly porous and permeable. The older KwaMbonambi Formation forms the lower Embomveni (Western) dune ridge, whilst the younger Sibayi Formation covers the Kosi Bay formation to form the higher coastal dune in the east. The Mfabeni peat has accumulated in the valley between these two dune ridges.

2.3 METHODS

The geology of the dunes adjacent to Mfabeni Mire was examined at 7 terrestrial sites (Figure 2.2) by reverse circulation drilling (Sites A6, B3, D3, DWAF-A, UW1E1, UW2E1 and UW2W1). The lithology of each core was described in the field according to grain size, texture and colour. This investigation was intended to supplement previous geological investigations of the coastal plain including the Eastern Shores (Geological Survey, 1985a,b) by Davies *et al*. (1992), and to determine the extent of any impeding layers beneath and/or adjacent to Mfabeni Mire.

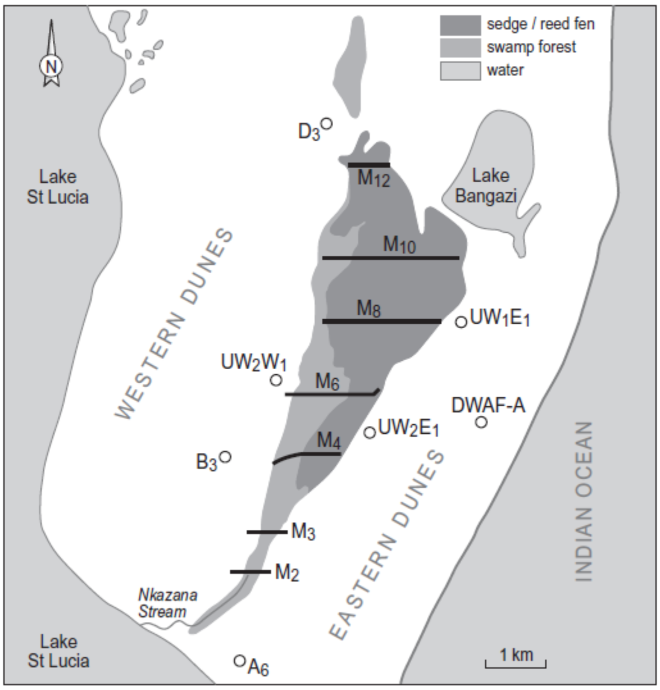

Figure 2.2: Sample sites in and adjacent to Mfabeni Mire.

The peatland was cored along eight east-west transects that were spaced 800 to 1600 m apart from south to north. The borehole spacing along transects was between 100 to 200 m. Peat was sampled with a Russian peat corer at 0.5 m increments, one half of which was described in the field according to the Von Post humification scale (Von Post, 1922) and the remainder sealed and returned to the laboratory to determine ash content. Samples were dried for 12 hours at 105 ˚C in an Optolab Term-o-mat 321 oven, and ashed at 815 ˚C for 3 hours in open ceramic crucibles in a Carbolite CSF furnace.

C^{14} dating of selected peat samples was performed by the Council for Scientific and Industrial Research laboratories in Pretoria, South Africa. The C^{14} age determinations are given in years before present. Dates are reported in conventional radiocarbon years, i.e. using a half-life of 5568 years for C^{14}. Ages are corrected for variations in isotope fractionation and ages are calibrated for the southern hemisphere using the Pretoria Calibration Programme (Talma and Vogel, 1993).

2.4 RESULTS

2.4.1 Basin Geology

Coring in and adjacent to Mfabeni Mire established that grey clay material occurs approximately at present day sea-level. In the middle of the mire (transect M8), the clay material below the base of the peat is at least 6 m thick (Figure 2.3), but the bottom of the deposit was not reached. At the deepest point sampled some silt was present in the clay. Coring at 7 sites adjacent to the peatland to depths below sea-level showed that the clay material does not extend beyond the width of Mfabeni Mire valley-bottom (Figure 2.3), but it might extend along the length of the peatland.

The cover sands adjacent to Mfabeni Mire (boreholes UW1E1 and UW2E1 to the east and UW2W1 and D3 to the west) are well sorted and contain typically less than 5 % clay in the upper layers. However, the clay content increases more rapidly with depth in the older western dunes (UW2W1 and D3) than the younger eastern dunes (UW1E1 and UW2E1). The sand in the boreholes adjacent to the central part of the peatland (UW2W1 and UW2E1) contains elevated clay and organic contents at a depth that equates to the present sea-level, but it is not comparable to the clay material beneath the peatland in either its thickness or clay content. Clay was found in the far northern and southern boreholes (D3 and A6 respectively; Figure 2.2), but at a greater depth than the clay beneath Mfabeni Mire (14 m below mean sea-level).

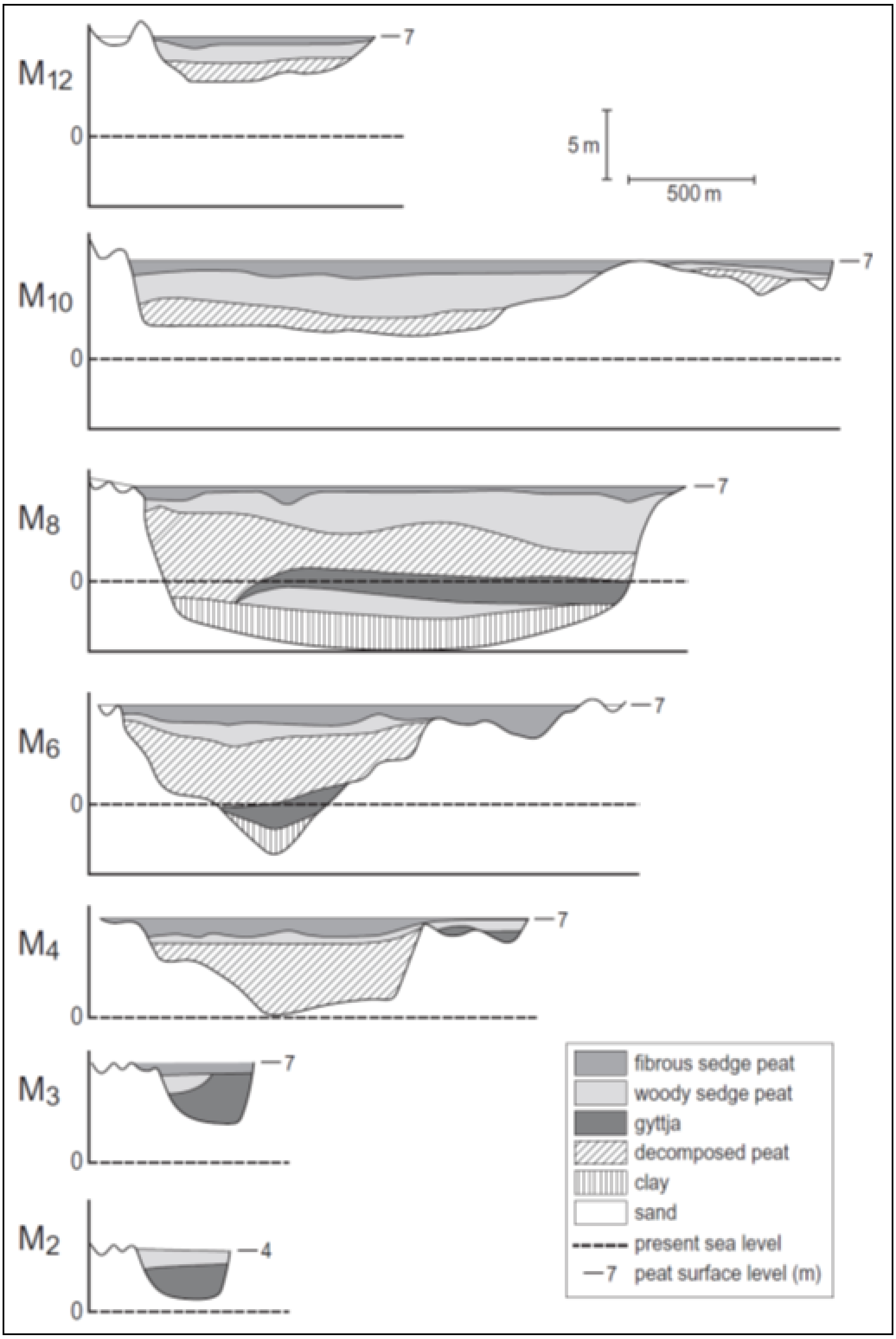

Figure 2.3: Stratigraphy of Mfabeni Mire along eight transects from West to East.

2.4.2 Morphological characteristics Mfabeni Mire

Mfabeni Mire has a complex morphology occupying a deep central depression that is oriented north-south, and with smaller depressions east and west of the main depression. In the main basin the peat body is up to 10.8 m thick, while in the lateral basins the peat depths do not exceed 2.5 m (Figure 2.3). The surface of the peatland slopes downwards from the central region of the peatland in a southerly direction, and also has a very gentle slope downwards from West to East (not shown). Between transects M3 and M2 the peat surface steepens with the present Nkazana stream channel incised into the peat surface draining towards Lake St. Lucia (Figure 2.2).

2.4.3 Peatland Stratigraphy

Variation in the fibre, organic and ash contents within the peat are relatively consistent down the length and across the width of the peatland. The number of layers and the complexity of their configuration are greatest where the peat is thickest (Figure 2.3).

A total of five distinct peat layers are recognised (Figure 2.3). The basal peat layer in transect M8 is resting on the clay material and consists of brown medium fibrous wood and sedge material (Von Post scale 4), with some sand and a thin ash layer. This peat is covered by a darker very fine-grained gyttja layer with some secondary layers of sand and more fibrous peat. The gyttja layer is overlain by a dark, medium fibrous layer with wood and sedge remains (Von Post scale 4), which in turn is covered by a decomposed dark sedge peat (Von Post scale 6). Higher in the profile a less decomposed fibrous sedge peat with some wood remnants was encountered (Von Post scale 3). A thin layer of iron nodules and wood chunks separates this layer from the top 1 m layer of peat. The top layer consists of a very poorly decomposed sedge and woody peat (Von Post scale 1 to 2); it is more fibrous than all lower peat layers. Occasionally, localised sandy layers of about 0.2 m separate the peat layers (data not shown), in particular in the eastern part of the peatland in the decomposed peat layer (Figure 2.3). In the western part of the mire and in the more shallow peat deposits in the north, thin ash layers occur (data not shown).

2.4.4 Radiocarbon dating

The radiocarbon dating of the bottom peat at 9.9 m indicates that peat growth started about 44 000 cal years BP, which is very close to the detection limit of C^{14} dating (Van der Plicht and Hogg, 2006). The contact between the basal peat layer and the underlying clay was dated at 43 000 +4 900 to -3 000 cal years BP. An older date of 45 100 +4 900 to -3 000 cal years BP was determined for the peat two meters above the basal peat, but this is within the error range of the dating method. Therefore, it’s estimated that the start of the peat growth at about 44 000 cal years BP. The age-depth curve of the M8 profile (Figure 2.4) based on eight radiocarbon dates shows a very slow accumulation rate between 45 000 and 10 000 cal years BP. After 10 000 cal years BP, which marks the Pleistocene-Holocene boundary, the accumulation rates increased considerably (Figure 2.4). Two additional dates (not shown) were obtained for core M10-10 in order to date a 0.47 m thick ash layer. The peat at 4.35 m, immediately below the ash layer was, dated at 25 700 ± 410 years BP and the age above the ash layer was 12 430 ± 120 years BP.

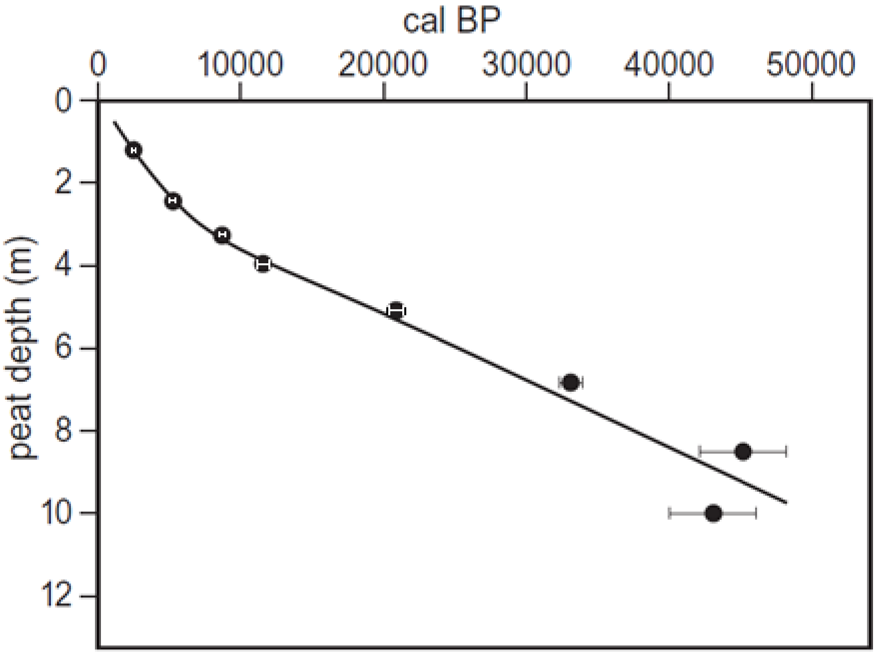

Figure 2.4: Age-depth curve of Mfabeni Mire, South Africa, based on C^{14}-dating of a profile in the centre of the M8 profile (see Figure 2.2). A distinct increase in peat accumulation rate can be observed after 10 000 BP, which is the Pleistocene-Holocene boundary.

2.5 DISCUSSION

2.5.1 The geological setting of Mfabeni Mire

Mfabeni Mire peat is located on clay material within a valley-bottom setting (Figure 2.3). The peat deposit thins out to the south and the north where it is underlain by reworked aeolian marine sands. The development of Mfabeni Mire's depositional setting in relation to sea-level change is presented in Table 2.1. Through the Late Pleistocene the sea-level fluctuated 5 – 7 m above the present sea-level during the last Interglacial High Stand from *ca.*115 000 – 90 000 years BP (Ramsay and Cooper, 2002).

Table 2.1: Development of Mfabeni Mire depositional environment in relation to sea-level change from the Late Pleistocene to the Holocene. Geological information older than 65 000 years BP are according to Ramsay and Cooper (2002), while information younger than 65 000 years BP are according to Ramsay (1995).

Years BP	**Sea-level**	**Mfabeni Mire's depositional environment Note: all elevations are levels relative to present sea-level (PSL)**
300 000	+5	High stand - Formation of western dune complex
200 000	- 150	Incising of coastal rivers
125 000	+5-7 m	Last Glacial High Stand – deposition of Isipingo beach rock and sediments forming the core of the eastern Dune complex
118 000	- 45 m	Incising of coastal rivers and Nkazana tributary to -10 m PSL and deeper
95 000 - 115 000	+5-7 m	Last Glacial High Stand – Deposition of Isipingo beach rocks, core of the eastern Dune complex Deposition of clay layer to 0 m (PSL). Formation of beach terraces in Mfabeni basin? Incising clay layer to -4 m PSL? Formation of beach ridges in Mfabeni Basin?
45 000	- 45 m	Peat accumulation starts in Mfabeni Basin at -4 m PSL?
33 000	- 62 m	Peat accumulation reaches 0 m (PSL) in the

		Mfabeni Basin
18 000	- 125 m	Incising of coastal rivers NOT Nkazana tributary. Peat at 2m PSL.
12 500	- 95 m	Northern part of basin experiences peat fire. Rest of basin peat at 3 m PSL.
10 000	-50 m	Pleistocene/Holocene boundary at 3 m. 20- 50cm sand layers in peat (central). Ash layers in north and south at 3.5m PSL.
6 500	0 m	Peat accumulation reaches 4.5 m PSL in the Mfabeni Basin
4 400	+ 3.5 m	Peat accumulation reaches 5.0 m PSL in the Mfabeni Basin.
3 000	-2 m	Peat accumulation reaches 5.5 m PSL in the Mfabeni Basin. Some ash layers in the northern section
1 500	+1.5 m	Peat accumulation reaches 6 m PSL in the Mfabeni Basin
Present	0 m	Peat accumulation reaches 7 m PSL in the Mfabeni Basin

The valley-bottom in which the peat has formed probably represents the southward course of the Nkazana paleo-channel, a tributary of the Mkuze River (Figure 2.1). The valley may have undergone several phases of erosion that accompanied rejuvenation of coastal rivers during and since the last Interglacial High Stand until the Last Glacial Maximum, *ca.*18 000 years BP (Taylor *et al.*, 2006; Wright *et al.*, 2000). The Nkazana paleo-channel was probably incised into Early Pleistocene estuarine/lacustrine mud and carbonaceous sand of the Port Durnford Formation (Wright *et al.*, 2000; Taylor *et al.*, 2006), with the clay material underlying Mfabeni Mire of lacustrine or intertidal origin. This lacustrine or intertidal material was deposited since the last Interglacial High Stand period in this tributary following blockage of the tributary valley with clastic sediment during the ongoing aggradation along the Mkuze River. During the Late Pleistocene this aggradation resulted in the shifting of the Mkuze River estuary to the south to form a combined mouth with the Mfolozi River (Wright *et al.*, 2000). The blockage of the Nkazana channel raised the base level and established an ideal low energy environment for the accumulation of peat as is described for similar but younger upstream environments in the Mkuze River floodplain by Ellery *et al.* (2012).

Results from the terrestrial boreholes indicated that the clay layer is restricted to the valley-bottom in an east – west direction (Figure 2.3). It is possible that the clay layer extends further north and south but this was not investigated. This clay material plays an important role in the formation and development of Mfabeni Mire by preventing water losses from *ca.*45 000 years BP when sea-level was about 50 m below current sea-level (Ramsay and Cooper, 2002) to *ca.*6 500 years BP (Table 2.1) when the present sea-level was reached (Ramsay, 1995).

2.5.2 Chronology of Mfabeni Mire

The various peat layers (Figure 2.3) and plant remains in Mfabeni Mire represent different environmental conditions. Regular occurrence of wood fragments may represent swamp forests, while sedges or grasses indicate more open herbaceous fen conditions. Peat fires, as represented by ash and charcoal in peat profiles, and the accompanying release of nutrients and minerals (Ellery *et al.*, 1989) were probably instrumental in contributing to spatial heterogeneity in vegetation distribution within Mfabeni Mire. Sedge remains in the clay beneath Mfabeni Mire and wood remains in the basal peat (Figure 2.3) point to the presence of riparian or swamp forest at the time when peat accumulation commenced in the Nkazana paleo-channel *ca.* 43 000 years ago. The occurrence of *Typha* throughout the pollen record as reported by Mazus (in Grundling *et al.*, 1998) suggests the prevalence of fresh water conditions from this Late Pleistocene period until present. The presence of gyttja (Figure 2.3) above this basal peat indicates flooding of the peat in that period, leading to the emergence of a shallow lake in the eastern and southern parts of the mire until *ca.* 33 000 years BP. This rather sudden increase in water levels was probably caused by the blocking of the Nkazana paleo-channel. The gyttja and peat layers are often interbedded with thin layers of sand (Figure 2.3), representing periods of aeolian sediment transport and deposition (Wright *et al.*, 2000).

After *ca.* 33 000 years BP a fen environment developed with peat accumulation derived mainly from sedges such as *Cladium mariscus.* Finch and Hill (2008) report the appearance of *Haloragidaceae* in the Mfabeni Mire pollen record between 30 000 and 20 000 years BP, which together with the dominance of *Cyperaceae* and the presence of pollen of aquatic species point to very wet conditions during this period (Grundling *et al*., 1998). Peat with a highly decomposed and finer texture with dispersed and thin layers of sand were deposited from *ca.* 20 800 years BP to *ca.*11 570 years BP suggesting drier conditions at the onset of the last Glacial Maximum at *ca.*21 000 years BP (Partridge *et al.*, 1999). The shift towards a drier and cooler climate is also supported by the pollen record, with *Poaceae* becoming dominant, while *Cyperaceae* steadily declined (Finch and Hill, 2008). The presence of a prominent ash layer at M10 (Figure 2.2) between 4.35 to 3.88 m above sea-level further supports the idea of a drier climate.

The periods of aeolian sedimentation in the peatland ceased in the early Holocene, suggesting wetter conditions and increased vegetation cover that would have stabilised the soil surface. A rapid increase in pollen of wetland species (*Cyperaceae*) in the Holocene suggests wetter conditions and a rise in water level in the peatland. The alternating layers of finer and fibrous peat from the early to middle Holocene (*ca.* 5 280 ± 70 years BP) represent wetter conditions such as open sedge fen (sedge peat).

Chunky wood layers within the upper woody sedge layer (Figure 2.3) present in the western and central part of the wetland shows that by *ca.* 2 450 ± 50 years BP most of the peatland was covered by swamp forest. After that a fibrous sedge peat layer developed, reflecting a sharp decline in swamp forest cover, with practically all swamp forest giving way to open sedge fen over the next 2 500 years, probably due to wetter conditions in the fen as a result of an increase of groundwater discharge from the adjacent dunes. The current distribution of the swamp forest (Figure 2.2 - only in the western and southern parts of Mfabeni Mire) indicates that the swamp forest has expanded again during recent periods, possibly due to slightly drier conditions in the fen as a consequence of incision along the Nkazana stream, which has developed along the relatively steep slope between M3 and M2.

2.5.3 Peat accumulation rates

On the basis of peat thickness (depth) and radiocarbon dating, two distinct trends are reflected in the accumulation rates for Mfabeni Mire: 0.15 mm/year during the Late Pleistocene and 0.3 mm/year during the Holocene (Figure 2.4). The Pleistocene/Holocene boundary clearly coincides with an increased peat accumulation rate in Mfabeni Mire. The different accumulation rates are likely to be a reflection of the different environmental conditions in the Late Pleistocene and Holocene as described above indicating that the conditions during the Holocene were more favourable for peat accumulation than conditions during the Late Pleistocene. It is of interest that the Mfabeni Holocene peat accumulation rate of 0.3 mm/year is considerably lower than younger Holocene peatlands of this region reported by Grundling *et al*. (1998), which may vary between 0.9 – 2.1 mm/year, with an average of 1.1 mm/year. However, the accumulation rate is similar to the global average accumulation rates for Holocene peatlands in the Northern Hemisphere of 0.3 – 0.55 mm/year (Verhoeven *et al*., 2006; Joosten and Clarke, 2002).

2.5.4 A conceptual model of Mfabeni Mire hydrology

The inundated clay-bottom valley, which was formed in backwater conditions, where a low energy environment prevailed probably due to aggradation of the Mkuze River as well as the Mfolozi River floodplain to the south (Grenfell *et al*., 2009, 2010), produced a hydrogeomorphic setting suitable for initiation of peat formation in the Nkazana paleo-valley ~44 000 cal years BP. It is therefore hypothesised that changes in groundwater flow patterns on the Eastern Shores, east of Lake St. Lucia (Figure 2.2), over time are due to peat accumulation in Mfabeni Mire as represented in Figure 2.5. Groundwater discharge from the western dune accumulated in the valley-bottom to initially form a shallow lake on the basal clay layer, with some of the water flowing towards the east and recharging the groundwater below the eastern dune (Figure 2.5-1). This phase was followed by gyttja deposition in the open water (Figure 2.5-2), colonisation of the surface by vegetation and subsequent infilling of the valley-bottom with peat (Figure 2.5-3) which has a lower hydraulic conductivity than the surrounding sandy reworked marine deposits (Figure 2.5-4). The presence of a barrier such as this to the lateral flow of water caused the groundwater table in the western Embomveni dune cordon to rise, accompanied by prolonged inundation of the peatland, promoting further peat accumulation. Over time there must have been a steepening of the groundwater surface east of Mfabeni Mire (Figure 2.5-4) as the mire surface level (and water table) rose with respect to sea-level on the extreme eastern margin of the eastern dunes (Figure 2.5-4).

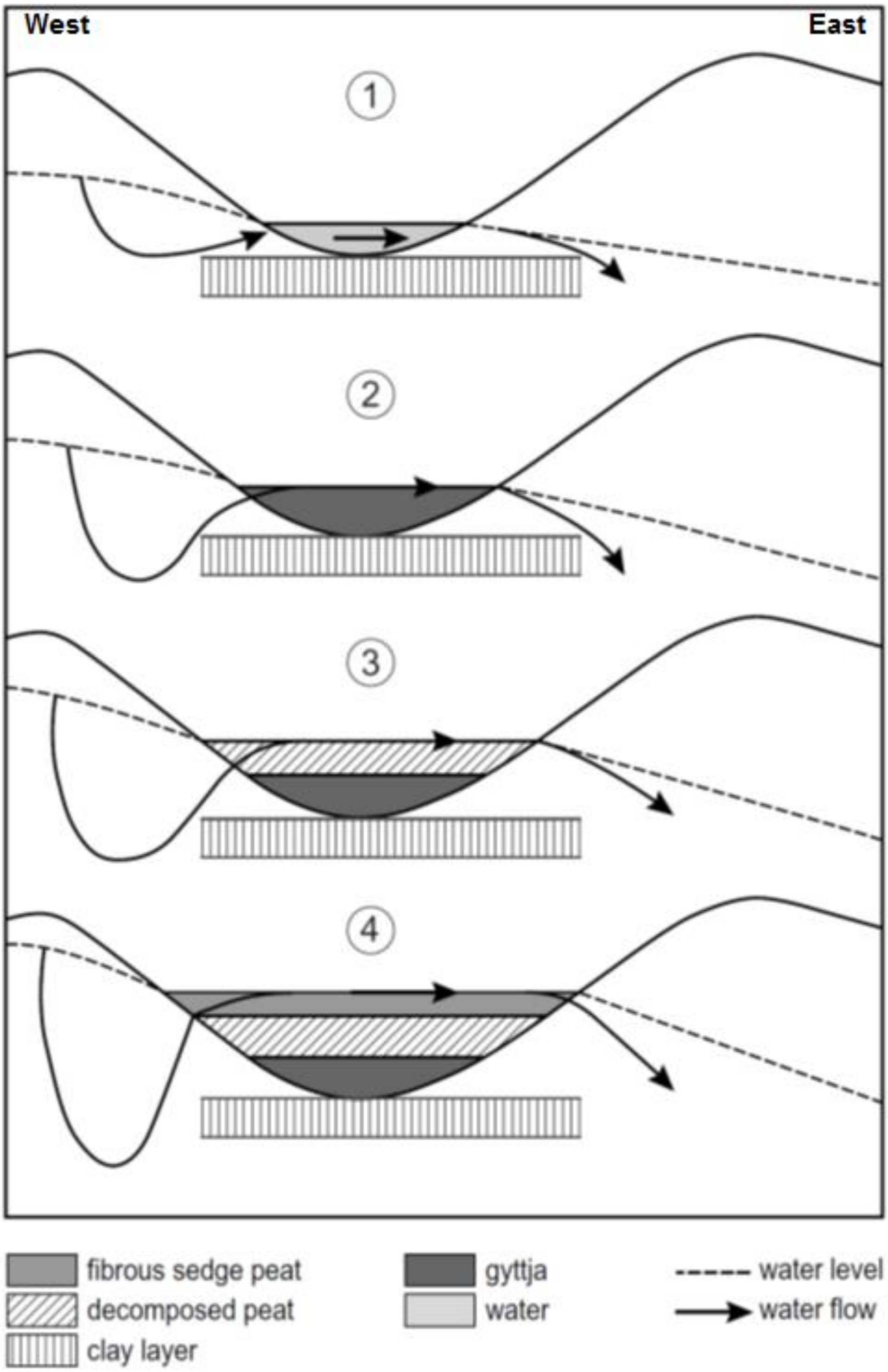

Figure 2.5-1,2,3,4: Possible changes in groundwater flow during peat accumulation in Mfabeni Mire.

It is further hypothesised that Mfabeni Mire, because it is a groundwater fed system, has been able to cope with climate changes since its formation in the Late Pleistocene, by influencing the regional water table in the western dune cordon through infilling of the valley with peat. This process of infilling of with peat (Figure 2.5) is thus a consequence of one or more of the following (Figure 2.6): (1) the regional water table rising due to increased groundwater input (GW) during the Late Pleistocene; wetter conditions with higher precipitation (P); sea-level rise after the last glacial maximum, as well as the raising of the base level due to sediment aggradation. Wetter conditions likely increase water discharge (Q) into Mfabeni Mire valley, (2) inundating the valley floor with surface water and saturating lower laying areas. Increased inundation of the land surface (3) results in increased plant growth and biomass production of fibrous plant tissue. Coupled with (4) a decrease in O_2 availability in the soil due to (2) inundation and saturation, decreased mineralisation rates (5) follow, promoting peat accumulation (6). The infilling of the valley-bottom with peat (7), which has a lower hydraulic conductivity than the sand of the surrounding terrain, results in a reduction in the eastward flow of groundwater from the west across the valley. As peat accumulates in the valley, the water table west of the valley rises (1), a positive feedback develops favouring peat accumulation. However, as the peat accumulates the peatland and surface vegetation expand laterally (8) in relation to basin morphology, resulting in (1) increased evapotranspiration losses [ET]. This negative feedback moderates the increase in discharge [Q] and controls the elevation to which peat is able to accumulate, because peat will accumulate to an elevation where average long-term inputs and outputs are equal. This conceptual model indicates the importance of sustained groundwater discharge as a critical contribution of water to the system, providing sufficient wetness to maintain peat accumulation processes and dampening the effects of climatic perturbations.

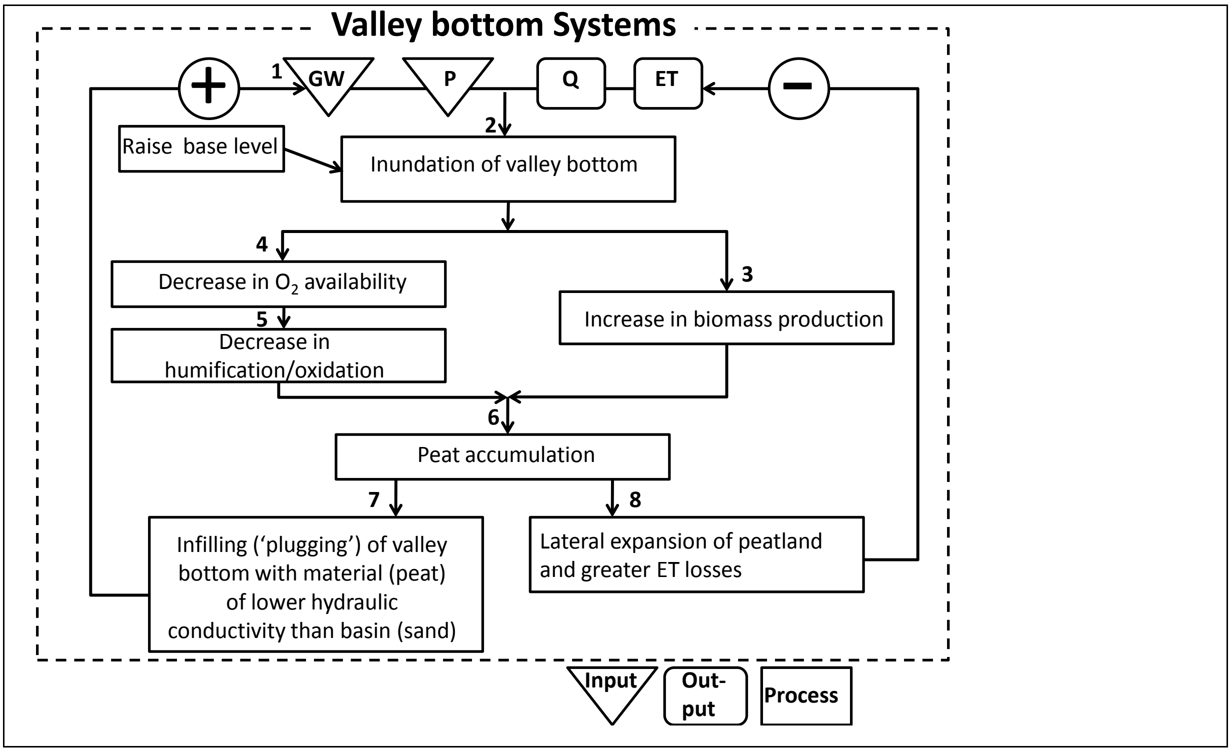

Figure 2.6: A conceptual model of processes that contribute to peat formation of the Nkazana paleo-channel over extended time periods (tens of thousands of years).

2.6 CONCLUSION

Mfabeni Mire is a groundwater dependant ecosystem that was formed in the Late Pleistocene and continued to develop during the Holocene. This paper shows that the infilling of a valley bottom with peat resulted in a plug effect which forced a rise in the elevation of the influent groundwater surface in the adjacent upland as peat accumulated in the lowland. In addition to favouring the development of a series of ephemeral non-peat wetlands adjacent to the mire, the consistent and permanent discharge of groundwater into the peatland from the upland allowed for the almost uninterrupted formation of peat over an extended period. This expansion of the groundwater source resulted in a buffering effect against climatic turbations in a semi-arid region providing a more stable localised environment for this mire to develop. Our ability to manage and conserve such systems in future will depend on the insight we gain in understanding the processes driving formation and evolution during periods of change. Further research on flow patterns within mires is needed to understand the mechanisms that can buffer groundwater fed fens against changes in climate.

2.7 ACKNOWLEDGEMENTS

The financial support of the Water Research Commission of South Africa (Project no WRC K5/1704and1857) is appreciated. The Council for Geoscience and Department of Water Affairs are acknowledged for in-kind contributions; the staff of the iSimangaliso Wetland Authority and KwaZulu-Natal Wildlife for institutional and research support; Siphiwe Mfeka and Andre von Plaster for their dedication in the field.

3. HYDROLOGY

Hydrological function of a subtropical African mire: Contributing flow to adjacent and downstream ecosystems

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Abstract

Peatlands in drier climates are dependent on groundwater input to maintain a favourable peat forming environment, and seasonal water deficits and surpluses may therefore be a key determinant in the ability of these wetlands to contribute to downstream ecosystems. The surface and groundwater exchanges of Mfabeni Mire in southern Africa were studied to understand the role of large wetlands in maintaining downstream water flows in a semi-arid environment where rainfall is not only seasonal, but also highly variable and considerably less than the maximum potential evapotranspiration rate. This mire of 1 462 ha is located in a low-lying valley between a coastal vegetated dune cordon in the east and western inland dune complex. It is covered in the north and the east with sedge/reed communities and with swamp forest in the south and west. Water efflux from the western inland dune complex provides substantial recharge towards Mfabeni Mire, discharging on its western edge coincident with the occurrence of a swamp forest ecosystem; only a small portion of groundwater from the inland dunes flows through the mire, eastward to the coast. The major portion of groundwater from the inland dunes is forced to the surface, due to the plugging effect of the relatively low hydraulic conductivity peat in Mfabeni Mire, then discharges southwards via a stream into Lake St. Lucia. This stream maintains a relatively low baseflow (360 m^3/day) due to sustained groundwater inputs from the western dunes, but does respond rapidly to larger rainfall events (≥40mm). The links between groundwater inflow and storage change in the wetland are therefore important in maintaining internal ecosystem processes and regulating stream flow towards Lake St. Lucia. Wetlands in semi-arid environments may be more of a conduit responding to regional hydrological dynamics than a source of water.

Keywords: *wetland, semi-arid, hydrogeology, groundwater, stream flow, ecosystem services.*

3.1 INTRODUCTION

While wetlands may provide various ecosystem services such as flood attenuation, flow augmentation and water quality enhancement (Mitsch and Gosselink, 1993; Costanza *et al*., 1998), there is a dearth of information on the integrated function of wetland complexes, especially in subtropical and semi-arid regions (Ghermandi *et al.*, 2010). In these areas the cycling of seasonal water surpluses through the groundwater reservoir can create and maintain water stores and biogeochemical conditions that are key to ecosystem and habitat diversity (McCarthy, 2006). Furthermore, the link between hydrological processes in large wetland systems and downstream environments in semi-arid regions is poorly understood, although their impact on downstream ecosystems can be critical (Yetter, 2004; Smaktin and Bachelor, 2005; Taylor *et al*., 2006). Wetland hydrological functions that control downstream discharge and water quality (Bullock and Acreman, 2003) are dependent on the type of wetland, relative size and position in the landscape, as well as local climate (Brinson, 1993; Kotze *et al.,* 2008; McCartney and Acreman, 2009). Extensive wetlands such as floodplains can control flood magnitude (Archer 1989; Kotze, *et al.,* 2008), while unchannelled valley-bottom wetlands with thick accumulations of sediment such as peat or sand can sustain baseflow (Joosten and Clark, 2002; Smakhtin and Bachelor, 2005).

Wetlands in semi-arid climates are often dependant on groundwater discharge as seasonal rainfall is highly variable and considerably less than the maximum potential evapotranspiration rate (Jolly, *et al*. 2008; Sanderson and Cooper, 2008). High water availability generally promotes large evapotranspiration losses (Penman, 1948) especially in subtropical wetlands, although some wetland plants (including trees) can restrict water losses (Clulow *et al*., 2012). Groundwater recharge wetlands can impact local water resources (Roulet, 1990; Branfireun and Roulet, 1998; Bullock and Acreman, 2003), although the implications such as maintaining groundwater level or water quality improvement are often difficult to define. Wetlands receiving groundwater discharge reflect the input in terms of sustained wetness and water quality, and transform these into outputs such as organic (peat) accumulation that may directly affect downstream systems by augmenting flow in drier periods (Smaktin and Bachelor, 2005).

Typically single wetlands are not isolated features in the landscape but often part of wetland complexes linked by streams and or groundwater flow systems (Winter, 1999). It is necessary to understand the role of groundwater linking discharge and recharge wetlands in larger wetland systems, and their role in sustaining flow to downstream aquatic ecosystems so as to inform sound management decisions. Barnes *et al.* (2002) in a study on wetland water chemistry found that the Lake St. Lucia estuary on the Mozambique Coastal Plain of south eastern Africa is dependent on freshwater inflow filtered in the Mkuze Wetland System, which itself depends on stream flow and groundwater discharge. Sliva (2004) indicated that groundwater might play a role in swamp forest distribution on this coastal plain, and Grobler *et al.* (2004) concluded that the functioning of swamp forests in this region is strongly dependent upon their hydrological regime, and that hydrology best explains the vegetation relationships between natural and recovering previously disturbed sites. However, the hydrological regime and relationships were not measured and described in these studies.

This study focuses on the landscape hydrological setting of a large valley-bottom peatland (Mfabeni) that is straddled by large vegetated dunes and small isolated perched wetlands occurring in depressions between dune ridges. This wetland system is located on the Eastern Shores of Lake St. Lucia in the iSimangaliso Wetland Park, a World Heritage Site on the southern extent of the Mozambique Coastal Plain, South Africa (Figure 3.1). The surface and groundwater discharge from Mfabeni Mire and the adjacent Eastern Shores have created a freshwater refugia during hypersaline conditions in the St. Lucia Estuary (Colvin *et al*., 2007; Taylor *et al.*, 2006). The surface and groundwater exchanges of Mfabeni Mire were studied to understand the role of this large wetland complex in maintaining downstream water flows in a changing environment. The aim of this study was to characterize the groundwater exchanges through the system with specific objectives being 1) to understand the feedbacks between regional and local flow systems that contribute flow to downstream ecosystems, and 2) to develop a conceptual model of the system's hydrological function.

3.2 STUDY AREA

The Eastern Shores, the undulating landscape hosting Mfabeni Mire, comprises coastal dunes and wetlands bordered by the Indian Ocean to the east and Lake St. Lucia to the west (Figure 3.1). The region has a subtropical climate with hot and humid summers and mild winters (Taylor, 1991) with 60% of the annual precipitation occurring in summer; the mean annual temperature is 21ºC with the mean maximum monthly 35.3 ºC for January and the mean minimum monthly 5.5 ºC for June (Mucina and Rutherford, 2006). The mean annual precipitation is 1364 mm/year (1961 to 1989) at the coast and is 950 mm/year (1957-1989) at Charters Creek, 10 km inland (Wejden, 2003).

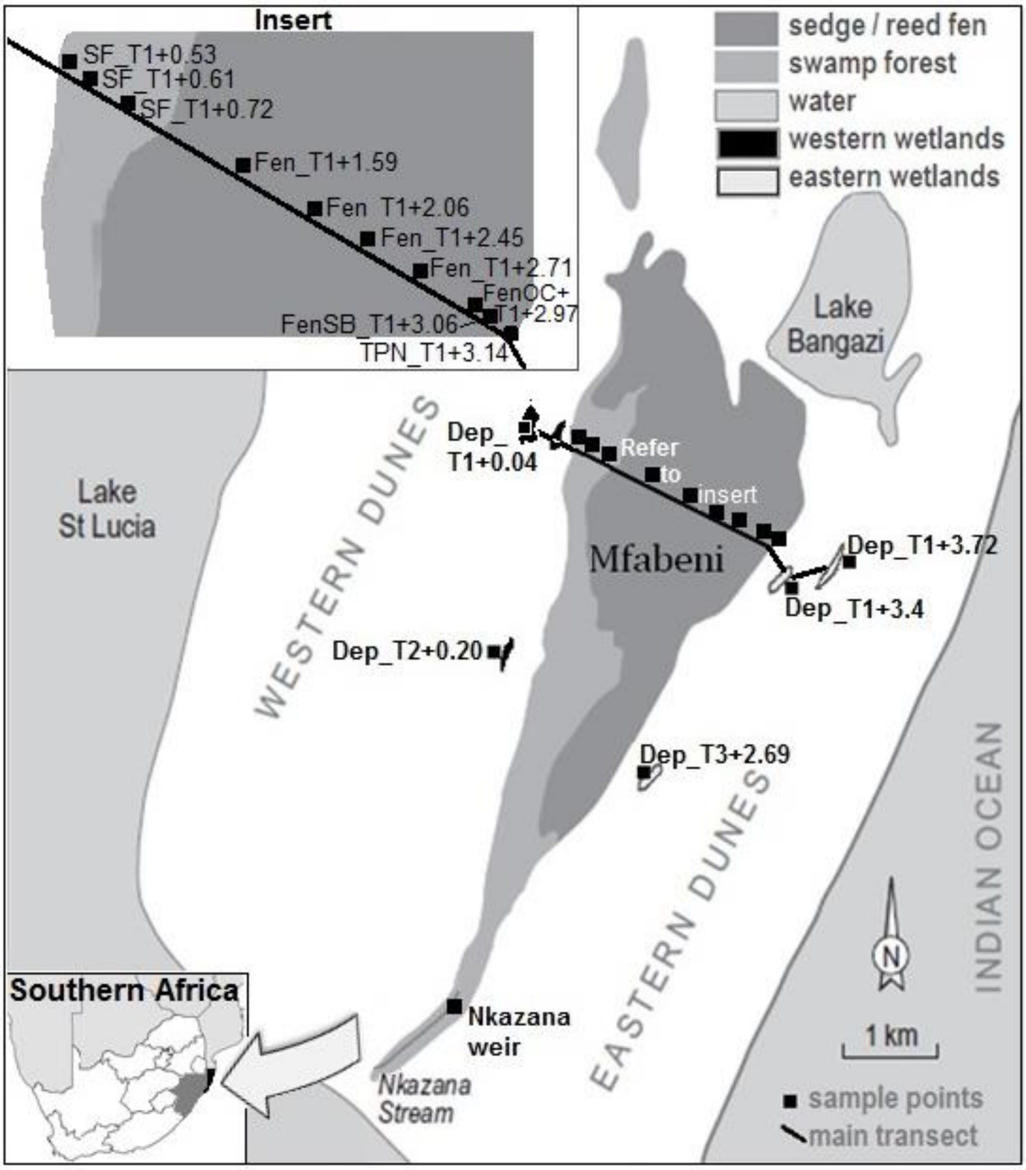

Figure 3.1: The landscape setting of Mfabeni Mire within the Eastern Shores of the iSimanagaliso Wetland Park, located between Lake St. Lucia in the west and the Indian Ocean in the east. Sample points and piezometer nests along the main transect are indicated.

Mfabeni Mire is located in a low-lying valley, bordered in the east by an 80-100 m high coastal vegetated dune cordon (eastern dunes) and in the west by the 15-70 m high Embombveni dune ridge (western dunes) (Davies *et al*., 1992). It is covered in the north and the east with sedge/reed communities (such as *Fimbristylis longiculmis*, *Cladium mariscus* and *Phragmites australis*), with swamp forest (dominated mainly by *Ficus trichopoda, Barringtonia racemosa,* and *Syzigium cordatum)* in the south and west (Grundling *et al*., 2000). The swamp forest achieves its maximum extent across the peatland towards the centre of the system. On the Eastern Shores land-use in the past focused on *Pinus* plantations established on terrestrial areas and in wetlands. These plantations were cleared in the early 2 000's to make way for wildlife conservation and tourism, now the primary designated land use activities.

Mfabeni Mire is an extensive fen, which has accumulated 11 m of peat during the past 44 000 years (Grundling *et al*., 2000; Chapter 2) in a landscape with a significant precipitation deficit (Munica and Rutherford, 2006). The peatland formed on a basal clay layer within an incised valley-bottom comprising reworked dune sands, and is bound in the north and south by beach ridges that separate it from Lake Bangazi and Lake St. Lucia, respectively (Chapter 2). Surface drainage is mainly southwards to Lake St. Lucia through the swamp forest on the western margin of the peatland with minor intermittent water exchanges to or from Lake Bangazi depending on lake levels. Rawlins and Kelbe (1991) investigated the impact of plantations on Lake St. Lucia and found that groundwater efflux from the western dunes may provide substantial recharge towards Mfabeni. Bjørkenes *et al*. (2006) supported this in a study on the groundwater-dependent ecology of the shoreline of Lake St. Lucia and speculated that discharge from the eastern dunes is intercepted by the Nkazana stream. Modelling by Været *et al.* (2009) suggested that groundwater seepage into Nkazana stream is maintained even though groundwater levels on the Eastern Shores drop significantly during dry periods. None of the previous groundwater investigations included the major peatland (Mfabeni) that separates the eastern and western dunes, and from which water discharges into the Nkazana Stream (Figure 3.1). Consequently, the linkages between the different dune systems, the peatland and its water regulation function that dictates the nature and magnitude of freshwater discharge to the St. Lucia estuary, remains undetermined. Typically these linkages would be a function of the hydraulic characteristics of the different sand and peat types comprising the Eastern Shores. Karupa (2008) found that the dunes comprise coarser sand than the smaller wetlands adjacent to Mfabeni Mire. Of the sand in the dunes 80% was between 200 µm and 500 µm compared to 60% of the sand in these wetlands, whilst the majority of the sand lenses in Mfabeni Mire's peat was mostly less than 200 µm. The sand dunes are therefore expected to be more permeable than the peat and sand lenses in the mire.

3.3 METHODOLOGY

The approach was to expand the existing terrestrial groundwater monitoring network (Taylor *et al.*, 2006) to include four transects across the mire from the western to the eastern dune cordon. Monitoring sites (Figure 3.1) were numbered from the toe of the western dune (the "0"-point) towards the eastern dune. The numbering system incorporated landform, transect number and distance (in km) away from the 0-point. The following landforms were included: Dep = Depression wetland; SF = Swamp forest; Fen = Fen; FenOC = Sand outcrop in fen; FenSB = Secondary basin in fen, and TPN = Terrestrial point.

Well- and piezometer nests (Figure 3.1 and 3.2) were installed by hand in the peatland, and with a truck-mounted hollow-stem auger drill rig in the eastern and western dune cordons. Wells and multi-level piezometer nests at 43 sites were installed at different depths based on the peat or dune stratigraphy; up to depths of ~10 m in the peat, 16 m in the clay beneath the peatland, and to a depth of 30 m in the sandy uplands (24 of the 43 sites were located within Mfabeni Mire). Wells and piezometers within the peat were 0.05 m diameter PVC tubes covered with geotextile screening; slot lengths for piezometers were 0.2 m. Solinst^{TM} Model 615 20 mm diameter drivepoint piezometers were installed in the sand or clay below the peat. Wells and piezometers in the adjacent sand dunes were 0.05 m diameter PVC tubes; slot lengths were 1.0 m and were covered with a geotextile screening. Water levels within the wells and piezometers were monitored manually with an electronic probe on a weekly basis for 4 years from April 2008 to May 2012.

The rainfall in the mire was measured during this 4-year period with 13 manual rain gauges and two tipping bucket rain gauges (TE525, Texas Electronics Inc., Dallas, Texas, USA) (refer to Chapter 5 for more detail on rainfall measurements). A compound weir was constructed beneath the Nkazana Bridge to measure the efflux from Mfabeni Mire to Lake St. Lucia. The weir was calibrated by damming the water behind the weir and releasing the water at different levels in order to measure discharge at these flow levels with a calibrated bucket and using the Kindsvater-Carter equation for the V-notch (Kindsvater and Carter, 1959)

$$Q = 8/15\ c_d\,(2\ g)^{1/2}\ tan(\theta/2)\ h^{5/2} \qquad 1$$

where, Q = water flow rate, m^3/sec; θ = v-notch angle; h = head on the weir (m); Cd = discharge coefficient, average 0.469; g = gravitational constant, 9.81 m/s^2; b = width of the weir (m)

Bazin's formula (Bansal, 2010) was used for the square (rectangular) section

$$Q = 0.66\ (Cd)(B)(2g)^{0.66}\ H^{1.5} \qquad 2$$

where Q = water flow rate, m^3/sec; B = width of the weir, metres; Cd = discharge coefficient, average 0.62; g = gravitational constant, 9.81 m/s^2; H = height of the water over the weir, measured behind the weir edge, m.

The water level behind the Nkazana weir was measured every 15 minutes with a Solinst^{TM} pressure transducer. The calibrated Kindsvater-Carter equation was applied to the measured water levels to determine the discharge of the Nkazana stream at the bridge. Data was lost for the period mid February 2009 till May 2009. Therefore discharge for this period was inferred for the Nkazana stream by correlation with the discharge pattern of the Mpate stream measuring weir 15 km to the southwest and 8 km from the coast, which exhibits similar discharge patterns to the Nkazana weir (Appendix 1). This rectangular weir measures stream flow from a 10 300 ha catchment on the Western Shores of Lake St. Lucia located on the Maputaland primary aquifer comprising highly permeable sandy soils. The $18x10^6m^3$/year estimated stream flow from the Mpate River is approximately four times the groundwater flow of the Eastern Shores (Nomquphu, 1998).

The hydraulic parameters: gravimetric and volumetric water content, bulk density, porosity, specific yield and hydraulic conductivity for sand and peat were measured. The gravimetric content, bulk density and volumetric water content were calculated and determined using the following methods (Rowell, 1994):

Gravimetric water content in percentage (%) was determined using

$$\theta m = 100 \frac{mt - ms}{ms} \qquad 3$$

where Θm is gravimetric water content; *mt* is the weight of wet soil sample, and *ms* is the weight of dry soil sample.

Bulk density of dry soil sample, which is expressed in g/cm^3, was determined as

$$pb = \frac{ms}{Vt} \qquad 4$$

where, ρb is the bulk density and *Vt* is the volume of wet soil sample.

Volumetric water content in percentage (%) was determined as

$$\theta = \theta m \left(\frac{\rho b}{\rho t}\right) \qquad 5$$

where Θ is the volumetric water content and ρt is particle density, which is assumed to be 2.73 g/cm^3 (standard value for sand particles) and 1.4 g/cm^3 (for dried peat) (Brady and Weil, 1998).

Porosity expressed in percentage (%) was calculated using

$$\alpha = 100 - \left[100 \left(\frac{\rho b}{\rho t}\right)\right] \qquad 6$$

Specific yield (*Sy*) is the volume of water released per unit area of soil, for unit change in water table, and was measured from 0.05 m sections of peat monoliths which were saturated, then drained for 24 h. Specific yield was calculated as

$$Sy = \frac{[(\mathrm{M}saturated - \mathrm{M}drained)/\rho\mathrm{w}]}{\mathrm{M}saturated/\rho\mathrm{w}} \qquad 7$$

where *M* is mass, and ρw is density of water, assumed to be 1000 kg m^{-3}.

Vertical hydraulic conductivity was determined with a constant head permeameter on cores extracted from 5 peatland sites, 2 depressions and 1 terrestrial site. Additional horizontal hydraulic conductivity measurements were made using the bail test procedure described by Hvorslev (1951), in the wells and piezometers described above. Well and piezometer tops and surface elevation were surveyed using DGPS and a dumpy level was used to determine elevation changes within the swamp forest. The two-dimensional groundwater software package USGS Topodrive was used to guide the depiction of isopotential lines and flow net for the main transect.

3.4 RESULTS

3.4.1 Hydrology - Regional Water Table Distribution

The most distinct feature of the regional water table is the groundwater mound beneath the western dunes, which creates a water table divide isolating the wetland complex from Lake St. Lucia to the west. This groundwater mound (previously reported by Rawlins and Kelbe (1991) and Taylor *et al.* (2006)) was assessed with February 2009 (summer) water table data provided by the KwaZulu-Natal Wildlife Research Office in iSimanagaliso Wetland Park. This study considers only the area to the east of this divide, from which the water table slopes towards the Indian Ocean (Figure 3.2). The water table (February 2009) was 13 m above mean sea-level (a.m.s.l.) beneath the western dune complex (20 to 50 m below its surface). From the western mound to the swamp forest on the western margin of the peatland it followed a shallow consistent gradient (0.5 to 2.0 m below surface). At the swamp forest the gradient steepened (0.2 to 0.1 m below surface), from where it sloped gently towards the east along the surface of the sedge fen section (7 m a.m.s.l.) and from its eastern margin the water table dipped more steeply below the eastern plain and the coastal dune (1 to 80 m below surface) towards the ocean (Figure 3.2). Perched conditions (between 7 and 7.5 m a.m.s.l., associated with a thin subterranean organic layer bordering the mire) are evident on the eastern margin of the mire. Further to the south where the system narrows and the swamp forest covers its full extent the water table is characterised by a strong gradient southwards to Lake St. Lucia (Figure 3.2)

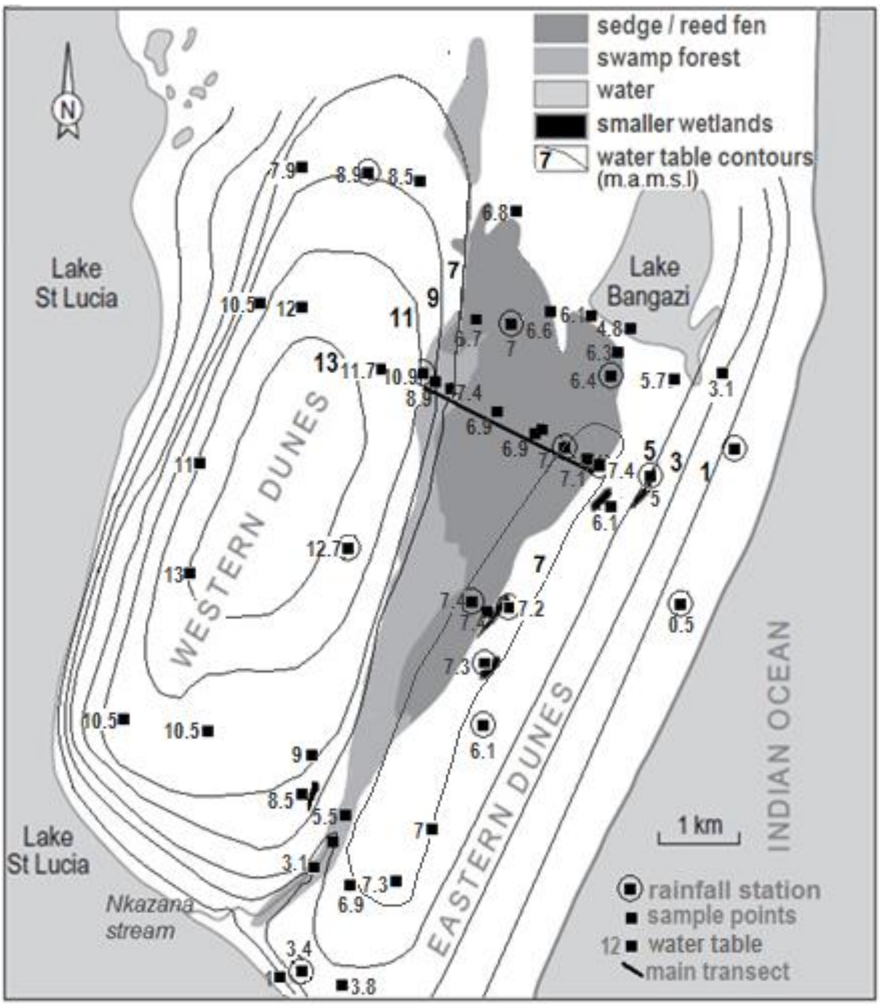

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Figure 3.2: The water table during a relatively wet period (February 2009). Contour interval is 2 m.

3.4.2 Hydrogeology

Mfabeni Mire consists of an ~11 m thick peat deposit, located on an impeding clay layer (Figure 3.3) within a valley-bottom setting with permeable reworked aeolian marine sands defining the peat basin margins (Chapter 2). Relatively thin sand layers (0.3 to 0.5 m) interbedded in peat act as preferential flow zones in the eastern part of the peatland (Figure 3.3). The peat consists of a fairly coarse surface layer (H3 on the Von Post Humification Scale) and increase rapidly in humification with depth. Mire vegetation comprises swamp forest in the west, partially on the footslope of an east-facing dune, with the majority of the mire consisting of sedge/reed fen (Figure 3.3). Grassland covers the dunes to the west with mixed grassland dune forest covering the coastal dunes in the east.

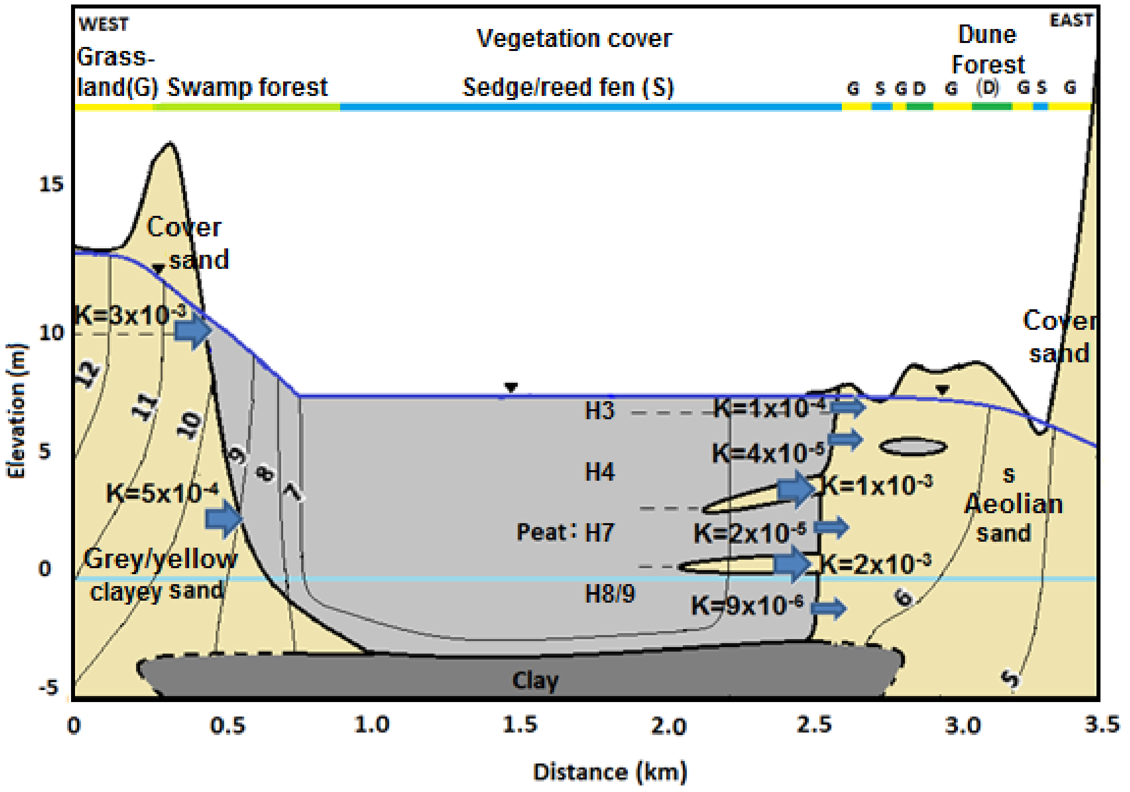

Figure 3.3: Schematic diagram of the simplified hydrogeology of Mfabeni Mire with hydraulic conductivity in cm s^{-1} and equipotential lines (grey lines). Large blue arrows indicate flow through sand and the smaller arrows the flow through peat. Peat humification based on the Von Post scale is indicated by H.

3.4.3 Groundwater flow

The hydraulic gradients in the summer groundwater flow net (Figure 3.4) indicated water arriving from the western dune following a horizontal gradient. The flow lines indicate groundwater discharges at the swamp forest and flows across the fen along the gentle slope to the east.

At the eastern margin of the fen where there are interbedded sand layers (Figure 3.4), there was a downward hydraulic gradient and the flow lines turn downward (recharge), after which groundwater flows underneath the coastal dune complex towards the ocean. The winter flow patterns (not shown) were similar to summer with a marginal (0.2 m) decrease in hydraulic head on average in winter, the drier period. The hydraulic gradient was somewhat steeper below the swamp forest (0.006) compared to the fen (0.001) and in sand layers (0.002) east of the fen with an upward groundwater flow (0.06) developing in western half of the mire. Flow lines (not shown) based on the water table elevations (Figure 3.2) suggest flow is captured further downstream by the Nkazana stream draining southwards to Lake St. Lucia; whilst northwards flow into Lake Bangazi occurs only during high rainfall events. The output from USGS Topodrive used to guide the depiction of isopotential lines and flow paths shown in Figure 3.4 are included in Appendix 2.

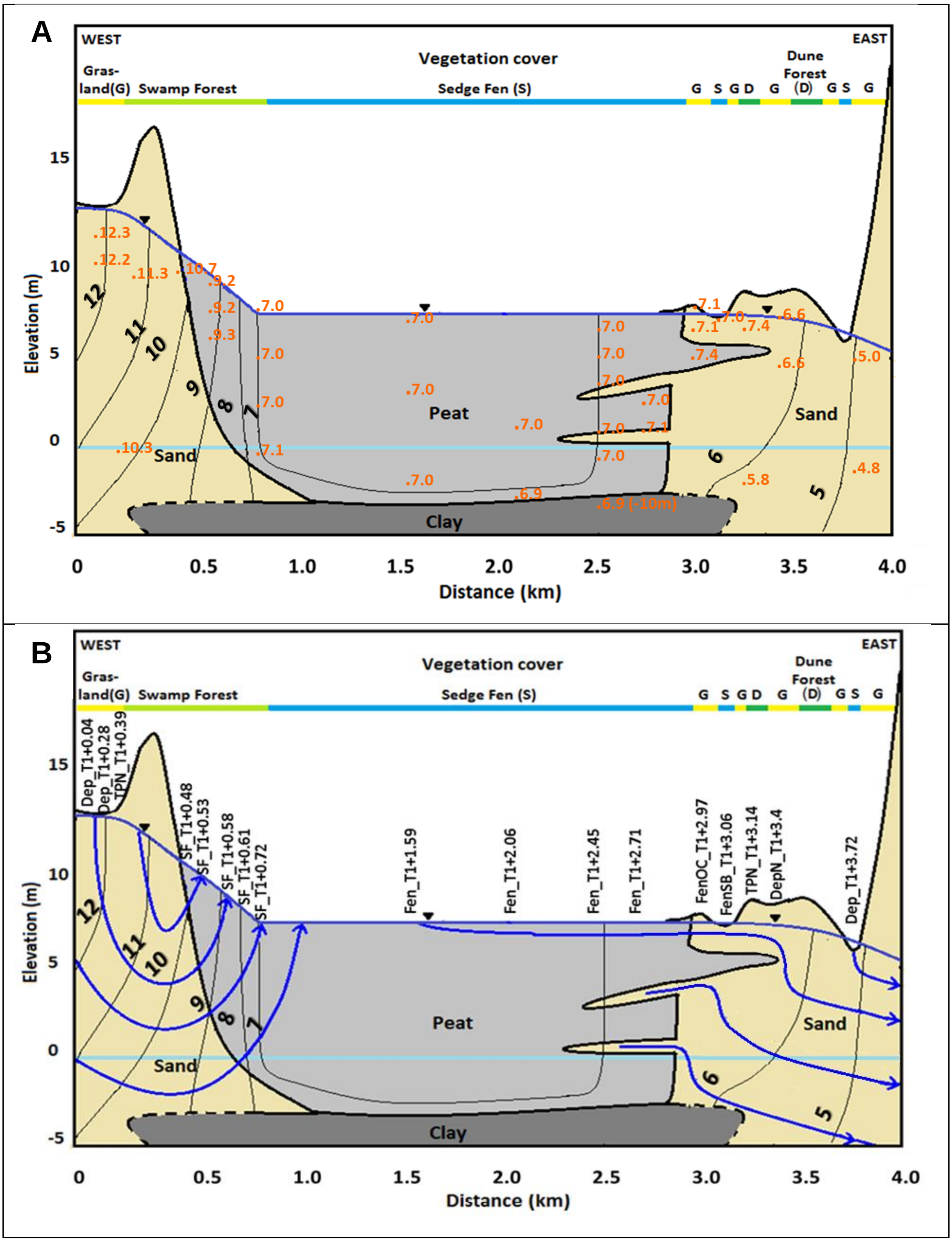

Figure 3.4: A) Measured hydraulic head of the main transect; and B) Flow patterns along the main transect through Mfabeni for the summer, February 2009.

3.4.4 *Response to rainfall events*

Rainfall occurred throughout the year, but with medium to large events (> 25mm/day) occurring more frequently in summer compared to winter (Figure 3.5). An average rainfall of

942 mm/year was recorded for the calendar years of 2008 to 2012, with the driest year 2010 (816 mm) and 2011 the wettest (1 136 mm). Hydraulic head decreased with time at all sites from April 2008 - September 2011, stabilised with spring rains in October 2010 and rose significantly after extensive winter rains in 2011. Tropical storm Irene in March 2012 flooded the Eastern Shores with 280 mm of rain in 24 hours, raising water levels sharply, after which it dropped again (within 30 days) to pre-event levels in the swamp forest (SF_T1+0.72) and fen (Fen_T1+2.45). However, the adjacent terrestrial site (TPN_T1+3.14) maintained higher levels (~0.4 m) than before the event for 90 days.

The swamp forest (SF_T1+0.61 and SF_T1+0.72) and fen (Fen_T1+2.45) hydrograph peaked faster in response to rainfall and had a faster initial drawdown (Figure 3.5), but maintained a higher base level than the terrestrial site (TPN+3.14) and smaller depression wetlands to the west (Dep_T1+0.04) and east (Dep_T1+3.72). The western depression (Dep_T1+0.04) at the toe of the western dune complex experienced a deeper drawdown (0.4 m) than the other sites during the drier period in 2008/09. The swamp forest (SF_T1+0.72) hydrograph showed a more dampened response (0.15 – 0.25 m in water table fluctuation) similar to that of the fen (0.1 – 0.15 m), whilst the terrestrial site (TPN_T1+3.14) indicate a larger drawdown (0.3 m) during the drier period (but not as large as that of the western depression). The eastern depression (Dep_T1+3.72) indicates lower groundwater levels of 0.3 m during this drier period.

During the severe dry period of the 2011 winter the western depression (Dep_T1+0.04) experienced a deeper drawdown of 1.2 m compared to the swamp forest (SF_T1+0.72), fen (Fen_T1+2.45) and terrestrial site (TPN_T1+3.14) with a drawdown of 1.0 m. The eastern depression (Dep_T1+3.72) hydrograph indicates a drawdown of only 0.8 m during this dry period.

This dry winter period was followed by a very wet summer resulting in very pronounced differences between low and high levels of 0.5 and 0.8 m for the swamp forest (SF_T1+0.72) and fen (Fen_T1+2.45), respectively. The groundwater immediately east of the fen at (TPN_T1+3.14) fluctuated with 1.2 m, and effectively reached the same level as in the fen during the high stand in March 2012. No flow reversals were evident at this time between the different sites (i.e. flow direction was consistently to the east).

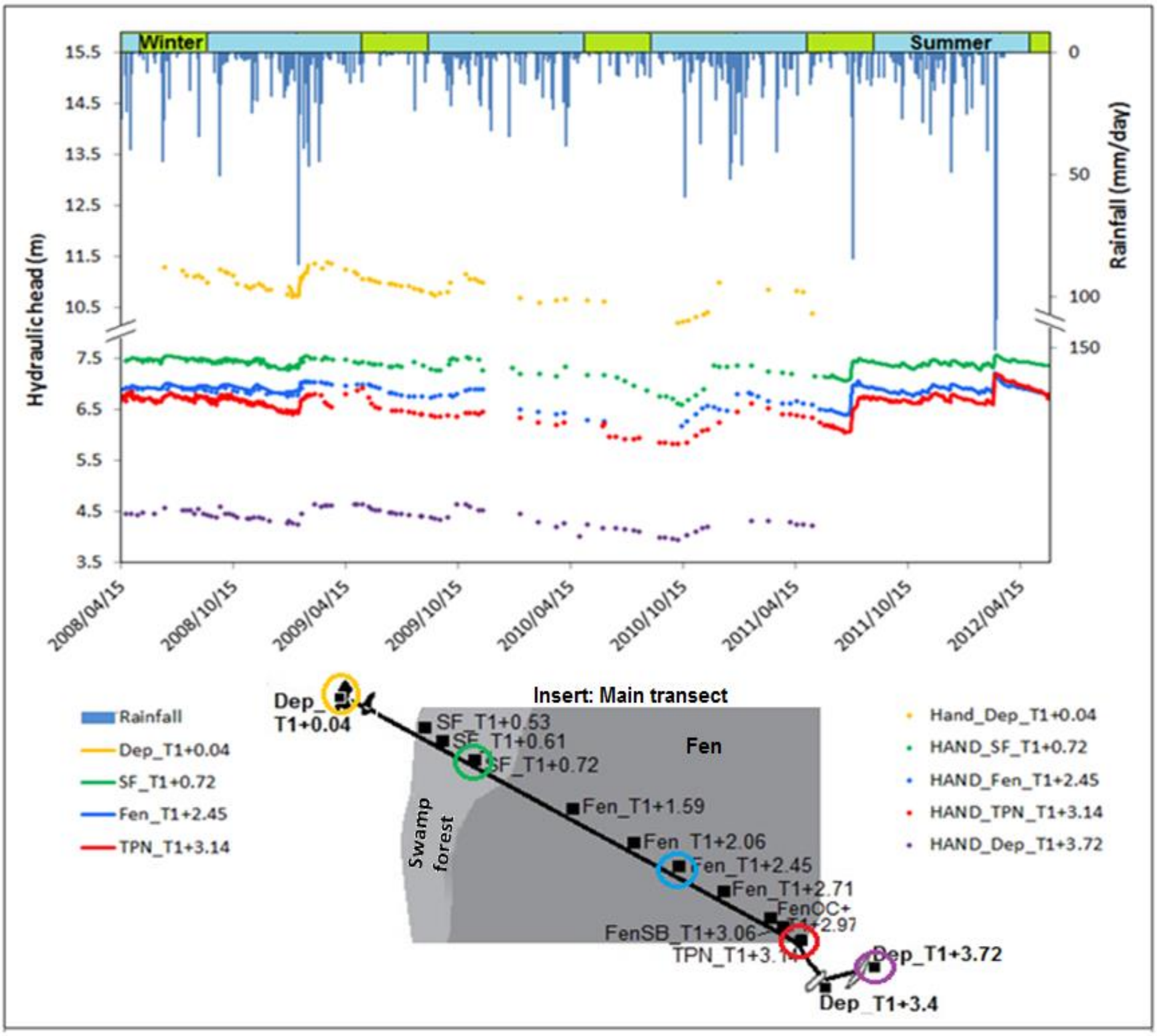

Figure 3.5: Hydrograph of the hydraulic head response to rainfall events across the peatland and adjacent wetlands to the west and east. Points represent manual measurements; lines are continuous data from pressure transducers. Note: no rainfall data available from middle March to April 2012.

3.4.5 Inundation patterns of Mfabeni Mire and adjacent wetlands

Stage duration curves showing the proportion of time for specified water levels are much flatter for the swamp forest and eastern depression sites (represented by SF_T1+0.72 and Dep_T1+3.72 respectively, Figure 3.6) compared to the fen (represented by Fen_T1+2.71, Figure 3.6) and western depression sites (represented by Dep_T1+0.04; Figure 3.6). The temporary wet western depression was not inundated during the monitoring period (Jun 2008 to May 2011), with the water table 0.96 m below surface at median, and above 1.25 m below surface for more than 80% of the time. The swamp forest sites were not inundated during the monitoring period (Aug 2007 to May 2011), with the water table 0.23 m below surface at median, and above 0.35 m below surface for more than 80% of the time. The fen sites (monitoring period May 2008 to May 2011) were inundated 10 to 20% of the time, with the water table 0.15 m below surface at median, and above 0.48 m below surface for more than 80% of the time. The seasonally wet eastern depression was not inundated during the monitoring period (May 2007 to May 2011), with the water table 0.75 m below surface at median, and above 0.88 m below surface for more than 80% of the time.

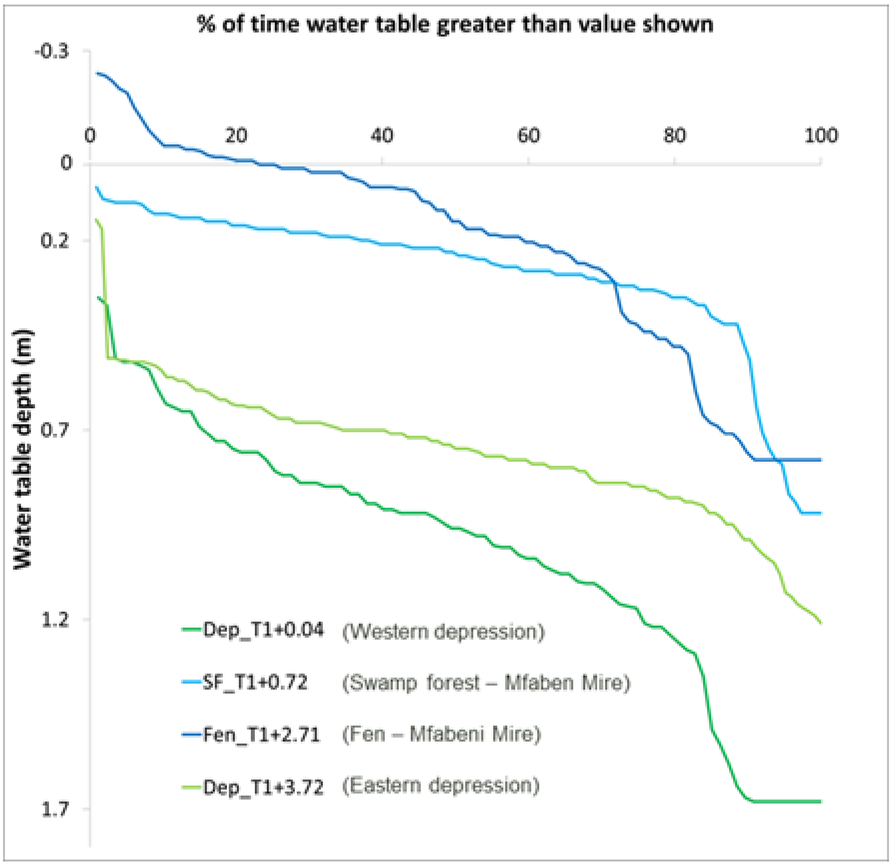

Figure 3.6: Water table duration curves for Mfabeni Mire and selected adjacent wetlands. Flat curves towards the end of the time indicate periods when the water table dropped below well level.

3.4.6 Streamflow response to rainfall

The streamflow hydrograph indicates a rapid response of the Nkazana stream to rainfall events (Figure 3.7). It shows a high peak with a near vertical rising limb that developed within a day, with the falling limb gradually declining over one to five weeks depending on the magnitude of rainfall events and the season (dry or wet). Peak flows occurred within 12 hours of large rainfall events (≥40 mm) during wet spells, with drawdown gradually over time (four to five weeks). The stream responded within 12 to 36 hours during large rainfall events during drier periods with a shorter drawdown of two to three weeks. Even smaller rainfall events of 10 to 15 mm resulted in a noticeable response in a wet season (e.g. the end of May 2008), whilst larger events (20 to 25 mm) produced a subdued peak in drier periods (e.g. middle November 2008). Sustained low flows of less than 120 m^3/day occurred for 35% of the time.

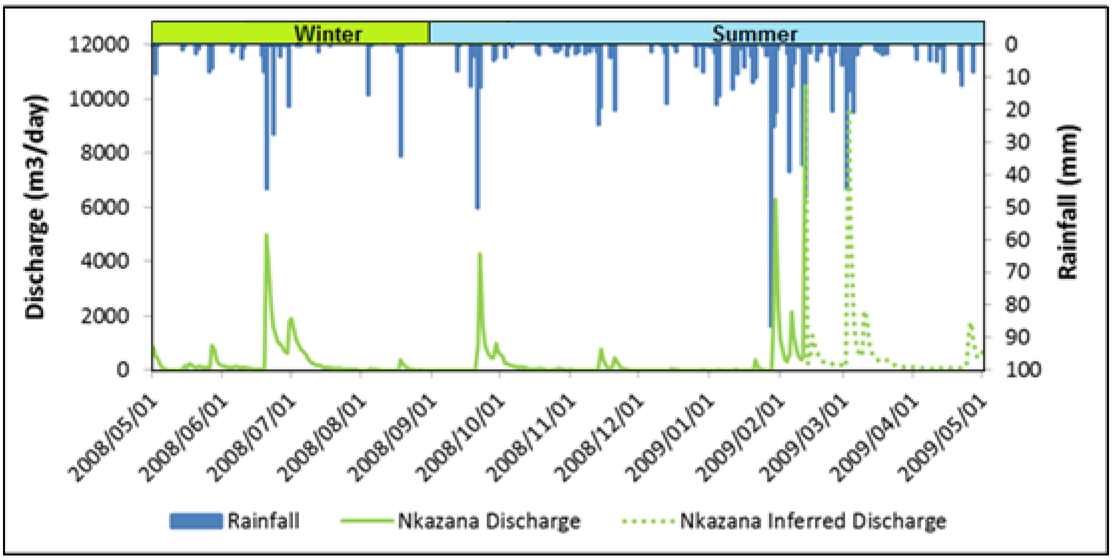

Figure 3.7: The hydrograph for the Nkazana stream indicates the nature and persistence of the efflux (360 m^3/day) from Mfabeni to Lake St. Lucia.

3.4.7 Hydraulic properties

The vertical hydraulic conductivity of the fen peat near the surface (Fen_T0+3.52, Fen_T1+2.71, FenSB_T1+3.06 and Fen_T2+2.04) was typically between 10^{-3} and 10^{-4} cm/s, and decreased about half an order-of-magnitude at 2.5 m depth (Figure 3.8). Swamp forest peat (SF_T1+0.53) was within this range but showed a smaller decrease with depth in the upper layer. Sand with substantially higher hydraulic conductivity was found at the base of most peat profiles. The exception was in the central part of the peat basin (Fen_T1+2.71), which was underlain by clay, but with interbedded layers of sand with much higher hydraulic conductivity (about two orders-of-magnitude) towards the middle part of the peat profile. The shallower peat profiles are likely not underlain by anything but mineral sediments. In profiles dominated by sand (Dep_T1+0.04, FenOC_T1+2.97 and TPN_T1+3.14) the vertical hydraulic conductivity was ~10^{-2} to10^{-3} cm/s.

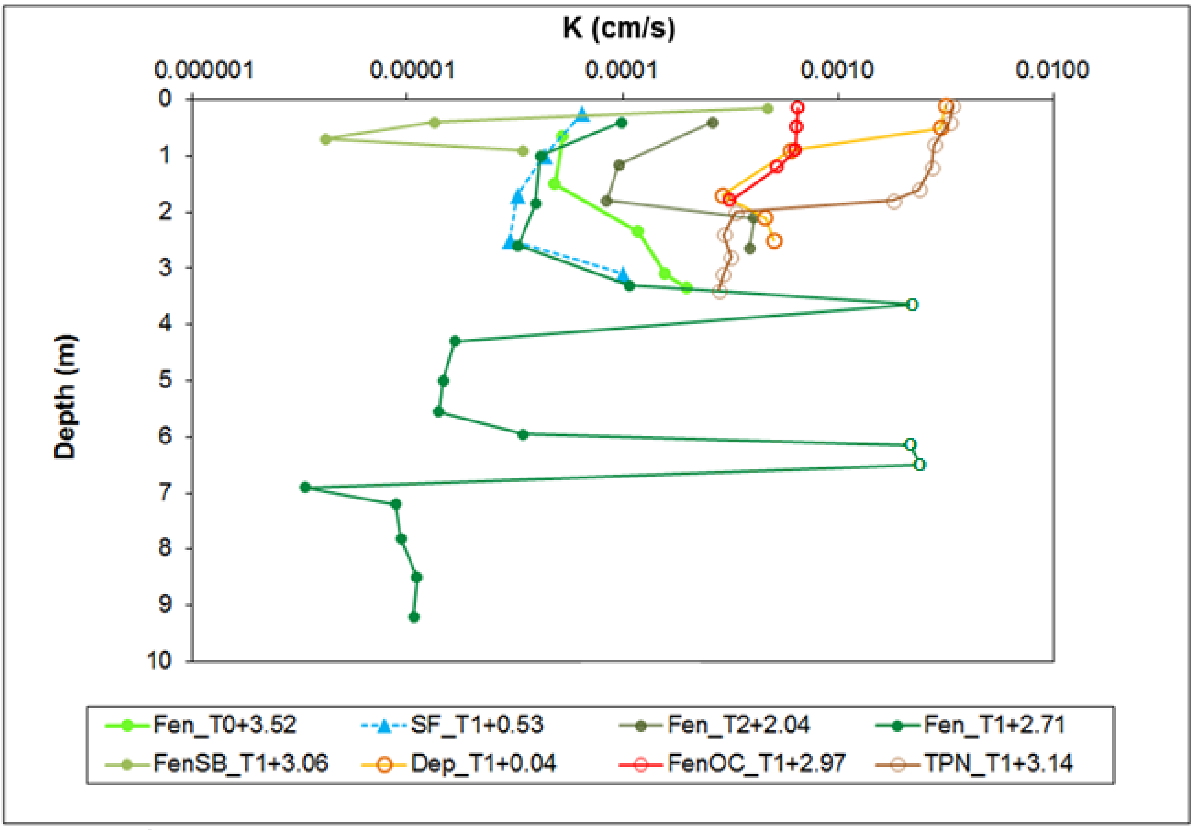

Figure 3.8: Vertical hydraulic conductivity of peat (solid circles) and sand (open circles.) of Mfabeni Mire and adjacent wetlands.

The different geometric means for horizontal hydraulic conductivity of substrates comprising the hydrogeology of Mfabeni Mire are presented in Figure 3.9 compared to the geometric means of vertical hydraulic conductivity of substrates. The sand layers typically exhibit the same vertical and horizontal means of $2.7x10^{-3}$ cm/s with the lower sand layers with clay about half an order-of-magnitude less ($5.4x10^{-3}$ cm/s). The horizontal mean hydraulic conductivity for the swamp forest peat ($5.4x10^{-3}$ cm/s) is an order of magnitude more than the vertical value ($4.9x10^{-5}$ cm/s). The difference is even more pronounced for the fen peat, with horizontal mean of $2.2x10^{-3}$ cm/s compared to the vertical of $4.6x10^{-5}$ cm/s. The basal clay layer has a horizontal hydraulic conductivity of $5.1x10^{-6}$ cm/s; no vertical values were determined.

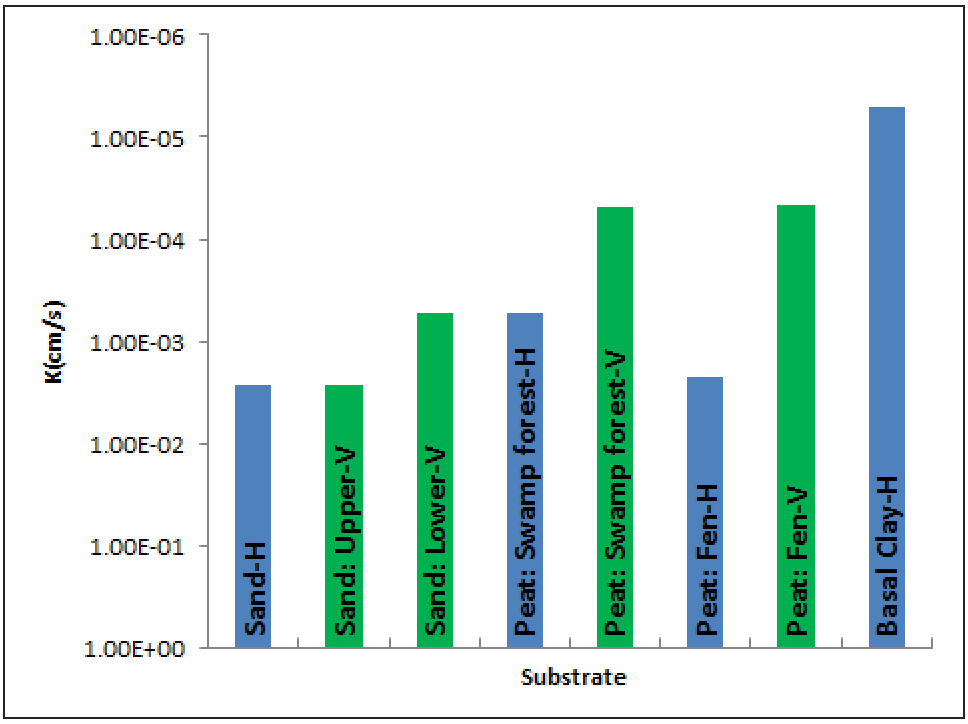

Figure 3.9: The geometric mean of the horizontal hydraulic conductivity (blue bar:H) for the different substrates comprising the hydrogeology of the Mfabeni Mire, based on piezometer bail tests, compared to the geometric mean of the vertical hydraulic conductivity (green bar:V), determined with a permeameter.

Specific yield for the upper 0.4 m of peat at 7 individual sites were determined. The 4 sites in the sedge fen had an average of 0.19 (n = 25; standard deviation = 0.062) and 3 sites in the swamp forest averaged 0.15 (n = 8; standard deviation = 0.055).

3.5 DISCUSSION

Rainfall measured from 2008 to 2012 indicates an average rainfall of 942 mm/year compared to the long-term average of 1 364 mm/year (1961 to 1989) at the coast and is 950 mm/year (1957 to 1989) at Charters Creek, 10 km inland (Wejden, 2003). A drying trend commencing in the 2008 season is evident; it intensified in 2010 and persisted until 2011. Monitoring for this study in 2007 commenced in a cyclical drier period during which rainfall was well below average. This dry period began in 2001 and lasted until 2012 (Taylor, 2013. The water table in the fen and swamp forest dropped to 0.7 to 0.9 m, respectively, below the peat surface as these drier periods intensified (Figure 3.6); likely resulting in accelerated decomposition of the peat in these mires during drier periods. It has been noted that peatlands in this region experience marked lower water levels, and that it is usually only during larger (extreme) rainfall events such as tropical storms responsible for recharging the groundwater of the regional primary aquifer that inundation is restored (Grundling, 2014).

The groundwater flow patterns across Mfabeni Mire (Figure 3.4) suggest the western dunes are the primary recharge zone; the water discharges into the peatland primarily at the western margin corresponding to the position of the swamp forest. Swamp forests elsewhere on the coastal aquifer are also associated with drainage lines (Grundling *et al.*, 2013) where groundwater discharge is probable. The open fen receives some groundwater directly from deep discharge but also receives water from the adjacent swamp forest, as the relative positions of their water tables suggest (Figure 3.5). However, upward hydraulic gradients of between 0.06 to 0.17 occur in the western part of the mire (between SF_T1+0.72 and Fen_T1+1.59) compared to no upward gradients in the eastern part of the mire between Fen_T1+2.45 and Fen_T1+271, therefore suggesting this is a minor water source for the open fen (Figure 3.4). Likewise, the low hydraulic gradients over the peatland that range from 0.006 between the western edge (TPN_T1+0.39) of the swamp forest to SF_T1+0.72 within, to 0.001 between the swamp forest (SF_T1+0.72) and the fen (Fen_T1+1.59) (Figure 3.4). Evapotranspiration is a major water sink for Mfabeni Mire and may exceed rainfall in drier periods (Clulow *et al*., 2012). Direct rainfall on the fen due to its relatively large size is important and together with groundwater inflows these water inputs maintain a high water level in the fen (80% of the time less than 0.4 m below surface), with the surface inundated 10 - 20 % of time (Figure 3.7). The input of groundwater is an important feature of peatlands where there is a strong water deficit (Glaser *et al*., 1997; Almendinger and Leete, 1998); here it has an important stabilizing effect on water table elevation, as evident from the relatively flat stage-duration curves for peatland sites (Figure 3.7). Since the water table dips downward from the fen under the eastern dunes, the eastern side of Mfabeni appears to be a recharge zone. This recharge may be enhanced by the lenses of sand buried in the eastern section of the peatland (Figure 3.4), which correspond to incursion/expansion of the dune over the peatland at an earlier time in its development (Chapter 2).

Groundwater recharge in the western dunes was previously noted by Rawlings and Kelbe (1991), Kelbe and Rawlings (1992), Bjørkenes *et al.* (2006) and Taylor *et al*. (2006). While these modelling studies did not include any groundwater measurements in Mfabeni Mire, they suggested (and supported by Vaeret, 2009) groundwater flow from the eastern dunes towards Mfabeni Mire. However, this study does not support these findings as the abrupt steepening of the water table from west to east at the eastern margin of the mire and the hydraulic gradients clearly indicate flow eastwards away from the mire to the ocean. A likely explanation is that a change occurs in the underlying geological strata at the eastern edge of the mire. The basal clay lens present below the mire (Figure 3.4), which separates it from deeper hydrogeological connections, gives way to younger more permeable cover sands (Chapter 2) that increase the flow rate towards the Indian Ocean, and lower the water table beneath the eastern dunes.

This and other studies (Rawlings and Kelbe (1991), Taylor *et al. (*2006), Vaeret *et al*. (2009) indicate that the primary recharge zone is the western dunes, which are ~2.8 – 3.4 km wide and up to 60 m high). Originally, a symmetrical pattern of recharge was anticipated in the eastern dune cordon (~1.7 – 2.2 km wide and up to 90 m high) and corresponding discharge on the eastern side of Mfabeni. The apparent absence of an eastern groundwater mound was initially postulated by Rawlings and Kelbe (1991) and Kelbe and Rawlings (1992) on the basis of modelling with limited field verification. While the mound was not present during the course of this study it is potentially a transient feature or it may have waned over the previous 5 decades while pine plantations were present on the eastern dune (before being removed in 2006). It is uncertain, therefore, if the eastern dune was ever a long-term source of water for Mfabeni; the absence of a swamp forest at the eastern margin of the peatland adjacent to the eastern dunes, seems to indicate an absence of groundwater discharge at that location (Grobler *et al.,* 2004), hence the absence of a stable groundwater mound in the eastern dunes.

In contrast to the above statement, the presence of a woody peat layer across the surface of the mire (Chapter 2) indicates historically favourable conditions for swamp forest colonisation of the mire as is still present in the southern part of the mire. As alluded in Chapter 2 the historic climatic conditions indicated that the swamp forest reached its maximum distribution during a warm moist period which ended 2 450 years BP followed by a wetter period when waterlogged (inundated conditions) dominated the surface of Mfabei Mire. The current extent of the swamp forest in the mire is linked to areas where the topography is sloped and where groundwater discharge is evident. Therefore conditions favourable for swamp forest colonization are a persistent and stable water supply, but without inundation (damming) on the surface. Personal observations further north in the park support this conclusion where a low level bridge caused damming of a swamp forest (a raise in the water level of 0.2 m was noted) with the resultant extensive swamp forest die-back.

In Chapter 2 it was hypothesised that Mfabeni Mire might have lost water through the eastern dune to the coast due to the regional geology. Currently, the western dunes are either bare or vegetated by relatively sparse graminoid cover, compared to remnant dune forests on the eastern dune, which still cover ~ 40% of it. The absence of a forest cover on the western dune and its lower elevation and broader extent, all conspire to enhance recharge thus providing a continuous water supply for Mfabeni, and eventually the St. Lucia Estuary.

It appears that the surface and subsurface flow along the topographic gradient are more critical in keeping the peatland wet and maintaining its functions as the groundwater contribution through the peat are limited due to the low hydraulic conductivity of the deeper more decomposed peat layers. The hydraulic conductivity in the sand (10^{-2} to 10^{-3} cm/s) is more than an order of magnitude higher than in peat (10^{-3} to 10^{-5} cm/s). Consequently water migrating eastward through the western sand dune encounters the Mfabeni peat which acts as a plug, forcing water to discharge at its western margin, most strongly where the swamp forest is present, with subsurface flows towards the east in the upper less humified peat layers. Deeper flows pass more slowly into the fen through the more humified peat, and water moves towards the eastern margin and eventually to the sea (Figure 3.9). The Nkazana stream, within the swamp forest, captures surface water in the southern section and drains to Lake St. Lucia. Given the elevation of the groundwater mound beneath the western dunes, groundwater flow is also directed to the Estuary to the west (not shown) and to the south (Figure 3.9).

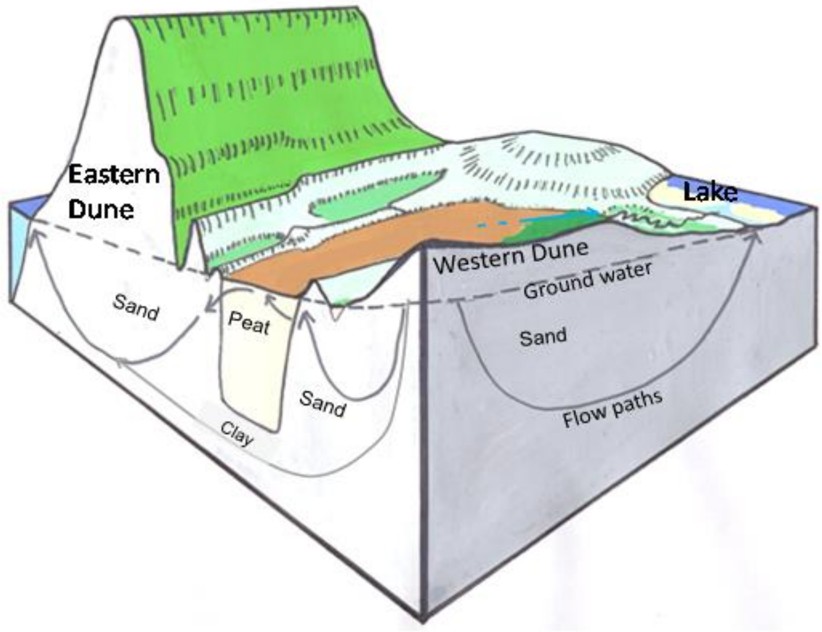

Figure 3.9: Conceptual model for groundwater flow from the western dune through Mfabeni Mire to the coast (grey arrows). Surface flow is intercepted in the south by the Nkazana stream flowing to Lake St. Lucia (blue arrow).

Nkazana Stream originates from within the swamp forest, with a distinct channel extending to about 4 km upstream from Nkazana crossing. The catchment area is difficult to determine, and probably transient. Drainage from the open sedge fen is not occurring at Transect 1, where swamp forest water table elevation is higher than the adjacent fen. The hydrograph for Nkazana Stream had a rapid response to rainfall ≥40 mm (Figure 3.7). During these larger rainfall events when the peatland is inundated to higher levels the contributing area expands (Devito *et al*., 1996) and streamflow response increases (Boelter and Verry, 1977). The swamp forest being the primary contributing area, maintains wet antecedent conditions due to the groundwater discharge that occurs there (Figure 3.7). Baseflow in the stream was maintained at 360 m^3/day, which is likely due to the steady input of groundwater originating in the western dune system. Consequently, groundwater inflow and storage change in the wetland are important components in maintaining internal ecological processes and regulating stream flow towards Lake St. Lucia. The relatively wet condition of the fen and swamp forest, however, causes a rapid translocation of rainwater through streamflow. On the other hand, the relatively wet condition of the fen and swamp forest increase the evapotranspiration losses compared to water that is recharged in the dunes (Clulow *et al*., 2013).

Mfabeni Mire covers 31% of its topographically defined catchment (but 44% of the catchment as defined by groundwater inflows – i.e. discounting the eastern dunes) and is inundated during wet periods. This relatively high percentage coverage by an inundated surface in the catchment with highly permeable sands has a profound impact on the hydrological characteristics of Mfabeni Mire and the nature of the efflux of water from this system to Lake St. Lucia. The Nkazana hydrograph indicate a rapid response of the stream to rainfall events (Figure 3.7), suggesting that rainfall events on the saturated surface of the mire (due to sustained groundwater discharge) is an important driver in determining high flow efflux events to Lake St. Lucia.

3.6 CONCLUSION

It is often assumed that wetlands are sources of water, sustaining base flow to downstream ecosystems (Bullock and Acreman, 2003; Charles and Nicholson, 2012). This study has shown that water efflux from the western inland dune complex provides substantial recharge towards Mfabeni, while coastward hydraulic gradients from the dune complex through the wetland are evident. However, only a small portion of groundwater from the inland dunes flows through the mire towards the coast in the east, whilst the major portion of groundwater from the inland dunes is forced to discharge southwards via Nkazana Stream into Lake St. Lucia due to the plug effect of the relatively low hydraulic conductivity peat in the Mfabeni mire (i.e. compared to the sands that carry water towards it). Therefore, these wetlands are more of a conduit responding to regional hydrological dynamics, rather than a source. The relatively wet condition of the peatland causes not only a rapid translocation of rainwater through streamflow but could contribute to an increase in the evapotranspiration losses.

These systems are susceptible to land-use change in catchments that will interrupt the feedbacks between regional and local flow systems. The depletion of the regional groundwater on the Eastern Shores by decades of commercial timber and the interception of rainwater by these unnatural forests (Rawlings and Kelbe, 1991; Taylor *et al*., 2006) could also have led to a significant lowering in the groundwater mound below the eastern dune complex. The cumulative impact of a lowered groundwater table could eventually impact on the ability of the larger primary aquifer underlying the Eastern Shores with associated habitats (such as the Mfabeni Mire) to sustain freshwater refugia in the St. Lucia Estuary during drier periods.

3.7 ACKNOWLEDGEMENT

We gratefully acknowledge the financial support of the Water Research Commission of South Africa (Project no WRC K5/1704and1857), and the Stichting Ecological Restoration Advice, The Netherlands. Ab Grootjans is thanked for the drafting the conceptual diagram (cartoon) depicting the groundwater flowas. We also acknowledge the Council for Geoscience and Department of Water Affairs for in-kind contributions, the staff of the iSimangaliso Wetland Authority and Ezemvelo KwaZulu-Natal Wildlife for institutional and research support, and Siphiwe Mfeka and Andre von Plaster for their dedication in the field. Lastly we appreciate the contribution of Rhodes University for administrating the project finances.

4. ISOTOPES AND GEOCHEMISTRY

Using stable isotope and geochemical tracers to gain insights into the groundwater flow of Mfabeni Mire

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Abstract

A study of the surface and groundwater exchanges of a large mire in southern Africa indicated that in semi-arid environments wetlands are likely to maintain internal ecosystem processes rather than regulating stream flow to downstream ecosystems. However, the links between the primary components were not clearly evident from this hydrological investigation and isoptopic, geochemical and thermal techniques were therefore used to improve the interpretation and verification of the feedbacks between rainfall, evaporation, groundwater and surface flow of Mfabeni Mire, South Africa using isoptopic, geochemical and thermal techniques.

Studying the stable isotope and geochemical composition of various hydrology components of Mfabeni Mire provided insight into the feedbacks between rainfall, evaporation, groundwater and surface flow through the mire. The tracers supported the hydrogeological evidence and illustrated the longer term persistence of the hydrological functions of this wetland. Groundwater discharging at the swamp forest, shallow subsurface flows and flow across the mire surface are all mechanisms maintaining the wetness of the mire's peat and therefore maintaining peatland integrity. The isotope signature of the Nkazana swamp forest strongly suggests that the source for its sustained base flow is groundwater discharging in the

swamp forest; therefore reiterating the importance of conserving the western dune as a water protection area.

Keywords: *Environmental tracers, isotopes, geochemical, thermal, mire, hydrological links*.

4.1 INTRODUCTION

Wetlands are often assumed to be sources of water, effectively producing water to sustain internal process and downstream ecosystems (Mitch and Gosselink, 2000; Bullock and Acreman, 2003). The hydrological study of Mfabeni Mire (Chapter 3) showed that wetlands in drier climates are more of a conduit responding to regional hydrological dynamics, rather than a source. The source of water and stable water levels in variable environments are consequently key determinants of wetland characteristics and function. Therefore, understanding the origin and variability of wetland water sources allows better assessment of wetland type, vulnerability and function (c.f. Gibson *et al.*, 2005).

Wetlands are an integral part of the hydrological cycle of many catchments, and their position in the landscape determines their role in regulating flow to downstream ecosystems (Ingram, 1983; Joosten and Clark, 2000; Bullock and Acreman, 2003; Maltby, 2009) by influencing basin water storage and flood attenuation (e.g. Siegel, 1988; Brinson, 1993; Smaktin and Bachelor, 2005). In sub-tropical, semi-arid areas wetlands are characterized by strong seasonal variations of water table and stream flow patterns (Clay *et al*., 2004), reflecting the variability in precipitation and evapotranspiration, and changing composition of surface and groundwater inflows (Bauer *et al*., 2004; Clulow *et al*., 2012). Using geochemical (e.g. Cl^- and Si^{4+}) and stable isotope tracers (δ^2H and $\delta^{18}O$) can provide insights into the sources and proportions of water, as well as storage times and water sinks in wetland ecosystems (e.g. Waddington *et al*, 1993; Gibson, 2002; Carey and Quinton, 2005). Barnes *et al*. (2002) used chloride, sodium, potassium, calcium, magnesium, iron and silicon as geochemical tracers to distinguish between two main sources of water in the Mkuze Delta feeding Lake St. Lucia South Africa. Alternatively, Van Wirdum (1993) applied temperature gradients in peat profiles to indicate surface water flow differences related to the development of rainwater lenses in floating fens in The Netherlands, whilst temperature profiles in the Štrba spring mire in Slovakia were used to show groundwater flow through a cascade of pools (Grootjans *et al*., 2006).

During the different phases of the hydrological cycle^{18}O and ^{2}H isotopes in water are selectively partitioned from the common isotopes of water (^{18}O and ^{2}H) beginning with evaporation of ocean water, with the vapour becoming ever-more depleted in the heavier isotopes as atmospheric water is lost through condensation and precipitation (Gat *et al*., 2001). In this way precipitation, and ultimately groundwater recharge inherits an isotopic signature that can provide a characteristic pattern of water's origin and history (Gat *et al*., 2001; Clark and Aravena, 2005). Furthermore, the isotopic composition of surface water will change as a result of evaporation when light isotopes are preferentially diffused into the air over heavier isotopes (Gat *et al*., 2001), and ^{18}O more so than ^{2}H. Therefore, surface water enriched by evaporation will be offset from the global meteoric water line (GMWL) (Figure 4.1), which is the slope of the relationship between global averages of ^{18}O and ^{2}H in precipitation (Gat, 1996). Local meteoric water lines (LMWL) in humid regions shifts toward increased δ^{18}O because of the phase change that tends toward liquid precipitation but it maintains the GMWL slope of 8; whilst in arid regions the LMWL plot higher (at the same slope) in relation to δ^{2}H because of increased evaporation (*web.sahra.arizona.edu/programs/ isotopes/oxygen.html)*

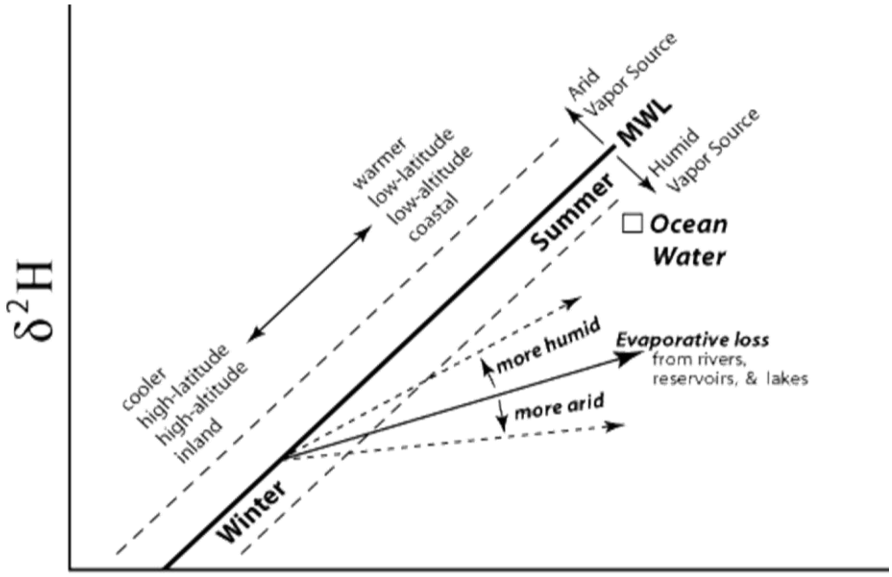


Figure 4.1: The global meteoric waterline (GMLW) and various deviations as a result of regional and environmental factors (from: web.sahra.arizona.edu/programs/ isotopes/oxygen.html).

Monitoring groundwater, surface flow, precipitation (Chapter 3) and evapotranspiration (Clulow *et al*., 2012) has highlighted the dominant role of rainfall and evapotranspiration as the primary components in the hydrology of Mfabeni Mire. However, the role of groundwater inflow in sustaining a high water table position, allowing the peatland to sustain peat accumulation and other ecological processes was recognised to be substantial (Chapter 2; Chapter 3). Results from these investigations on the origin and development of Mfabeni, and on its water balance indicated a groundwater discharge from the western dune towards the peatland and the Indian Ocean, with stream flow southwards to Lake St. Lucia. However, the links between the primary components were not clearly evident from the mire development and water balance investigations. The objective of this study is to improve the interpretation and verification of the feedbacks between rainfall, evaporation, groundwater and surface flow through Mfabeni Mire using isoptopic, hydrochemical and thermal techniques. The specific objectives of this study are to 1) establish the source area of the stream flow of Mfabeni 2) determine the area where groundwater recharge occurs for Mfabeni Mire, and 3) investigate the mechanism of maintaining the wetness of the mire’s peat (surface or groundwater throughflow).

4.2 STUDY AREA

Mfabeni Mire on the low-lying plains of the Eastern Shores in iSimangaliso Wetland Park, South Africa, is bordered by smaller wetlands comprising inter-dune depressions, fens and seep zones adjacent to high coastal sand dunes and (Figure 4.2). The peatland formed on a basal clay layer within an incised valley bottom and is bound in the north and south by beach ridges that separate it from Lake Bangazi and Lake St. Lucia, respectively (Chapter 2). The peat with a thickness close to 11 m has a thin fibrous upper layer and is highly humified with depth (Chapter 2) and it is acid with pH ranging between 5.5 to 5.9 (Venter, 2003). The mean annual precipitation of the Eastern Shores decreases from east (1 200 mm/year) to west (900 mm/year) between the coastal dune and Charters Creek, 10 km inland on the western shores of Lake St. Lucia (Taylor *et al*., 2006). The mean annual temperature is 21ºC and the mean annual potential evaporation 1549 mm/year (Mucina and Rutherford, 2006). Actual evapotranspiration for a 12-month period from October 2009 to September 2010 for the Mfabeni Mire was 900 mm (Clulow *et al.*, 2012). The surface drainage is mainly southwards to Lake St. Lucia through the swamp forest on the western margin of the peatland, with minor intermittent water exchanges to or from Lake Bangazi depending on lake levels, which varies with wet and dry climate cycles (Hart and Appleton, 1997; Været *et al.*, 2009). Groundwater efflux from the western dunes provides substantial recharge towards Mfabeni (Chapter 3). Two distinct groundwater types were recognised by Bjørkenes *et al.* (2006) on the Eastern Shores, with the aquifer below the western dunes having a more distinct sodium and chloride signature and the coastal dune aquifer a calcium and bicarbonate signature. Numme (2007) described the variation of the isotopic composition of the water in the Lake St. Lucia estuary and reported that the ^{2}H and ^{18}O signature for groundwater on the Eastern Shores reflect an evaporation trend.

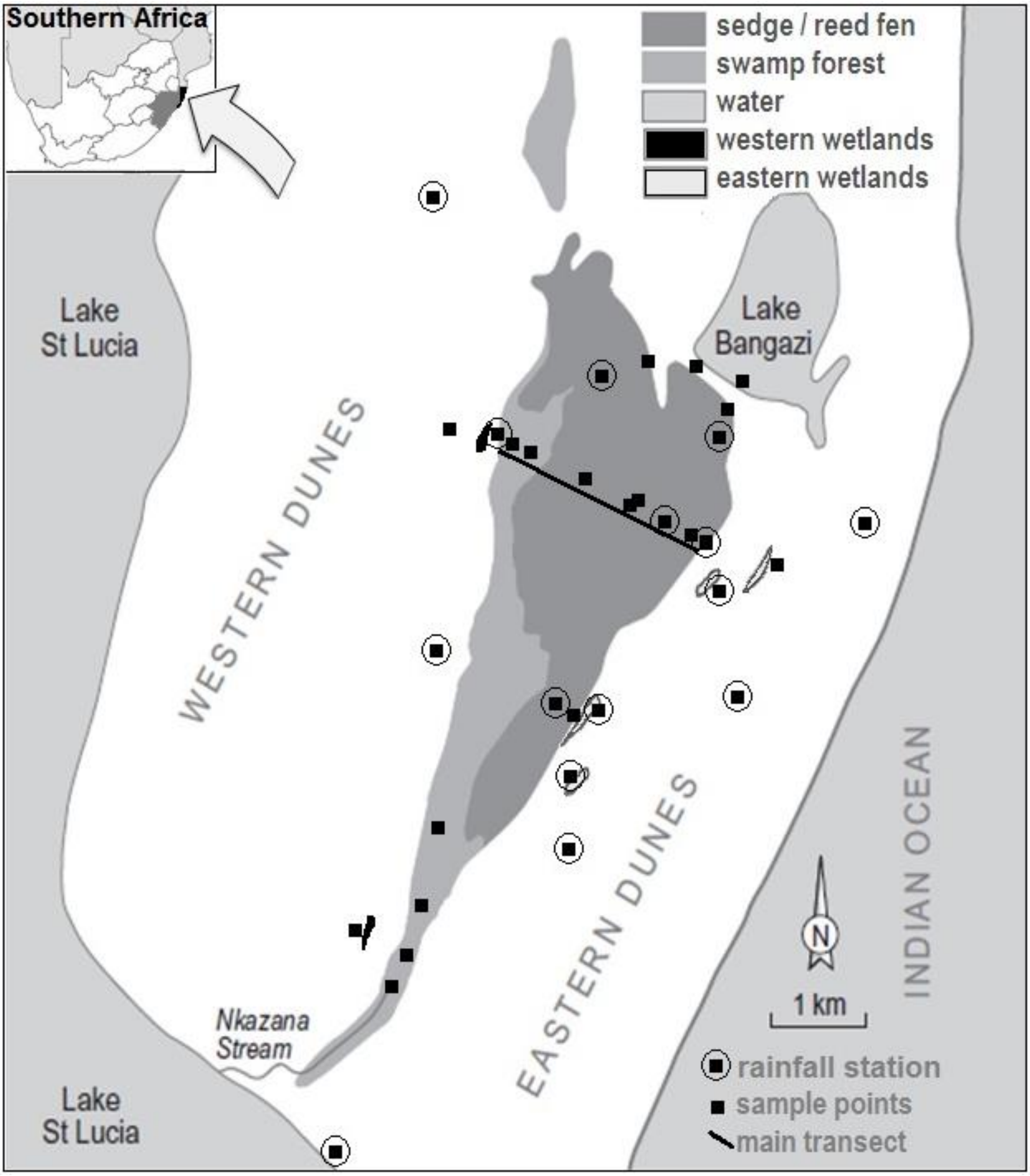


Figure 4.2: *The landscape setting of the Mfabeni Peatland within the Eastern Shores of the iSimanagaliso Wetland Park, located between Lake St. Lucia in the west and the Indian Ocean in the east. Sample points (squares) and the main transect (line) are indicated.*

4.3 METHODS

Water samples were taken from rain gauges, boreholes (wells and piezometers) and surface water for analysis of $\delta^{18}O$ and $\delta^{2}H$ directly after 5 rainfall events from August 2008 to February 2009 covering both winter and summer rainfall. Samples were filled to the brim and stored in Polyethylene Terephthalate (PTET) bottles, then analysed with the Los Gatos Research (LGR) DT-100 Liquid Water Isotope Laser Analyser at the University of KwaZulu-Natal. This analyser does not report δ values on a V-SMOW (Vienna Standard Mean Ocean Water) scale, but as $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios. Post processing therefore requires determining these ratios for the standards, developing a relationship between the known V-SMOW δ values and the measured ratios of the standards and then applying the relationship to the sub-sample measured ratios. Sub-sample results are reported as the average and standard deviation of injections 3-6 of the 6 sub-sample determinations. Analytical precision is typically less than 2*‰* for $\delta^{2}H$ and, less than 0.3*‰* for $\delta^{18}O$.

Groundwater for major cation and anion analyses was sampled in April 2010 from boreholes (wells and piezometers, which were pumped out the previous day before sampling) along the main transect (Figure 4.2) and stored in PTET bottles, which were filled to the brim. The samples were stored at 4°C in the dark before analyses in the laboratory of the Institute Soil Climate and Water, Agriculture Research Council, Pretoria according to Franson *et al.* (1995): SO_4^{2-}, and Cl^- content were analysed with a Dionex Ion chromatograph. HCO_3^- was analyzed titrimetrically and for SiO_2 a Wirsam AES XRF was used. Temperature was measured in profiles with a 2 m long probe along the main transect at 7 sites in April 2009. Measurements were taken at depth intervals of 0.2 m until a sand- or clay layer was reached, or to the maximum probe depth (2 m).

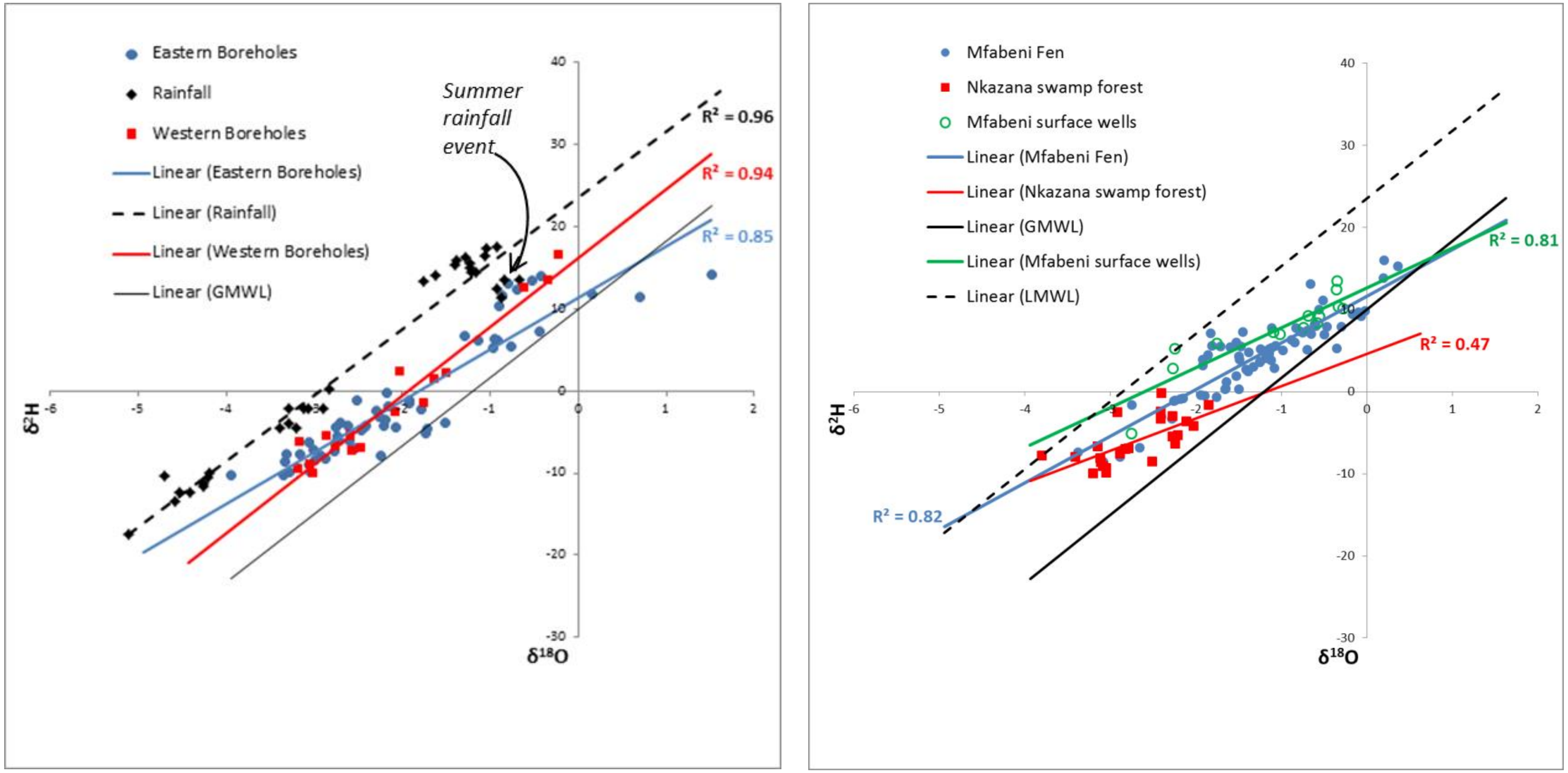
4.4 RESULTS

4.4.1 $\delta^{2}H$ and $\delta^{18}O$ in rainwater

The rainfall events sampled took place in winter (3 events in August 2008), in spring (1 event in September 2008), and in summer (1 event in February 2009). The $\delta^{2}H$ and $\delta^{18}O$ values of the rainwater of the winter and spring rainfall indicated that the local meteoric water line (LMWL) is shifted upward from, but parallel to the global meteoric water line (GMWL) (Figure 4.3A).

4.4.2 δ^2H and δ^{18}O in groundwater

The isotope composition of the groundwater in the Western Boreholes trended parallel to the Mfabeni LMWL (Figure 4.3A). On the other hand the isotopic signature of groundwater from Eastern Boreholes is clearly offset from the local meteoric water line along an evaporation line (Figure 4.3A). The mire’s groundwater isotopic composition varied distinctly between the swamp forest and the fen surface wells(Figure 4.3B), with Nkazana Swamp forest values exhibiting a more depleted signature and clustered together with the majority of the samples from the Western Boreholes, while both the fen and Eastern Boreholes signatures are enriched; the fen signature more so (Figure 4.3A and B). The isotopic composition of the surface water of Mfabeni Mire (as sampled in the Mfabeni wells) was enriched in heavy isotopes Figure 4.3B).



3A

3B

Figure 4.3: Isotopic signatures (δ^2H andδ^{18}O) of (A) rainfall and groundwater in the western and eastern dunes, and (B) in surface and groundwater in Mfabeni Fen and Nkazana Swamp Forest. The local meteoric water line (dashed line) is based on winter and spring rainfall events; the scattered summer rainfall event is indicated. Values are in %

4.4.3 Spatial distribution of $\delta^{18}O$ and $\delta^{2}H$ in groundwater

The distribution of δ^{18}O and δ^{2}H in the groundwater along the main transect indicates that the values trended to enrichment (isotopically heavier) from west to east (Figure 4.4AandB). Depleted δ^{18}O and δ^{2}H values (< -2 and <-7‰, respectively) were evident in the inflowing groundwater from the western dunes. Samples, particularly those from the eastern section of the mire, were relatively enriched, with δ^{18}O and δ^{2}H being > -2 and > -7‰, respectively, with even more enrichment evident in the deeper part of the peat profile.

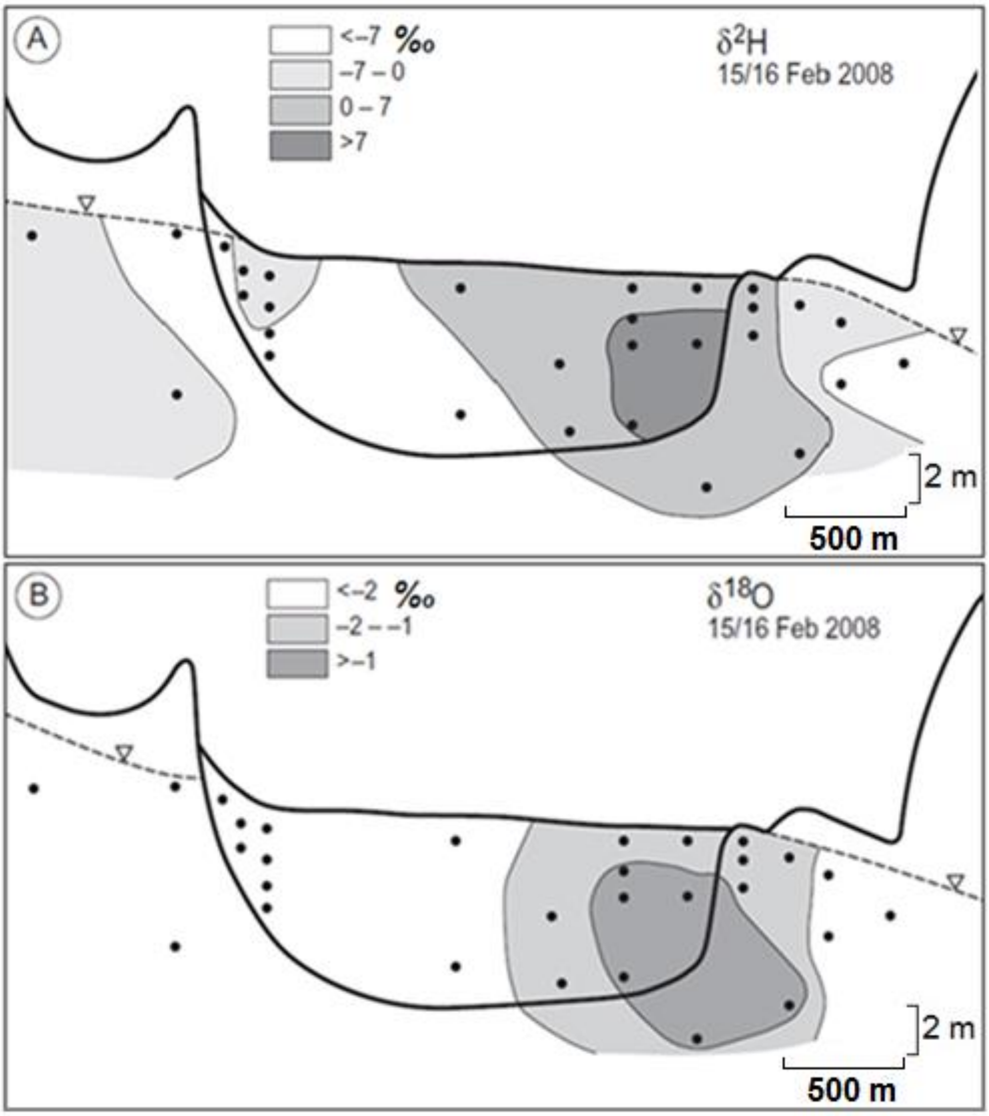
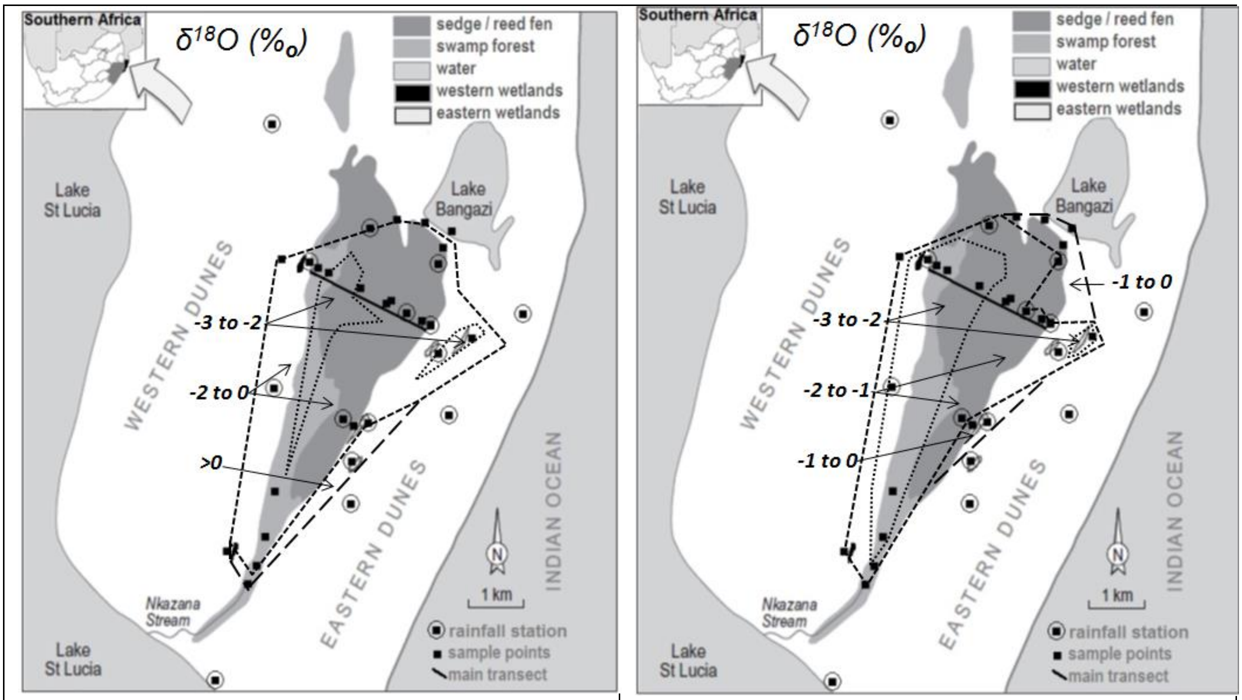


Figure 4.4: The δ^{2}H (A) and distribution δ^{18}O (B) in profile along the flow path from west to east in the main transect piezometers (shown as dots) in February 2009.

Surface water δ^{18}O across Mfabeni exhibits distinct spatial and temporal (seasonal) patterns (Figure 4.5). As shown in the cross sectional profile (Figure 4.4AandB) there is a zone of depleted δ^{18}O values at the swamp forest, and more enriched values eastwards across the fen. The extent of the zone with depleted δ^{18}O values in August 2008 (the dry winter season) at the swamp forest is smaller than February 2009 (the wet summer season extent) (Figure 4.5). This is also mirrored by the δ^{2}H values (not shown). Moderately depleted values (-3 to -2‰) are evident in a smaller depression wetland just east of Mfabeni Mire (the eastern-most sampling point along the transect).



August 2008

February 2009

Figure 4.5: The spatial distribution of δ^{18}O (‰) across Mfabeni Mire in a dry season (August 2008) and a wet season (February 2009).

4.4.4 Spatial distribution of dissolved ions in groundwater

Variation in groundwater composition is also evident in the concentrations of chloride, sulphate, bicarbonate and silicon (Figure 4.6). The analyses of the water samples from piezometers at various depths up to 16 m below the surface showed that the concentrations for these components are generally lowest in the western dune and higher towards the coastal dune. The highest values are found in the eastern side of the peatland at depths exceeding 4 m, with lower concentrations in the clay beneath the mire.

The distribution of Cl^- showed a general increase in concentration along the flow path from west to east (Figure 4.6). The same general increase in concentration occurred for Si^{4+} and HCO_3^- from the discharge zone in the swamp forest, eastwards along the flow path; however, a decrease was evident towards the surface. The distribution of SO_4^{2-} in the groundwater indicated higher concentrations in the inflowing groundwater from the western dunes and in the shallow groundwater at the eastern side of the mire and adjacent dune areas, being low elsewhere.

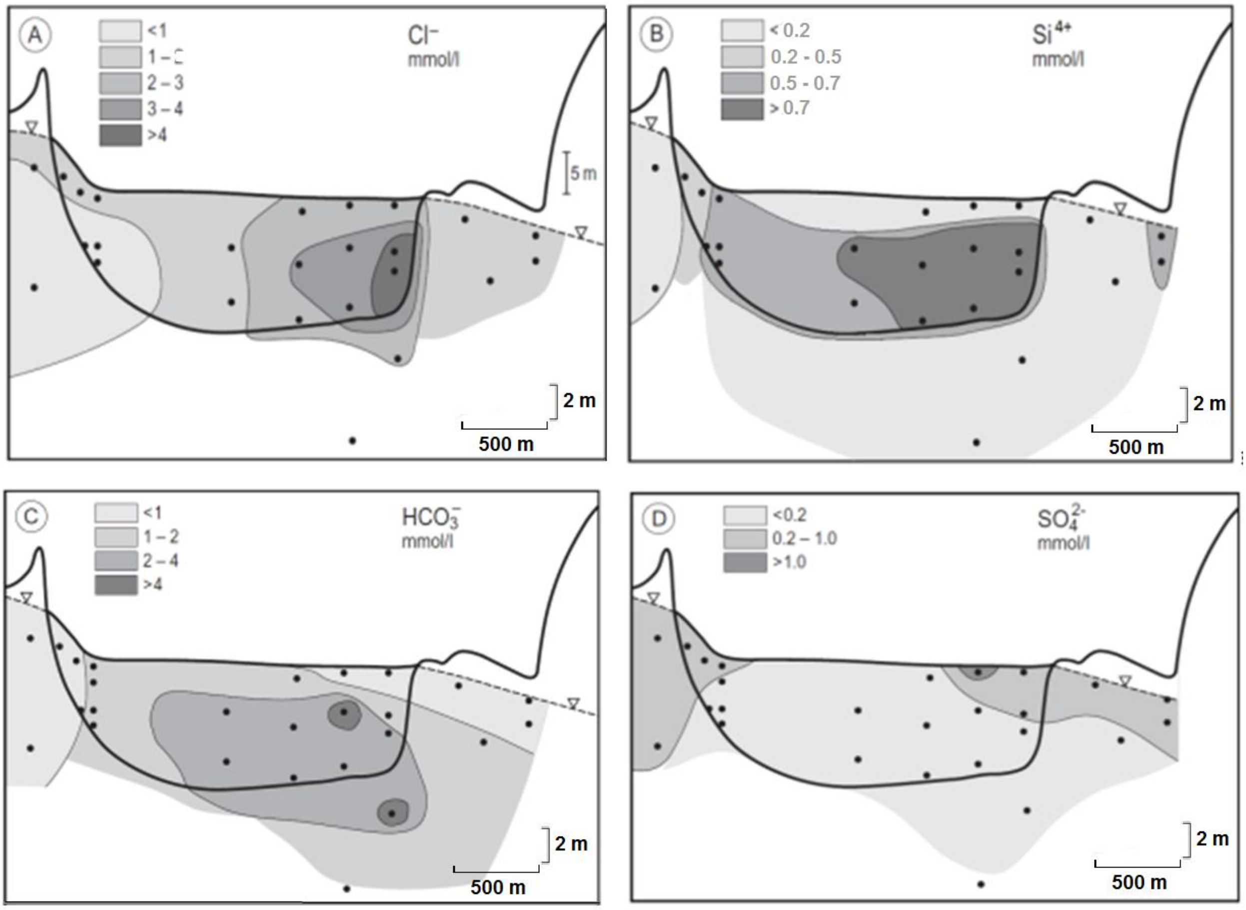


Figure 4.6: Distribution of concentrations (mmol/l) of chloride, silicon, bicarbonate and sulphate in groundwater to a depth of 16m.

4.4.5 *Temperature-profiles in the groundwater*

A temperature profile (for the upper 2 m of the peat profile) through the main transect from west to east measured at the end of summer in April 2009 showed a clear stratification (Figure 4.7). The coldest values were in the eastern part at the surface and 0.5 – 1m below surface. The warmest spot (0.5 to 1.5°C warmer) were located towards the centre 1.0 to 1.5 m below surface with cooler groundwater in the deeper part of the profile (1.5 to 2 m). A thicker layer of cooler water at 0.5 to 2.0 m occurred on the western side of the peatland (Figure 4.7). The temperature measurements were carried out during a rather cool day – the air temperature was 14.8°C at 07h00.

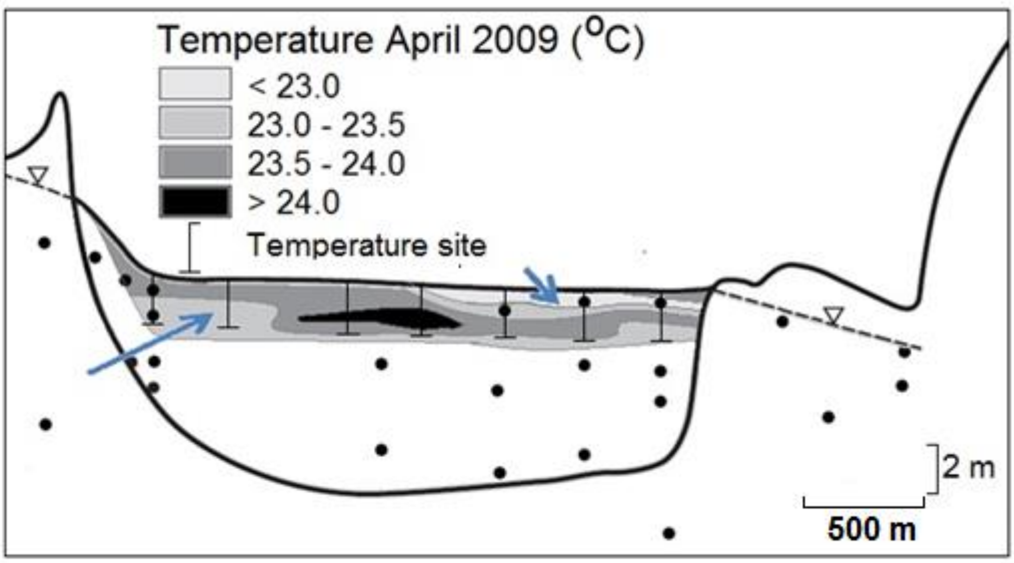


Figure 4.7: Temperature profiles to a depth of 2 meters along the main transect with cooler areas indicated by blue arrows.

4.5 DISCUSSION

The isotopic composition of precipitation water shows that the LMWL for Mfabeni Mire is parallel to the GMWL with an offset of -2‰ in the δ^2H winter rainfall values and compares well for longer term recordings from 1970 – 1973 with a parallel offset of - 1 ‰ for the nearby (11 km south west) Charters Creek LMWL (Vogel and Van Urk, 1973). Numme (2007) found the LMWL was similarly offset from the GMWL in the St. Lucia region, possibly due to cold (convective in summer) and warm (frontal in winter) weather systems. The rainfall isotopic composition for Mfabeni Mire reflects this pattern with the winter measurements (August and September 2008) having a -2‰ offset in δ^2H values compared to the -1‰ offset in the δ^2H for the single summer (February 2009 – indicated in Figure 4.5) event.

The stable isotope composition of groundwater at the western dunes (Figure 4.3A) reflects the same slope as that of the LMWL (Figure 4.3), albeit slightly enriched compared to the LMWL measured in this study. However, the western borehole groundwater values correspond well to longer-term precipitation values reported by Vogel and Van Urk (1973) for Charter’s Creek rainfall, suggesting that the western dunes are a recharge area (Gat *et al*., 2001). The somewhat isotopically depleted composition of the western dune groundwater is similar to values reported by Numme (2007). The swamp forest (including the Nkazana stream within the swamp forest) and the fen have isotopic signatures distinctly different from each other, with more depleted values in the swamp forest that correspond well to the isotopic composition of groundwater of the western dunes (Figures 4.3A and 4.3B). The depleted signature of the swamp forest groundwater, clustering with the western dune groundwater, has a wide scatter without a distinct evaporation line (Figure 4.3B). Some of this scatter might in be in part due to the enriched rainfall during the more humid summer months (with reference to the background provided in Figure 4.1) as reflected in February 2009 (Figure 4.3A). In contrast, surface and groundwater of the fen are somewhat enriched relative to water from the western dunes, and have a distinct evaporation line (Gat, 1996); especially surface water with a slope of 5 compared to 8 for the LMWL, suggesting evaporation enrichment. Given the west-to-east groundwater flow (Chapter 3) this suggests water discharged from the western dune and Nkazana becomes enriched as it crosses the fen.

In the eastern dunes (Figure 4.3A) the δ^2H - $\delta^{18}O$ line follows similar slopes (i.e. having an evaporation signature) to fen waters, suggesting that evaporatively enriched water from the fen enters the eastern dune at the margin. The fen is more likely to undergo evaporative enrichment than the uplands because of its higher evaporation rate as water is at the surface of the fen (Clulow *et al*., 2012). Since groundwater discharge comprises a small fraction of the water entering the mire (Chapter 5), the evaporatively enriched water discharging to the eastern dunes originates from rainfall onto the fen.

The position of δ^2H - $\delta^{18}O$ line for fen groundwater (Figure 4.3B) plots below the rainfall line measured in this study, indicating a water source other than rainfall likely related to the deeper groundwater flows indicated in Chapter 3 originating in the western dunes, but flowing at slower rates through the deeper clay and silt rich sands as well as the more decomposed basal peat layers in the fen (refer to Appendix 2 for an indication of alternative deeper flow paths).

The cross sectional profile of $\delta^{18}O$ and $\delta^{2}H$ (Figure 4.4) confirm the similarity of water in the western dune and swamp forest, and its enrichment as water flows eastward across the fen (Chapter 3). The enriched water from the fen becomes recharged at its eastern edge, and moves into the eastern dune, whereupon it becomes somewhat depleted as it mixes with recharging rainwater (Figure 4.4). The map of $\delta^{18}O$ values (Figure 4.5) confirms the spatial extent of these patterns and processes. The zone of depleted $\delta^{18}O$ values corresponding with the smaller wetlands east of Mfabeni Mire (Figure 4.2 and 4.5) reflects direct rainfall inundation of these mostly perched systems (Chapter 3).

The geochemical tracers Cl^-, Si^{4+}, and HCO_3^- all increase in concentration from beneath the western dunes to the deeper eastern part of the peat basin, but decrease from west to east two meters below surface (Figure 4.6). The higher Cl^-, Si^{4+} and HCO_3^-values in the deeper eastern section of the mire are all likely influenced by the presence of deeper interbedded sand layers in this part of the peat basin (Chapter 2). The higher Cl^- values are likely a result of relict saline water contained within the deeper peat when sea water may have penetrated the peat through these sand layers during the Holocene sea level high stand (~3.5 m above present amsl (Chapter 2). The slightly higher surface concentration of Cl^- could indicate a sea spray influence as the mire is less than 3 km from the ocean. The higher Si^{4+} values in the eastern basin might be a result of the silica sand layers in the acidic peat, whilst moderately elevated values in the root zone of the swamp forest may be due to chemical precipitation of silica caused by transpiration (McCarthy *et al*, 1998). The eastern dunes are characterised by calcium (Ca^{2+}) and bicarbonate (HCO_3^-) from calcarenite in the dune sand (Davies *et al*., 1992). Therefore it is to be expected that the interbedded sand layers blown in from these dunes during the late Pleistocene are enriched in HCO_3^-. The elevated HCO_3^- in the groundwater from boreholes in the eastern dunes was also reported by Bjørkenes *et al*. (2006).

The explanation for the general decrease from west to east is similar to that outlined for $\delta^{18}O$ and $\delta^{2}H$: concentrations below the western dune are relatively low reflecting water derived from rainfall and passing through the durable silicate minerals that comprise the sands. The higher SO_4^{2-} concentrations in the west, derived from higher values in the western dune (Bjørkenes *et al.,* 2006), decreased initially as groundwater emerged from the mineral sediments to the peat, probably reflecting the strongly reducing conditions there (Chapman and Davidson, 2001). However, SO_4^{2-} concentration also underwent an increase due to evaporative enrichment and oxidation (Howarth and Teal, 1979), as water moved from west to east across the mire's surface. The pattern of groundwater discharge at the swamp forest is also shown by the temperature distribution with colder groundwater, representing the long term average air temperature ($21^{o}C$), emerging on the western part of the mire (Figure 4.7) confirming modelling expectations (Rawlings and Kelbe, 1991) and hydrogeological data (Chapter 3). Migration of cooler water, representing the cooler April air temperatures, takes place from the surface of the mire (but not from the central part of the fen) to deeper levels at the eastern edge whereupon it recharges the groundwater below the eastern dune (Figure 4.7). This supports previous assumptions (Chapter 3) that the recharge at the eastern margin is likely from rainwater on the surface of the mire and not subsurface groundwater flow from the western dune.

Previous groundwater studies noted recharge in the western dunes with the groundwater flow westwards to Lake St. Lucia and eastwards towards the Indian Ocean (Rawlings and Kelbe, 1991; Kelbe and Rawlings, 1992; Bjørkenes *et al*,. 2006 and Taylor *et al.*, 2006). However, these studies did not include any groundwater measurements in Mfabeni Mire, and suggested the eastern dunes could support a groundwater mound with efflux westwards to Mfabeni Mire and eastwards to the ocean. Isotopic, geochemical and temperature evidence support the hydrological evidence that groundwater discharge only along the western margin of the peatland where the swamp forest occurs (Chapter 3). Water migrating eastward through the western dune encounters the thick peat layer in Mfabeni Mire, which acts as a plug, forcing water to discharge at its western margin (Chapter 2), flow across the open fen whereupon it becomes enriched and an evaporation signature develops. Then it recharges again at the eastern part of the fen towards the eastern dunes and the ocean. Below the peat in the clay layer, lower concentrations of isotope and cation/anion values suggest the hydrogeological and geochemical exchanges with this layer are limited.

4.6 CONCLUSION

Studying the stable isotope and geochemical composition of various hydrology components of Mfabeni Mire provided insight into the feedbacks between rainfall, evaporation, groundwater and surface flow through Mfabeni Mire. The distribution of the geochemical and isotope tracers resulted from the patterns of water flow through Mfabeni Mire as demonstrated by Chapter 3. These tracers are indeed supporting the hydrogeological evidence and illustrate the longer term persistence of the hydrological functions of this wetland ecosystem. Groundwater discharging at the swamp forest, shallow subsurface flows and flow across the peatland surface are all mechanisms maintaining the wetness of the mire's peat and therefore maintaining peatland integrity.

The significance of the western dune as primary groundwater recharge area feeding the mire is emphasised with all tracers supporting flow from these dunes to the mire. The isotope signature of the Nkazana swamp forest strongly suggests that the source for its sustained base flow is groundwater discharging in the swamp forest; therefore reiterating the importance of conserving the western dune as a water protection area. Specifically no development in the western dunes should be allowed and the eradication of *Pinus* regrowth and bush encroachment must be continued to facilitate grassland establishment in former plantation areas. This will encourage former dune processes, will limit transpiration and support recharge of the aquifer feeding Mfabeni Mire.

Wetlands are multifaceted ecosystems with complex mechanisms and often conservation interventions are more appropriate in the surrounding catchment where landscape features such as land cover, slope and soil type control hydrological inputs into the system.

5. WATER BALANCE

The water balance of an African mire: perceptions, reality and the implications for wetland ecosystem service interpretation

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Abstract

Peatlands occurring in semi-arid regions where evapotranspiration (ET) exceeds precipitation during seasonal dry periods or longer term dry spells are dependent on sustained groundwater flows to ensure peat accumulation. The objective of this study is to quantify the annual water balance of Mfabeni Mire, a peatland in southern Africa, and thereby define its contribution to downstream and adjacent ecosystems. Rainfall (1 031 mm) and ET (1 053 mm) dominated the water balance measured from May 2008 to April 2009. These were followed by groundwater inflow (14 mm), stream outflow (9 mm) and storage change (-3 mm: a net loss in water stored in Mfabeni Mire) with the smallest flux being groundwater outflow (0.3 mm). There were noticeable differences in the seasonal patterns of ET from the two dominant plant communities of the Mfabeni Mire (swamp forest and sedge/reed fen) which was not surprising considering the significantly different canopy structures. Low vapour pressure deficit and cloud cover were considered the main limiting factors to ET. Although the water balance of Mfabeni Mire is dominated by ET and rainfall, it still contributed efflux to the downstream ecosystems by stream flow. Its value in a landscape, where seasonal change and long-term dry periods are major ecological drivers, lies in its dampening effects of climatic variability such as prolonged drier cycles. This creates a more stable environment for adjacent ecosystems by contributing to steady groundwater conditions. Mires in drier regions, where water stress frequently threatens biodiversity, should be recognised as assets in natural resource management and their potential to support adjacent ecosystems should be protected through proper planning and conservation practices.

Keywords: *wetland, groundwater, hydrology, peat*

5.1 INTRODUCTION

Peatlands are an integral part of the larger hydrological cycle and its different components, including precipitation, evapotranspiration, and surface and groundwater flows (Ingram, 1983). Peat development is usually associated with cooler, moist climates of the temperate and boreal zones where persistent water saturation occurs (Clymo, 1983; Maltby and Proctor, 1996). The interactions and magnitudes of processes giving rise to peatland occurrence in the drier climates of the world such as the sub-tropics of southern Africa (Lappalainen, 1996; Joosten and Clark 2000; Grundling and Grobler, 2005) are poorly understood, thus require further consideration to optimise their management within the hydrological environment. In these regions where evapotranspiration (ET) exceeds precipitation during seasonal dry periods or longer term dry cycles (Tyson, 1981; Mucina and Rutherford, 2006), the mechanisms ensuring waterlogged and anaerobic conditions - and therefore peat accumulation - are more sensitive to the complexities of internal water storage and redistribution by surface and groundwater flows.

In semi-arid South Africa, there has been concern that wetlands promote water loss through high ET. However, Bullock and Acreman (2003) found that wetlands are not necessarily the high water users they are perceived to be. While the seminal work of Allan *et al*. (1998) suggest a crop factor (multiplier relating evapotranspiration to a well-watered reference crop) of 1.05 for open water, Clulow *et al*. (2012) derived monthly crop factors of 0.5 in winter and 1.0 in summer for sedge/reed fen in southern Africa (Mfabeni Mire), indicating lower ET than open water.

Wetlands in southern Africa are mostly seasonally saturated, reflecting intra-annual precipitation patterns (Tooth and McCarthy, 2007; Grundling *et al.*, 2013) supporting higher ET rates in the wetter seasons (mostly summer). However, their hydrogeomorphic setting also strongly influences their form and function. McCarthy (2000) used a water balance study to show that a small headwater wetland in the Zimbabwean Highveld (interior high altitude grassland plateau) was not important in promoting downstream flow in dry seasons. This is contrary to the function of a headwater peatland in the Magalies Mountains of the South African Highveld, which released a significant baseflow contribution (Smaktin and Batchelor, 2005). The differences in function may reflect differences in annual weather patterns, but more likely the local landscape and lithology, which control water stores and flows (Chapter 1). This is important for the development of peat forming wetlands, which require sustained wet conditions, occurring where the climate is less seasonal (shorter dry periods) and precipitation less erratic, or where sustained groundwater discharge occurs (Chapter 2). For example, Ellery *et al.* (2012) found that peat accumulation on the Mkuze floodplain is largely a consequence of sustained groundwater flow, and the peatland itself was therefore not a source of water but simply an area where discharge occurs.

Accounting for water sources, stores and flows is therefore an important approach for evaluating ecosystem services. This is especially important where drier climates prevail, since linked ecosystems can be strongly affected by the water relations in adjacent or upstream wetlands. Consequently, the objective of this study is to quantify the water balance of Mfabeni Mire, a 1 462 ha fen and swamp forest peatland, and thereby define its contribution to downstream and adjacent ecosystems. This will provide authorities and policy makers that control and manage the wider area (iSimangaliso Wetland Park and surroundings) with information that will influence their decision-making in terms of groundwater abstraction within the area, land use zoning (e.g. establishment of timber plantations), burning regimes and vegetation changes.

5.1.2 Study Area and Hydrological Setting

Mfabeni Mire is located close to sea-level in a low-lying valley (Figure 5.1), bordered in the east by an 80 - 100 m high coastal vegetated dune cordon (eastern dunes) and in the west by the 15 – 70 m high Embomveni dune ridge (western dunes). A strong rainfall gradient, the main source of precipitation in the catchment, decreases from the coastal dunes towards Lake St. Lucia (Taylor *et al.*, 2006). The mire is an extensive fen that has accumulated 11 m of peat during the past 44 000 years (Grundling *et al.*, 2000), on a basal clay layer within an incised valley-bottom comprising reworked dune sands (Chapter 2). It is bound in the north and south by beach ridges that separate it from Lake Bangazi and Lake St. Lucia, respectively

(Chapter 2). Surface drainage, through the Nkazana Stream, is mainly southwards to Lake St. Lucia with minor intermittent water exchanges to or from Lake Bangazi depending on lake levels (Hart and Appleton, 1997). The regional water table slopes from the western dune towards the peatland and from the peatland towards the Indian Ocean (Chapter 3). The water table slopes gently towards the east along the sedge/reed fen section and sharply drops away between the eastern edge of the peatland and the coastal dune. The abrupt steepening of the water table gradient is due to the sudden change in the underlying geological strata, where the clay lens (and most likely the other minor discontinuous aquitards) that impedes vertical seepage loses, give way to the younger, more permeable cover sands of the eastern dune cordon (Chapter 3).

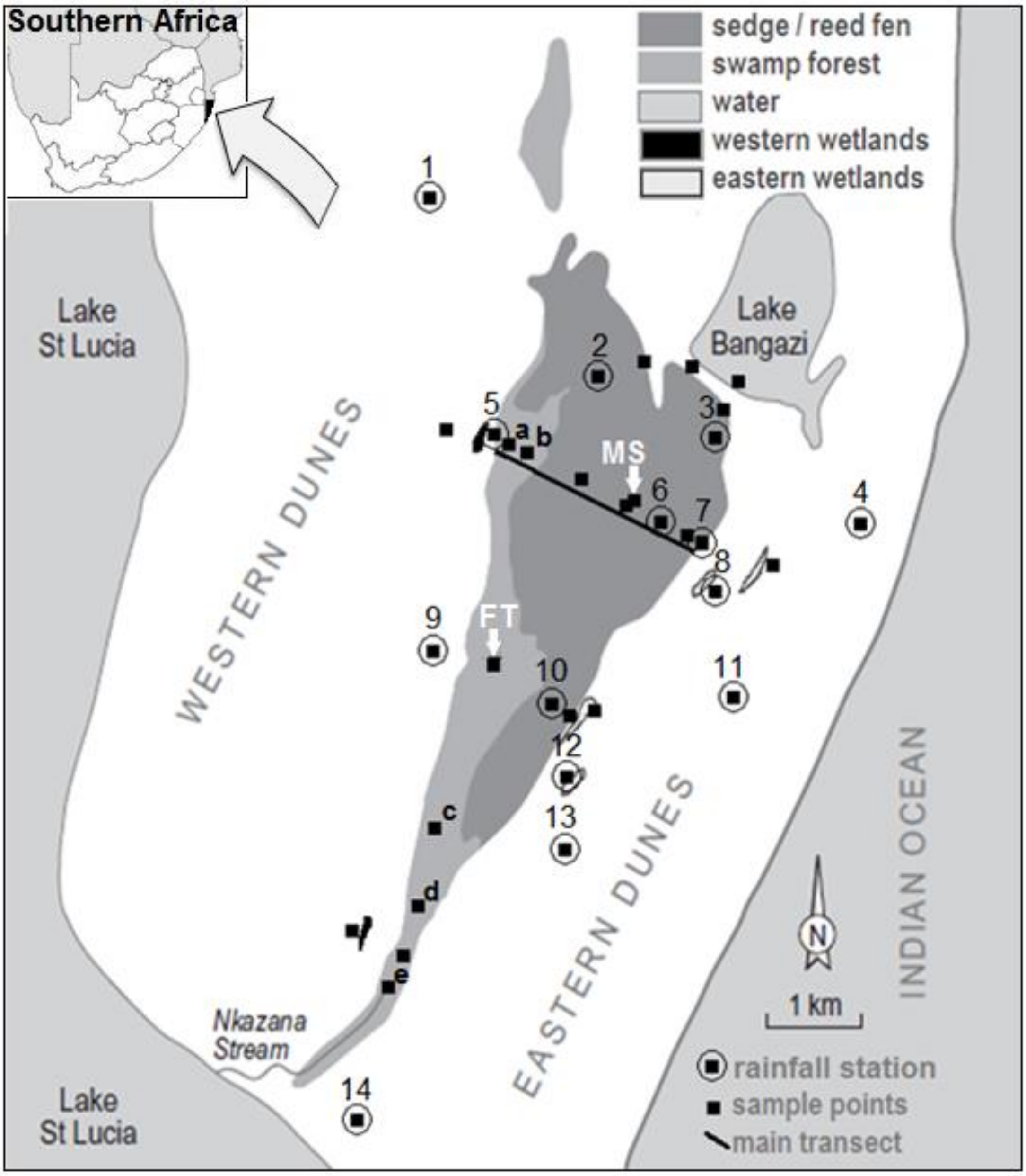

Figure 5.5.1: The study area. Rainfall stations and the main transect are indicated. Note the positions of the meteorological station (MS) and flux tower (FT).

Groundwater flows from the regional groundwater mound below the western dune complex (the primary recharge area) into the peatland (Figure 5.2) and discharges at the seepage area defined by the swamp forest (Chapter 4). The fen also receives groundwater from the western dune mound (directly, as well as via the swamp forest). Groundwater discharges towards the central area of the peatland, after which it moves over the mire surface and in shallow subsurface layers along the gentle slope to the east (Chapter 4). It is expected that the surface flow and shallow subsurface flow along the gradient are critical in keeping the peatland wet and maintaining its functions, as the deeper groundwater contribution through the peat are limited by its very low hydraulic conductivity (Chapter 3). The groundwater is recharged within the peatland along the eastern section and follows a more steeply sloped water table outside the wetland, eastwards towards the coastal dune complex (Chapter 3). Surface water in the southern section is captured by the Nkazana stream within the swamp forest, and drains southwards to Lake St. Lucia. Evapotranspiration plays a significant role in the hydrology of Mfabeni Mire and has been shown to exceed rainfall during drier cycles (Clulow *et al*., 2012, 2013).

5.2 METHODS

5.2.1 Water balance: assumptions

The water balance within a peatland depends on numerous flow and storage processes within the system and its catchment. It includes precipitation, flow in surface streams, seepage of water through peat, flows through pipes and fissures within the peat and adjacent substrate, diffuse flow over the peat surface, unconfined flow in directed channels and evapotranspiration (Ivanov, 1981). Various components of the water balance, such as surface and groundwater inflows and outflows, are measured quantitatively using a variety of hydrometric techniques and modelled accordingly. The water balance of a peatland according to Ingram (1983) is expressed as,

$$P + GW_{in} + S_{in} - ET - S_{out} - GW_{out} - \Delta V - ŋ = 0 \qquad \mathbf{1}$$

where P = precipitation (rainfall in this study); GW_{in} = groundwater seepage influxes; S_{in} = diffuse surface inflow and/or open channel inflow; ET = evapotranspiration: GW_{out} = groundwater seepage outflows; S_{out} = diffuse surface outflow and/or open channel outflow; ΔV = change in stored water*;* and ŋ = error term.

In water scarce regions ET usually dominates the water balance, and it is therefore important to understand and quantify the contribution of different wetland vegetation types and zones to the ET component of the water balance. Changes in peat volume, through peat surface oscillation (PSO), could also be important in calculating water storage changes (Price and Schlotzhauer, 1999), but significant PSO was not noted during the study period.

For this study groundwater in- and outflows linking Mfabeni Mire with the adjacent landscape units were measured across the widest portion of the mire (referred to as the main transect) covering the swamp forest and the fen (Figure 5.2). Groundwater inflow into Mfabeni Mire occurs from the western dunes, with groundwater outflows from the eastern portion of the mire to the east, beneath the coastal dune complex (Chapter 3). No surface inflows occurred over the duration of this study. Stream outflow occurs southwards through the Nkazana stream, and water storage changes in the peat were manifest as water table fluctuations over the measured period. Groundwater discharge northwards to Lake Bangazi was disregarded as it occurs only at a small portion of the outflow boundary. Stream outflow to Lake Bangazi occurred only intermittently and was assumed to be negligible.

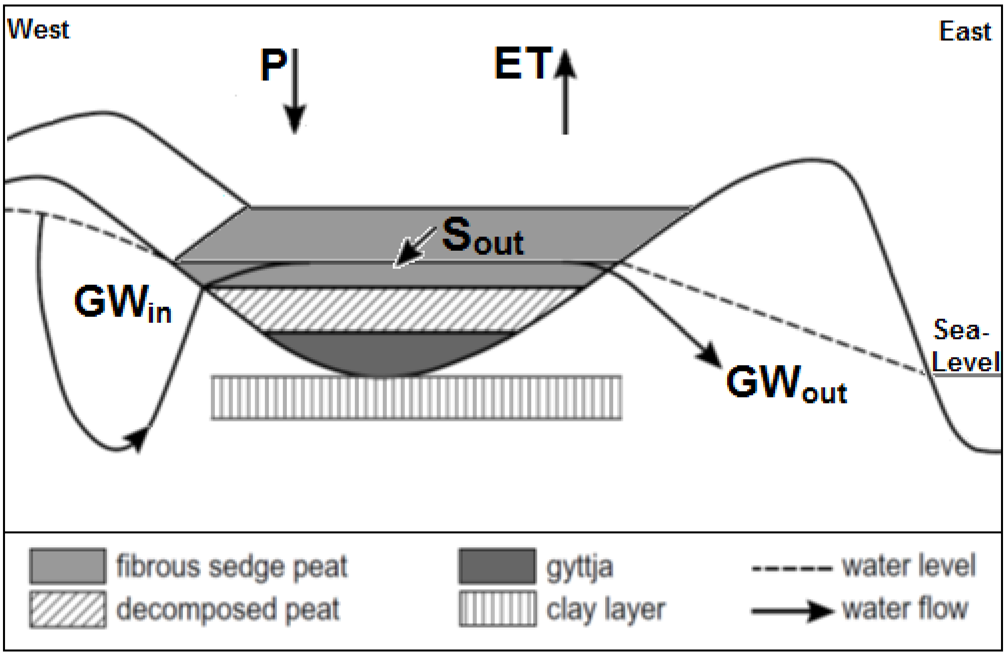

Figure 5.5.2*:* The schematic diagram of the basic assumptions of Mfabeni Mire's water balance. Note that no stream inflow occurs as the site is located in the headwaters of the Nkazana stream.

5.2.2 Measurement and modelling of the water balance

5.2.2.1 Rainfall

Rainfall was measured at 15 sites within and around Mfabeni Mire using a combination of tipping bucket raingauges (TE525, Texas Electronics Inc., Dallas, Texas, USA) and manual raingauges (read weekly) installed with an orifice height of 1.2 m above the ground surface. P data were interpolated over a period of a year (May 2008 to April 2009) to derive a spatial rainfall distribution map with 50 mm isohyet intervals. The rainfall distribution map was used to calculate an area-weighted rainfall for Mfabeni Mire.

5.2.2.2 Evapotranspiration

Evapotranspiration for Mfabeni Mire was modelled using meteorological data. A meteorological station was located near the centre of Mfabeni Mire and provided air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), net irradiance (NRLite, Kipp and Zonen, Delft, The Netherlands) solar irradiance (LI200X, LI-COR, Lincoln, Nebraska, USA), wind speed and direction (Model 03002, R. M. Young, Traverse city, Michigan, USA) measurements at 2 m above the ground surface. Soil heat flux was also measured using the method described by Tanner (1960). Two heat flux plates (HFT-3, REBS, Seattle, WA, USA) were buried at a depth of 0.08 m, a system of parallel thermocouples (Type K) were buried at depths of 0.02 m and 0.06 m (to measure the heat stored in the peat above the heat flux plates) and volumetric water content (CS615, Campbell Scientific Inc., Logan, Utah, USA) was determined in the upper 0.06 m of the profile. Appropriate statistical functions were applied to the observations made every 10 s and recorded on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA) at 5-min, 60-minute and daily intervals. Vapour pressure deficit (VPD) and reference evaporation were calculated on the datalogger using the methods described by Allan *et al*. (1998).

The two distinct vegetation types within Mfabeni Mire (swamp forest and sedge/reed fen) were modelled separately. The swamp forest has an approximately 20 m high canopy with understory trees and ferns approximately 7 m and 3 m high, respectively. The leaf area index below the trees was approximately 3.3 and below the tree and fern canopies, approximately 7.2. In contrast the sedge/reed fen plant community has an average height of approximately 0.4 m and a LAI that fluctuates between 0.85 in winter and 1.2 in summer. Clulow *et al.* (2012) measured the ET over the sedge/reed fen over the period of a year using a combination of the surface renewal and eddy covariance methods. They found that the Priestley and Taylor (1972) model explained 96% of the variation in ET over the sedge/reed fen vegetation type and derived α for the Priestley-Taylor model of 1.0, which could be used throughout the year. The Priestley-Taylor model was therefore used to estimate the contribution from the sedge/reed fen portion of Mfabeni Mire (1047 ha) at a daily level.

The swamp forest (415 ha) ET was measured and modelled by Clulow *et al*., (2013) from October 2009 to September 2010 using a combination of eddy covariance (window periods) based on a 20 m high flux tower and sapflow (long-term) equipment. They found that the ET of the swamp forest was best described using the FAO56 Penman-Monteith reference evaporation model (Allen *et al*., 2006) and derived monthly crop coefficients for the swamp forest over an annual cycle. Evapotranspiration was therefore calculated using the equation:

$$ET = ET_r.K_c \qquad \mathbf{2}$$

where, ET is evapotranspiration (mm), ET_r is reference evaporation (mm) and K_c is the crop factor. The FAO56 Penman-Monteith reference evaporation model was computed at hourly intervals as recommended by Irmak *et al*. (2005), and summed to daily and monthly values and the monthly crop factors applied (Eqn. 2).

5.2.2.3 Groundwater inflows and outflows

Groundwater well- and piezometer nests were installed with a truck-mounted hollow-stem auger drill rig in the eastern and western dune cordons adjacent to Mfabeni Mire and by hand in the mire itself. Based on the peat or dune stratigraphy, wells and multi-level piezometer nests were installed at 43 sites at appropriate depths; up to 30 m in the sandy uplands, ~11 m in the peat, and 16 m below the surface in the clay beneath the peat. In the dune cordons, wells and piezometers comprised 0.05 m diameter PVC tubes with slot lengths of 1.0 m covered with a geotextile screening. Twenty-four of the 43 sites were located within Mfabeni Mire. These were fabricated in the same way but with longitudinal slot lengths of 0.2 m. Drive-point piezometers (Solinst™ Model 615 with a 20 mm diameter) were installed in the sand or clay below the peat. Water levels within the wells and piezometers were monitored manually with an electronic dip-meter on a weekly basis from April 2008 to May 2012 however, hydraulic head was measured continuously in 6 piezometers along the main transect (Model Gold, Solinst™ Canada, Georgetown, CA).

Groundwater flow at a point can be measured if the hydraulic conductivity for the material in a homogeneous isotropic region of flow is known (Freeze and Cherry, 1979). The spatial heterogeneity within Mfabeni Mire was incorporated by applying the appropriate hydraulic properties to the different sedimentary units with K-values for these units derived in Chapter 3. In the western portion of Mfabeni Mire, groundwater flows (GW_{in}) into the peat body from two sand layers (Figure 5.3). On the eastern boundary of Mfabeni Mire, the outflow of groundwater (GW_{out}) occurs from the peat body (incorporating 4 peat layers and two sand layers) into the adjacent sand body (Figure 5.3). Discharge was calculated across the region of in- and outflow through a cross-sectional area of depth using Darcy's law for saturated flow*:*

$$Q = -K\left(\frac{dh}{dl}\right)A \qquad \textbf{3}$$

where, Q = discharge ($m^3\ s^{-1}$)*;* K = hydraulic conductivity ($m\ s^{-1}$); *d*h/*d*l = hydraulic gradient; *A* = cross-sectional area (m^2). The flow per unit width of the main transect was calculated, which were then extrapolated across the length of the different lithological units (Table 5.1) of the western (groundwater inflow boundary) and eastern edge of the mire (groundwater outflow boundary) to determine the system's groundwater flux.

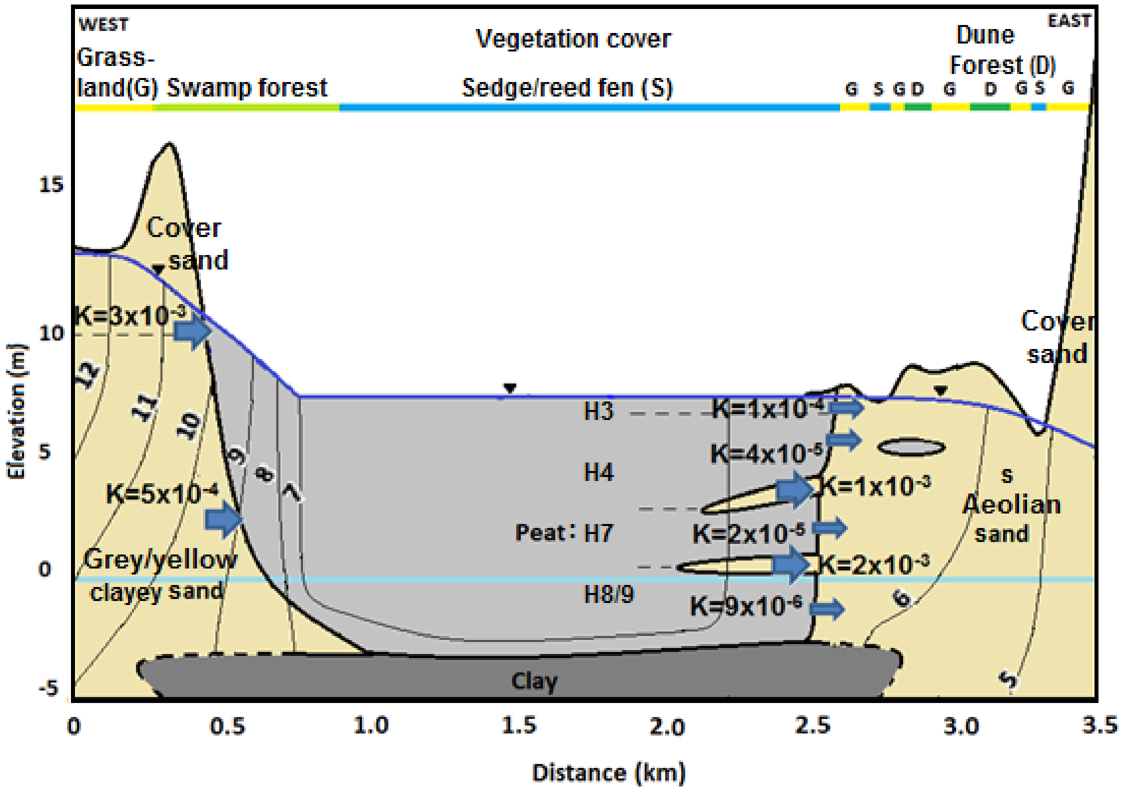

Figure 5.5.3*:* Schematic diagram of the simplified groundwater flow through Mfabeni peatland with hydraulic conductivity in $m\ s^{-1}$. Large blue arrows indicate flow through sand and the smaller arrows the flow through peat.

Table 5.1: The different lithological units and parameters used in the groundwater flow calculations.

Lithological Unit	K (m/s)	Length (m)	Thickness (m)
Western edge			
Cover sand	3.08E-05	8500	2.5
Grey/yellow sand and silt with clay	5.05E-06	8500	13
Eastern edge			
Peat: *H3	9.89E-07	8500	0.5
Peat: H4	3.80E-07	7480	2.5
Sand	1.19E-05	2380	0.6
Peat: H7	2.01E-07	6040	2.4
Sand	2.29E-05	2380	0.6
Peat: H8/9	1.09E-07	3230	3.4

**H refer to the level of humification based on the Von Post Humification Scale (Von Post, 1922) with H1 (completely undecomposed peat) to H10 (completely decomposed peat).*

5.2.2.4 Stream Outflow

A compound weir beneath the Nkazana Bridge (sample point e in Figure 5.1) measured the efflux from Mfabeni Mire into Lake St. Lucia. The stage height of the water in the weir was measured every 15 minutes (Model 3001 Levelogger Gold series, Solinst™, Ontario, Canada). A calibrated Kindsvater-Carter equation was applied to determine the discharge of the Nkazana stream (Chapter 3) from May 2008 to mid-February 2009. The discharge from mid-February to May 2009 was inferred from an adjacent measuring weir in the Mphate catchment operated by the Department of Water Affairs as described in Chapter 3.

5.2.2.5 Change in storage

Water storage change, ΔV, within Mfabeni Mire was determined from May 2008 to April 2009 based on water table fluctuations at seven individual sites across the peatland (four in the sedge/reed fen and three in the swamp forest).

Specific yield for the different peatland types were determined from peat monoliths sampled at each site. They were initially immersed in water for 8 hours. Excess water was removed and the samples weighed. The peat was then allowed to drain under gravitational force until dripping stopped before the samples were re-weighed and specific yield determined by:

$$Sy = V_{wd/}V_T \qquad 4$$

where, V_{wd} = volume of water (mm^3) drained and V_T is the total volume of material (mm^3).

The change in water table elevation over the annual water balance was measured at each site (Δh) and combined with the S_y to calculate ΔV at each site using

$$\Delta V = S\gamma * \Delta h \qquad 5$$

The final ΔV was calculated by area weighting the results from the sedge/reed fen and swamp forest.

5.3 RESULTS

5.3.1 Rainfall

Rainfall at Mfabeni Mire meteorological station exhibited the seasonality and variability of the rainfall in the area. The highest daily rainfall (not shown) was 93 mm on 27 January 2009, while there were five days, spread throughout the year, with rainfall of approximately 50 mm.

The monthly rainfall (Figure 5.4) was highest in January 2009 (250 mm) and lowest in July 2008 (4 mm). Despite falling in what is typically a summer (October to March) rainfall area, there was a noticeable delay in the onset of rainfall in the summer months of October, November and December 2008, which experienced relatively low rainfall totals of 21 mm, 87 mm and 48 mm, respectively.

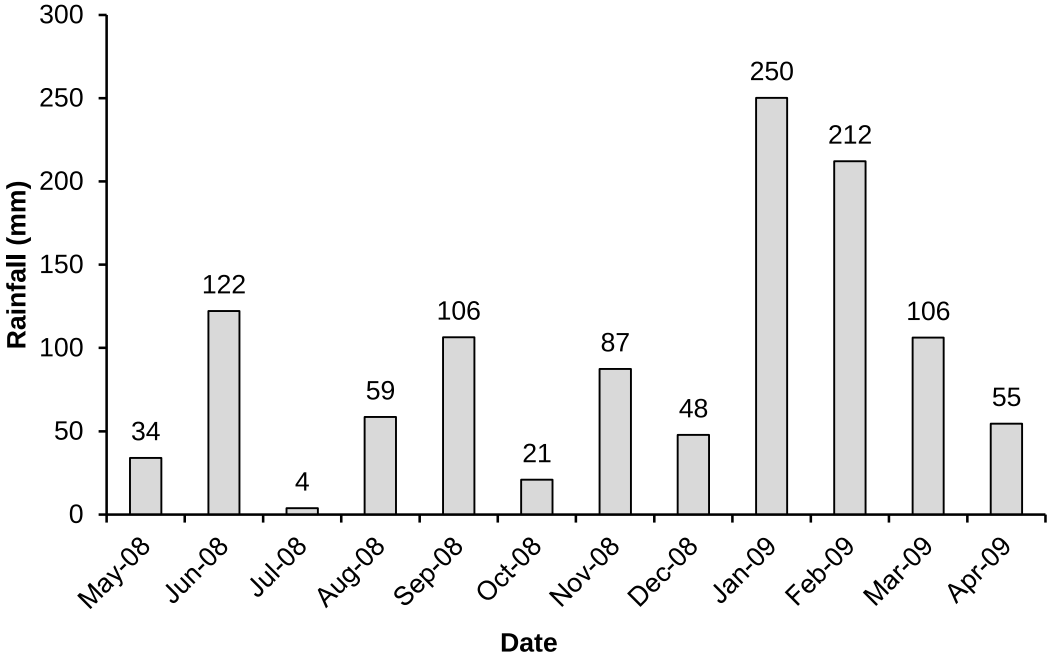

Figure 5.5.4*:* Monthly rainfall measured at the meteorological station in Mfabeni Mire using an automatic raingauge from May 2008 to April 2009.

The rainfall measured from a network of 15 raingauges over the full extent of Mfabeni Mire and the surrounding eastern and western dune areas indicated some spatial variability over a period of a year from May 2008 to April 2009 (Figure 5.5). The rainfall was higher in the northern parts (1 050 to 1 100 mm) of the mire compared to the southern region (1 000 to 1 050 mm). The area-weighted rainfall determined for the water balance of Mfabeni Mire was 1 031 mm.

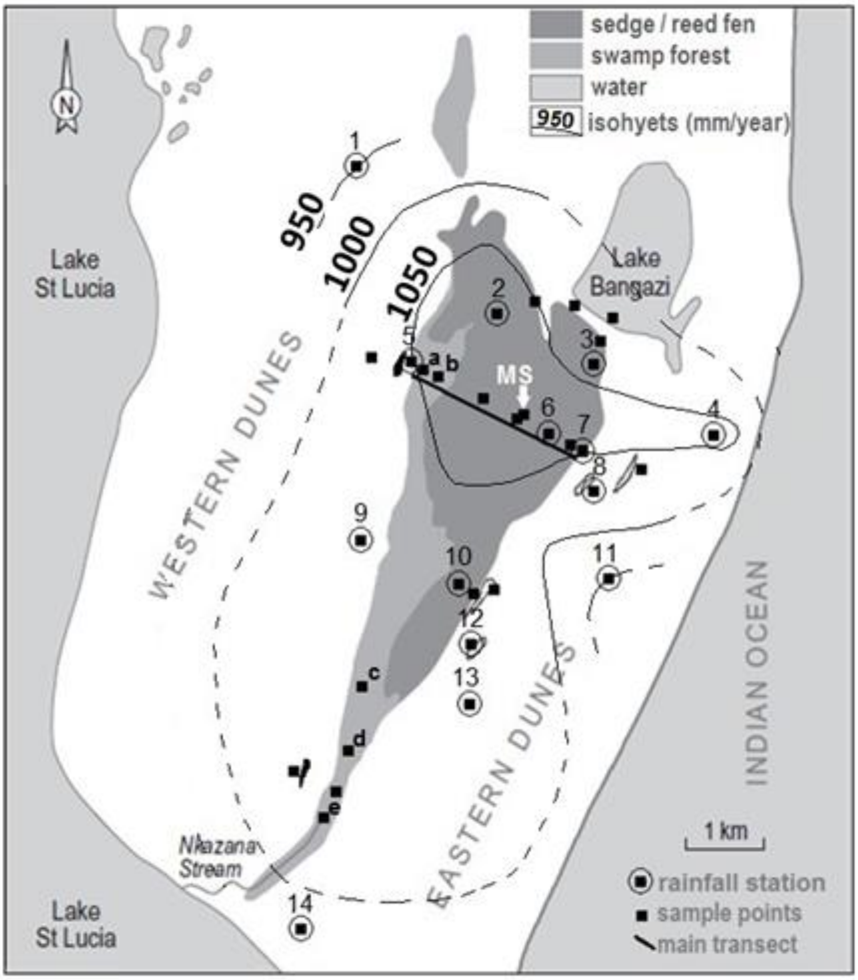

Figure 5.5.5: The spatial distribution of rainfall at Eastern Shores from May 2008 to April 2009. Dashed isohyets represent areas of greater uncertainty in the interpolation.

5.3.2 Evapotranspiration

The pattern of daily ET was seasonal from both the sedge/reed fen and swamp forest plant communities; however, the shape of the maximum daily ET was different between the plant communities (Figures 5.6a and 5.6b). The daily maximum ET on clear days from the sedge/reed fen plant community represented a smooth sinusoidal pattern whereas the swamp forest ET was more variable.

The peak summer rates of daily ET were 6 mm and 8 mm from the sedge/reed fen and swamp forest, respectively. The daily maximum winter ET of approximately 2 mm was significantly lower than the summer ET at both sites. The occurrence of cloud cover was noticeable particular over the summer period (October to March) by the numerous days on which ET was reduced.

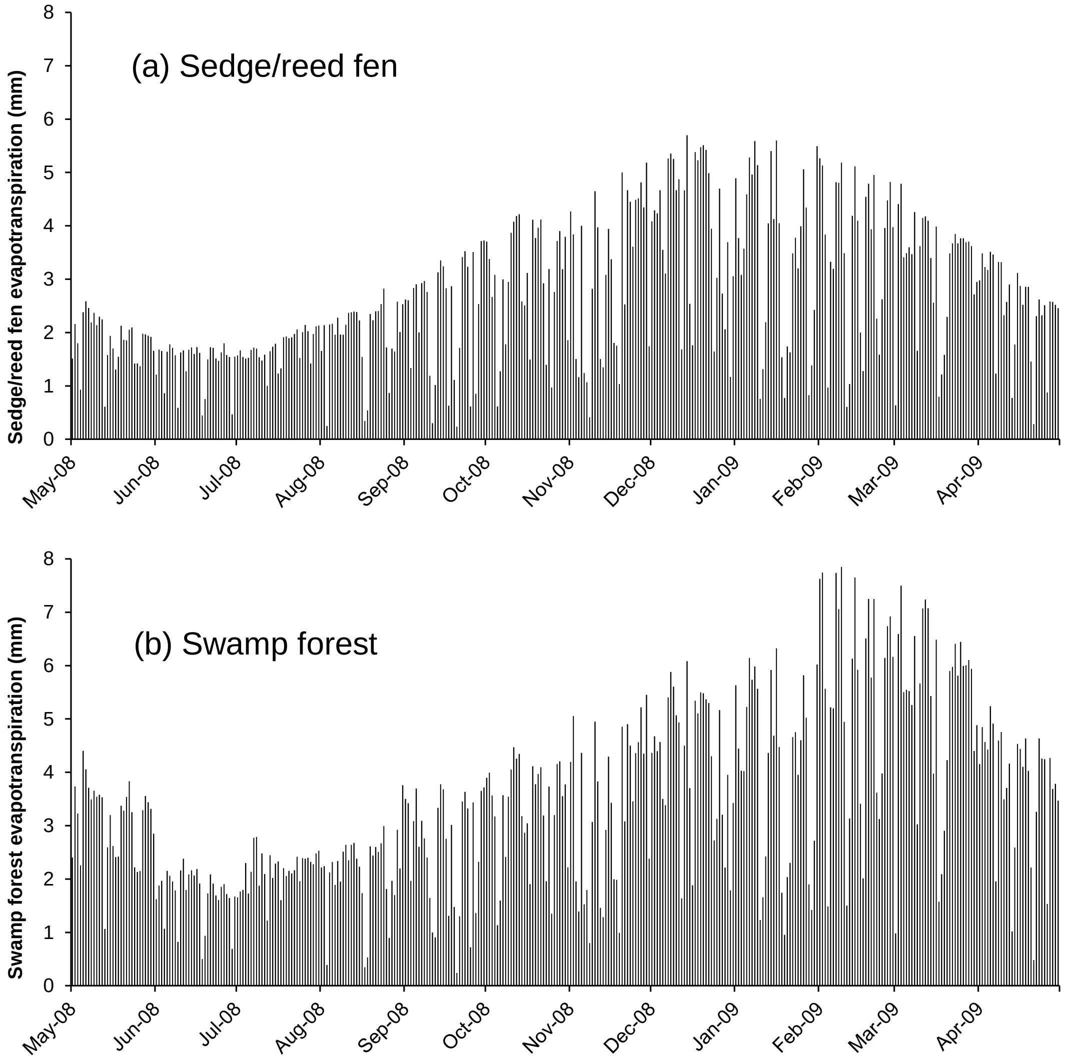

Figure 5.5.6: Daily evapotranspiration modelled for the (a) sedge/reed fen and (b) swamp forest plant communities.

Swamp forest ET was 28% higher than from the sedge/reed fen. The swamp forest (28% of the Mire surface area) contributed 34% (354 mm) of the mire evapotranspiration whilst the sedge/reed fen (72% of the mire surface area) contributed 66% (699 mm).

The monthly ET exhibited a seasonal pattern (Figure 5.7). The summer monthly ET (October to March) ranged between 94 mm (November 2008) and 126 mm (January 2009). The lower winter monthly ET (April to September) ranged between 46 mm (June 2008) and 85 mm (September 2008). Clearly there was a discernible difference in the winter and summer *Et* although the months with the higher ET values occurred from December to March and there was some delay between the start of the summer season and the higher ET rates.

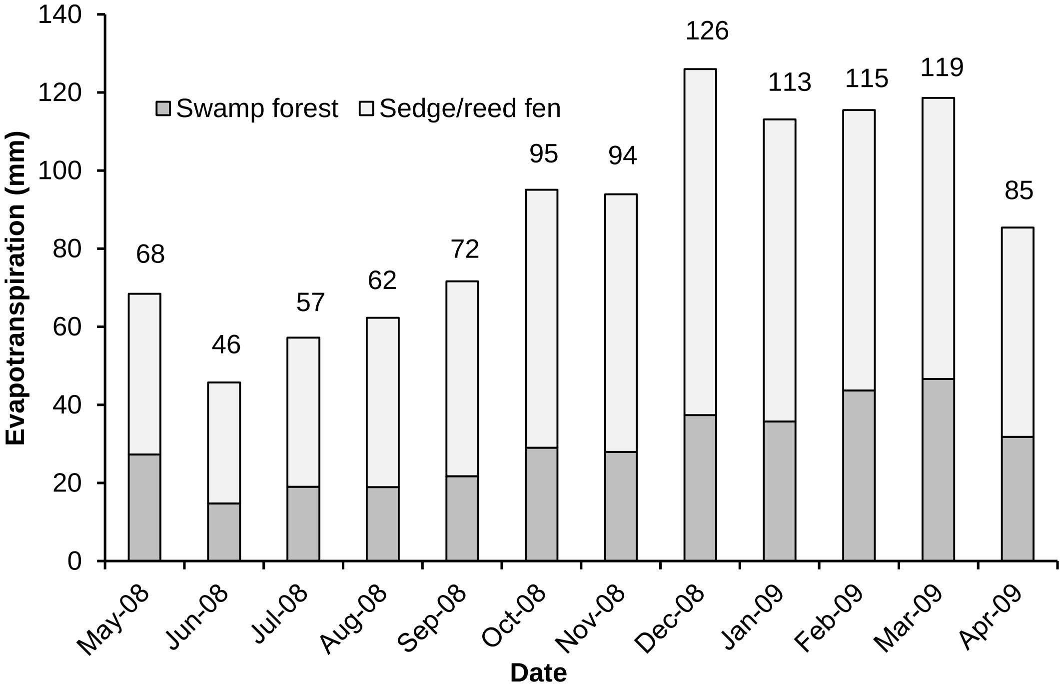

Figure 5.5.7*:* Total evapotranspiration modelled for Mfabeni Mire from May 2008 to April 2009 by area weighting the contribution to evapotranspiration from the swamp forest and sedge/reed fen plant communities.

5.3.3 Groundwater inflows and outflows

Groundwater flows through the peat body of Mfabeni Mire from west to east. Based on the simplified geology described in Chapter 2 and hydrology characteristics described by Chapter 3, the groundwater flows into and out of Mfabeni Mire along its western and eastern boundaries were quantified, respectively. Values determined at the boundaries along the main transect were assumed to represent the flow all along the respective boundary due to the consistent layering of substrates in the mire (Chapter 2). An annual GW_{in} of 2.01 x 10^5 m^3 $year^{-1}$ (14 mm $year^{-1}$) was calculated at the western boundary of the peatland (Table 5.2) with an outflow of 4.13 x 10^3 m^3 $year^{-1}$ (0.3 mm $year^{-1}$) at the eastern boundary of Mfabeni Mire (Table 5.3). Water table slope was derived from the wells straddling the respective in and outflow boundaries.

Table 5.2: Inputs to the Darcy equation (Equation 3) and the final annual groundwater inflow at the western boundary of Mfabeni Mire.

Flow Unit	**K(m/s)**	***d*h/*d*l (i)**	**Length (m)**	**Thickness (m)**	**A (m^2)**	**Q=-KiA (m^3 $year^{-1}$)**
Sand	3.08E-05	4.17E-03	8.50E+03	2.5	2.13E+04	86 000
Sand and Silt	5.05E-06	6.56E-03	8.50E+03	13	1.11E+05	115 000
Annual groundwater inflow (m^3)						**201 000**
Annual groundwater inflow (mm) (based on the mire area of 1 462 ha)						**14**

Table 5.3: Inputs to the Darcy equation (Equation 3) and calculations required to derive the annual groundwater outflow at the eastern boundary of Mfabeni Mire.

Flow Unit	**K(m/s)**	***d*h/*d*l (i)**	**Length (m)**	**Thick-ness (m)**	**A (m^2)**	**Q=-KiA (m^3 $year^{-1}$)**
Peat	9.89E-07	2.00E-03	8.50E+03	0.5	4.25E+03	2.65E+02
Peat	3.80E-07	2.00E-03	7.48E+03	2.5	1.86E+04	4.46E+02
Sand	1.19E-05	2.00E-03	2.38E+03	0.6	1.44E+03	1.08E+03
Peat	2.01E-07	2.00E-03	6.04E+03	2.4	1.44E+04	1.82E+02
Sand	2.29E-05	2.00E-03	2.38E+03	0.6	1.44E+03	2.08E+03
Peat	1.09E-07	2.00E-03	3.23E+03	3.4	1.09E+04	7.47E+01
Annual groundwater outflow (m^3)						**4 130**
Annual groundwater inflow (mm) (based on the mire area of 1 462 ha)						**0.3**

5.3.4 Streamflow

Monthly flows of the Nkazana stream from Mfabeni Mire into Lake St. Lucia ranged from 0.1 mm $month^{-1}$ (1 063 m^3 $month^{-1}$) in August (dry season) to 2.1 mm $month^{-1}$ (30 573 m^3 $month^{-1}$) in March 2009 (wet season). The unseasonal high flow rate in June 2008 (1.4 mm month^{-1}) and low flow rate of 0.02 mm month^{-1} (227 m^3 month^{-1}) in December 2008 (wet season) are noticeable (Figure 5.8) but are in agreement with the rainfall measured during those months (Figure 5.4). The annual stream flow was 9 mm year^{-1} (131 916 m^3 year^{-1} distributed over the 1 462 ha of the mire).

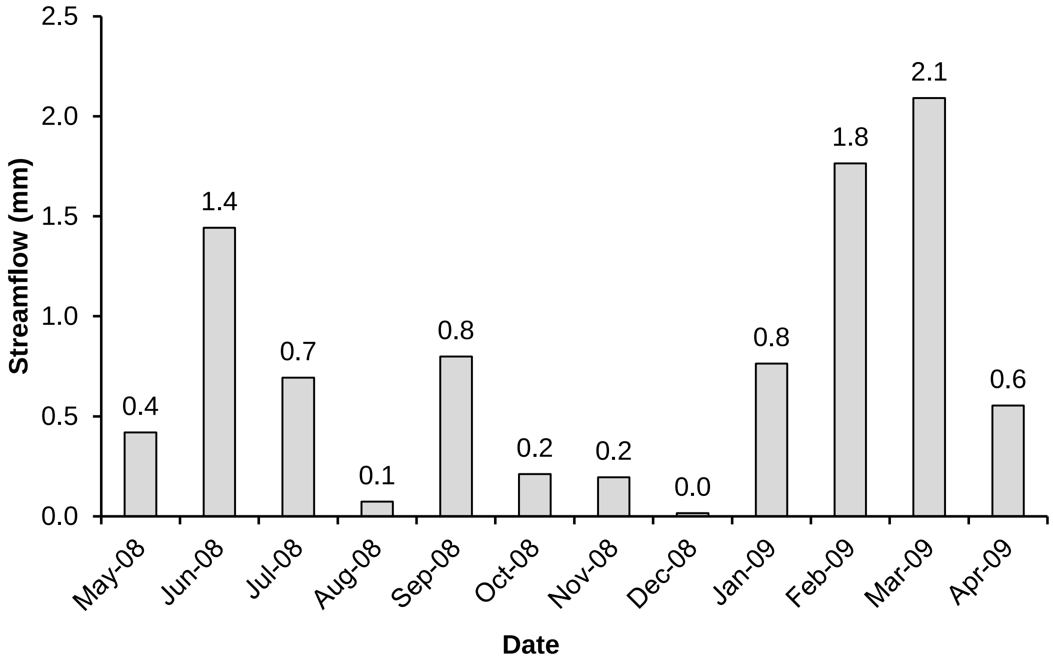

Figure 5.5.8*:* The monthly total streamflow for the Nkazana stream from May 2008 to April 2009.

5.3.5 Changes in storage

The water level differences in Mfabeni Mire over the 12-month period ranged from 0.01 m (May 2008) to 0.1 m (April 2009) in the northern parts of the sedge/reed fen area (sites 2 and 3) to -0.03 m in the central fen and -0.07 m in the southern fen area (Table 4.5). The water level differences over the same period in the swamp forest ranged between -0.04 m to 0.12 m on the sloped swamp forest areas to 0.06 m in lowland swamp forest area (Table 5.5). These results were used together with an average specific yield of 0.19 (n = 25; standard deviation = 0.062) for the sedge peat and 0.15 (n = 8; standard deviation = 0.055).for the swamp forest peat (Equation 5) to estimate the net ΔV, which amounted to -3 mm (-50 860 m^3) in Mfabeni Mire (Table 5.6).

Table 5.4: Water table fluctuation for the sedge/reed fen area

	Site				
Date of measurement	2	3	6	7	10
2 May 2008	0.73	0.57	0.34	0.52	0.66
30 Apr 2009	0.63	0.56	0.41	0.55	0.73
Change in water table below surface (m)	0.1	0.01	-0.07	-0.03	-0.07

Table 5.5: Water table fluctuation for the swamp forest area

	Site			
Date of measurement	a	b	c	d
2 May 2008	0.53	0.82	0.61	0.74
30 Apr 2009	0.58	0.76	0.73	0.78
Change in water table below surface (m)	-0.05	0.06	-0.12	-0.04

Table 5.6: The annual change in storage for Mfabeni Mire from May 2008 to April 2009

	Specific yield (%)	Area (ha)	Storage change in m^3	Storage change in mm
Sedge/reed fen	22	1 047	-23 034	-0.002
Swamp forest	19	415	-27 831	-0.007
ΔV		1 462	-50 865	-0.003

5.3.6 Water balance

The annual water balance was determined according to equation 1, where all components were measured or modelled and the equation rearranged to determine the error term (water balance residual term= ŋ). Evapotranspiration (1 053 mm) and rainfall (1 031 mm) dominated the water balance (Figure 5.9). These were followed by GW_{in} (14 mm), S_{out} (9 mm) and ΔV (-3 mm) with the smallest flux being GW_{out} (0.3 mm). The negative sign of ΔV indicates a net loss in water stored in Mfabeni Mire over the period (May 2008 to April 2009). After resolving all components of the water balance by measurement and modelling, water balance residual term, ŋ, was -15 mm. This deficit is however only 1.9% of the ET and considered good closure of the water balance.

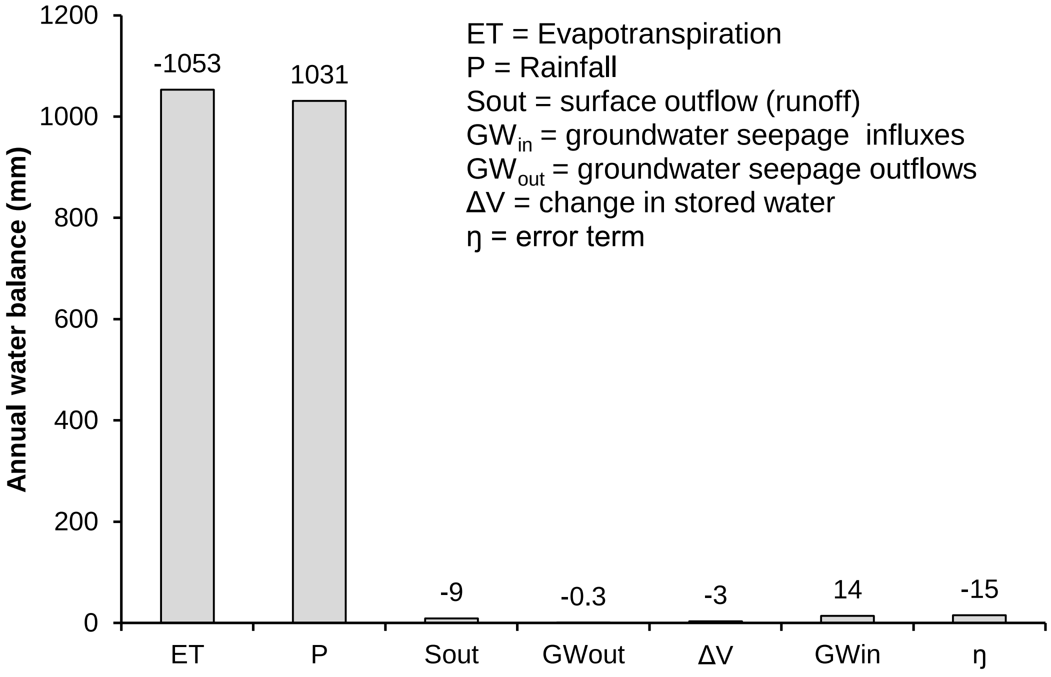

Figure 5.5.9*:* The water balance of Mfabeni Mire.

5.4 DISCUSSION

The average rainfall for Mfabeni peatland was determined over a period of 12 months from May 2008 to April 2009 and is about 14% below the long term annual average of 1 364 mm/year (1961 to 1989) at the coast (Wejden, 2003). Measured rainfall followed the general trend of wetter summer months in contrast to drier winter months. However, a dry period occurred in the summer months of October, November and December 2008 supporting the variability of the rainfall in the area (Taylor *et al.*, 2006). It was previously indicated that a strong rainfall gradient persisted from east to west across the Eastern Shores (Taylor *et al.,* 2006). The results from the 15 rain stations distributed across the Eastern Shores indicate in addition, an increasing south to north gradient for the period measured. Of particular interest is an indication that the western dune with its grassland and relatively extensive bare soil areas (which are the recharge areas for Mfabeni Mire groundwater), received approximately 50 mm/year less rainfall than the eastern dune which is covered in dune forest vegetation (Clulow *et al.*, 2013).

Evapotranspiration was the largest component of Mfabeni Mire water balance and exceeded rainfall during the period of monitoring by 22 mm (2.1% of the rainfall). The ET rates of the swamp forest, located on a groundwater discharge zone with stable and readily available water levels, were higher than the sedge/reed fen. However, the area of the swamp forest is only 28% of Mfabeni Mire, yet its contribution to Mfabeni Mire ET was 34%. Clearly the area of swamp forest in relation to sedge/reed fen plant community within Mfabeni Mire would significantly alter the water balance of Mfabeni Mire due to their different ET characteristics. Hence bush encroachment commonly associated with poor management practices in terms of a burning regime should be considered critical to the water balance of the mire.

The influence of cloud cover was noticeable in the daily ET data (Figures 5.6a and 6b) with reduced rates of ET from both plant communities. Cloud and low vapour pressure deficit were noted by Clulow *et al*. (2012) to suppress ET within the area. Despite the high wind speeds reported in the area and the readily available water in the mire, ET rates were lower than those few ET measurements available from other wetlands within South Africa. For example, Everson *et al*. (2001) measured summer maximum rates of ET as high as 9 mm/day and winter maximum rates of 4 mm/day within a riparian area of the Sabie River in the Kruger National Park. The differences in ET are likely to be as a result of the different geographical location (latitude, altitude) and climatic factors (proximity to the ocean). Both sites have readily available water throughout the year but the Sabie site has more solar irradiance (as a function of latitude but also less cloud cover, especially in summer) and higher vapour pressure deficit conditions in general due to the surrounding dry landscape. The suppression of the ET at the Mfabeni Mire due to cloud cover and low vapour pressure deficit are important controls that help maintain its water balance. They could, however, be considered to increase the risk and vulnerability of the Mfabeni Mire as any shift to these factors limiting ET, coupled with a reduced rainfall scenario or longer and more extreme periods of drought, will impact negatively on its water balance and particularly the water table level.

The seasonal patterns of the daily swamp forest and sedge/reed fen were noticeably different. The difference in summer and winter ET from both plant communities was driven primarily by the seasonal change in solar irradiance by virtue of the proximity of the groundwater to the surface in the Mfabeni Mire (Table 4 and 5). The sedge/reed fen pattern of maximum daily ET was a smooth sinusoidal curve whereas the maximum swamp forest evapotranspiration fluctuated. This could be as a result of the high and variable wind speeds recorded in the area (Clulow *et al*., 2012) which was used to model the ET of the swamp forest (FAO56 Penman-Monteith model) and not the sedge/reed fen (Priestley Taylor model). The increase in ET of the swamp forest into the summer months was delayed but then increased rapidly in February 2009. This delayed increase in ET of the swamp forest was also noted by Clulow *et al*. (2013) and may be as a result of the increase in the reported monthly average vapour pressure deficit from approximately 0.7 kPa in January to 1.0 kPa in February (Clulow *et al*., 2012). Such changes in the vapour pressure deficit are certain to influence the high swamp forest ET where the humid conditions are a limiting factor to tree transpiration. The leaf area index is extremely high below the canopy of the swamp forest (7.2) whereas the sedge/reed fen was much lower (0.85 to 1.2) providing a much greater surface area for transpiration from the leaves (Clulow et al., 2013). The high wind speeds shown to be dominant in the area are important to the estimation of ET. It likely contributes to the higher ET rates of the swamp forest as a result of the entrainment of warm, drier air down through the convective boundary layer removing the saturated air from above the swamp forest (Lhomme, 1997). The high surface roughness of the swamp forest canopy contributes to greater turbulence and atmospheric mixing above the SF canopy, hence greater ET.

The hydrological study in Chapter 3 shows that the water table descends abruptly on the eastern edge of Mfabeni, which is more than likely as a result of the absence of the highly humified peat and impeding basal clay layer beyond this point (Chapter 2) and the relatively permeable sediments through which flow occurs. Consequently the coastal eastern dunes are not contributing to the groundwater inflow component of Mfabeni water balance, contrary to the notion previously postulated by Rawlins (1991) and Taylor *et al*. (2006). Therefore, groundwater inflow (14 mm) occurs only from the western dunes. However, although it is a relatively small proportion of the water budget (<2% of rainfall), it represents a large proportion of the water deficit of 22 mm (64%) and is therefore a significant component in drier periods that helps sustain waterlogging and anaerobic conditions. Consequently the groundwater inflow has aided in peatland development and currently assists in maintaining its integrity (c.f. Lapen *et al.,* 2005). The groundwater outflow from Mfabeni Mire is insignificant compared to the other water balance components. It is therefore doubtful if groundwater outflows from Mfabeni contribute significantly to adjacent ecosystems such as Lake Bangazi and the smaller eastern wetlands.

Surface inflow does not occur into Mfabeni Mire as its catchment geology is dominated by highly permeable sands resulting in high infiltration rates with minimal surface runoff into the mire (Rawlins, 1991). The annual outflow through the Nkazana stream is more than two orders of magnitude less than the long-term annual average rainfall, underlining the importance of evapotranspiration losses from the system. Sustained groundwater discharge from the western dunes regulated baseflow in the Nkazana stream, which drained southward to Lake St. Lucia. Consequently the Nkazana stream is perennial, although it is characterised with persistently low flows during the dry season. However, this relatively low surface outflow is locally significant during drier periods, providing a freshwater refugia at its outfall to Lake St. Lucia (Taylor *et al.,* 2006).

Van Seters and Price (2001) concluded that in the error assessment of a peatland water balance the different components should be assessed in relative terms as there is no absolute standard for evaluation of errors. Rainfall data from the 13 manual gauges averaged 13% less than that collected in the two tipping bucket raingauges from May 2008 to April 2009. The difference was likely a consequence of the weekly monitoring interval of the manual gauges during which time evaporation from the collected samples could have taken place; they were corrected accordingly. The tipping bucket raingauges (TE525, Texas Electronics Inc., Dallas, Texas, USA) have an error range of 1% up to 25 mm/hour (Riddel, 2011). Winter (1981) suggests short-term average precipitation estimates are typically within 15-30% of the true value, but annual estimates can be better, at about 5% of the true value. Given the dominance of precipitation as a water input in this water balance, the potential error is larger than the annual inputs and losses from other sources, except ET.

Modelled estimates of ET using the Priestley and Taylor or FAO56 Penman-Monteith models rely on finding the most suitable estimates of α and K_c, respectively, from similar vegetation types and locations. In this study we had the advantage of having derived values of α and K_c for both dominant plant communities of the Mfabeni Mire and to model the ET from the same weather station site and same instruments used to derive the α and K_c. In addition, the models were applied over relatively homogeneous areas where the vegetation was not water limited at any stage and therefore suited to the application of these models. Quantifying the absolute accuracy the the ET measures used to derive α and K_c is complex. In both cases, the eddy covariance technique, which is considered the international standard in estimating ET, was used in discreet measurement periods that formed the basis for modelling ET from the sedge/reed fen and swamp forest plan communities. Although there is much discussion on the accuracy of eddy covariance ET estimates and associated energy balance closure problems it is the measurement technique used with which to assess others methods, and is generally considered 10 to 20% accurate (Simmons *et al*., 2006; Castelvi *et al*., 2008). At the swamp forest site, the sapflow technique used to infill the periodic eddy covariance data is also a highly regarded method as is the surface renewal technique used to infill the periodic eddy covariance measurements at the sedge/reed fen (Clulow et al., 2013).

The groundwater inflow and outflow calculations that formed the basis for the water balance are a function of the hydraulic characteristics (K) of the substrates adjacent and within the peatland and their extent (area and thickness). The hydraulic characteristics were determined along the main transect and then extrapolated to the whole mire. Elevation surveys could have vertical errors of 2 to 5 cm. Whilst the peat was investigated along several transects (seven with 100 to 200 m sampling intervals) the opposite holds true for the adjacent sand dunes (three sites on either margin). The expected margin of error could therefore be as much as 30 to 50%. However, given the small value of groundwater inflow and loss, relatively large errors result in very small differences in the absolute value for the flux. Water storage changes are also a function of the hydraulic character (Sy) of the peat in the mire, as well as the accuracy of water table measurements. Water table measurements were made broadly across the system to provide a representative value. Furthermore, water storage changes are not a cumulative measurement, and over a period of one-year errors cancel each other, and the total change is relatively small.

For streamflow estimates, the compound weir was well-calibrated for the V-notch portion that captured low-flow conditions well. Higher flows over the square-section occurred less than 10% of the time and were more difficult to calibrate accurately, thus have greater uncertainty. However, extremely low flows of 5 m^3/hour were measured for 35% of the time with several high flow measurements exceeding 250 m^3/hour. Due to data loss from mid-February to 1 May, 2009 discharge was inferred for the Nkazana stream. The Mpate stream measuring weir 15 km to the southwest exhibited similar discharge patterns to the Nkazana weir (correlation of R^2=0.77). The period of inferred discharge covers 20% of the monitoring period. The average flow in Nkazana stream of 15 m^3/hour from May 2008 to May 2009 compares well with previous estimates of 10 m^3/hour (no period provided) (Taylor, 2006) but is less than the 50m^3/hour determined for a limited period of time(June 1989 to August 1989) by Rawlins (1991). Given the relatively small value of the streamflow component of the water balance, the uncertainty results in a small absolute error.

The water balance provided a good overall indication of the relative importance of the individual components. Although the small residual term (-15 mm) provides good closure of the water balance it does not necessarily reflect the error of individual components and the larger errors discussed above. It is possible that errors in the large components, namely P and ET, could cancel each other, and there is no way to be certain if this occurs. However, even considering the potential errors, the water balance clearly illustrates the relative magnitude of the individual components. This system is dominated by, and thus most sensitive to P and ET, although as noted their similarity makes contributions and losses from other components highly important to the system function.

The Eastern Shores of the iSimangaliso Park was managed since the 1950's on a dual basis as a conservation area with commercial timber interests. Timber operations focused on planting *Pinus* species, exotic to southern Africa and often invasive, therefore resulting in lower groundwater levels with detrimental impacts on adjacent lakes and wetlands (Rawlins and Kelbe, 1991, Taylor *et al.*, 2006). Furthermore, the stabilising of active dunes in the western part of the Mfabeni Mire catchment by the planting of *Pinus* and *Casurina* species reduced recharge of rainwater to the aquifer Management interventions such as removing these plantations and other invasive species since 2000 (Været *et al*., 2009) have been a significant step in protecting the groundwater resource crucial to ecosystem support in iSimangaliso Wetland Park. Other conservation tools such as fire should be used with caution when the peatland is dry, as uncontrolled peat fires have occurred during drier periods (Clulow *et al*., 2012). However, conservation management should not only focus on environmental interventions in the mire but the catchment as a whole should be protected against groundwater abstraction and large scale tourism development. Active dune forming processes in the western dunes' groundwater recharge areas should be encouraged to stimulate recharge to the aquifer (Stuyfzand, 1993). This could be achieved by clearing invasive species which do not only intercept rainfall but through evapotranspiration reduce available groundwater.

5.5 CONCLUSION

Determining and quantifying the contribution of different components of the water balance enhances our understanding of wetland systems in various climates, and their ability to survive climatic instability. Knowledge of the water balance also improves our understanding of its components and how they contribute to the range of eco-services performed by wetlands.

The water balance of Mfabeni Mire was dominated by ET and P, however the wetland still contributed efflux to the downstream ecosystems (by stream flow) and to a lesser extent efflux to adjacent ecosystems (by groundwater). Mfabeni Mire primarily functions as a control of the regional water table, thereby maintaining high groundwater levels and wetness of the accumulated peat within the mire. However, its value in a landscape where seasonal change and long-term drier periods are major ecological drivers, are more likely in its role in dampening the effects of climate variations. The Mfabeni Mire does this by contributing to steadier groundwater conditions, thus a more stable environment for adjacent ecosystems. Consequently, peatlands in arid climates should be recognised as an asset in natural resource management and their potential to support adjacent ecosystems should be protected through proper planning and conservation practices.

5.6 ACKNOWLEDGEMENT

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6. SYNTHESIS, MANAGEMENT AND RESEARCH RECOMMENDATIONS

6.1 THE STUDY

Wetlands provide various ecosystem services such as flood attenuation, flow augmentation, carbon sequestration and water quality enhancement to society and the environment (Mitsch and Gosselink, 1993; Costanza *et al.*, 1998). However, not only are these services not well defined in subtropical and semi-arid regions, but there is a poor understanding on the integrated processes and functions of wetlands (Ghermandi *et al*., 2010) underpinning various ecosystem services. To understand these integrated processes and functions, the development, surface and groundwater exchanges and water balance of Mfabeni Mire, a large valley-bottom peatland located in the subtropical eastern part of South Africa, were studied.

In the initial stage of the study the focus was on the development of Mfabeni Mire in relation to the landscape position in order understand the hydrological conditions in which this peatland could survive in spite of a large regional water deficit and changing climatic conditions over time. Peatlands are not only ideal for studying ecosystem services as they are a large store of carbon, water and biodiversity, but they also represent stable environments in a changing landscape forming over extensive periods of time and often in changing climates. Typically these wetlands are not isolated features in the landscape but often part of wetland complexes linked by streams and or groundwater flow systems (Winter, 1999). They are often multifaceted ecosystems with complex mechanisms controlling their geomorphological, hydrological and biological processes.

From the initial research it can be concluded that Mfabeni Mire is a groundwater dependant ecosystem that developed with the infilling of a valley bottom with peat in the Late Pleistocene and continued to develop during the Holocene. The infilling resulted in a plug effect which forced a rise in the elevation of the influent groundwater surface in the adjacent upland as peat accumulated in the lowland. Consequently the consistent and permanent discharge of groundwater into the peatland from the upland allowed for the almost uninterrupted formation of peat over an extended period. This expansion of the groundwater source resulted in a buffering effect against climatic turbations in this semi-arid region providing a more stable localised environment for this mire to develop. Furthermore the elevated groundwater surface also favoured the development of a series of ephemeral non-peat wetlands adjacent to the mire, whilst discharge from the mire contributes in maintaining refugia within Lake St. Lucia during drier periods.

The development of peatlands is strongly linked to hydrological processes and in particular to groundwater sources in semi-arid regions. Wetlands receiving groundwater discharge reflect the input in terms of sustained wetness and water quality, and transform these into outputs such as peat that may directly affect downstream systems by augmenting flow in drier periods (Smaktin and Bachelor, 2005). Results from the investigations into the origin and development of Mfabeni indicated a groundwater discharge from the western dune towards the peatland and the Indian Ocean, with stream flow southwards to Lake St. Lucia. However, the links between the primary components were not clearly evident from the mire development and water balance investigations. Therefore surface and groundwater exchanges of Mfabeni Mire were studied to understand the role of this large wetland complex in maintaining downstream water flows in a changing environment by characterising the groundwater exchanges through the system, more specifically the feedbacks between regional and local flow systems that contribute flow to downstream ecosystems.

Wetlands are often assumed to be sources of water, effectively producing water to sustain internal process and stream flow to downstream ecosystems (Mitch and Gosselink, 1993; Bullock and Acreman, 2003; Charles and Nicholson, 2012). This second phase of the Mfabeni Mire study has shown that water efflux from the western inland dune complex provides substantial recharge towards the mire. Coastward hydraulic gradients from the dune complex through the wetland are evident, but only a small portion of groundwater from the inland dunes flows through the mire towards the coastal dunes in the east. However, rainwater accumulating on the eastern part of the mire are more likely recharging the groundwater of eastern dunes at the eastern margin of the fen. The major portion of groundwater from the inland dunes is forced to discharge southwards via Nkazana Stream into Lake St. Lucia. This is due to the plug effect of the relatively low hydraulic conductivity peat in Mfabeni Mire, compared to the adjacent sands that carry water towards it.

Direct rainfall on large wetland complexes might be important together with groundwater inflows in semi-arid regions such as Mfabeni Mire where these water inputs maintained a high water level in the mire. Groundwater hydrographs indicated clear responses between rainfall and groundwater in the mire and adjacent wetlands. However, the more damped responses to rainfall variation in the mire compared to the adjacent wetlands clearly demonstrate the important stabilizing effect of groundwater where there is a strong water deficit (Glaser *et al*., 1997; Almendinger and Leete, 1998). Surface and subsurface flow along a sloping mire are critical in keeping the peatland wet and maintaining its functions due to limited groundwater contributions through the deeper more decomposed peat with very low hydraulic conductivity. However, the relatively wet condition of such a mire will cause a rapid translocation of rainwater through streamflow, whilst the relatively wet condition of the wetland will increase the evapotranspiration losses compared to water that is recharged in the dunes (Clulow *et al*., 2013).

Peatlands are ecohydrological systems where there are strong feedbacks between vegetation and local precipitation, evapotranspiration, surface and groundwater flows (Ingram 1983, Emili and Price 2006). The hydrological study at Mfabeni Mire showed that wetlands in drier climates are more of a conduit responding to regional hydrological dynamics, rather than a source. Both the magnitude and source of water fluxes, the associated supply of dissolved minerals and nutrients influence the vegetation response and determine wetland form and function (Ivanov 1981, Rydin and Jeglum 2006). The source of water and stable water levels in variable environments are consequently key determinants of wetland characteristics and function. Understanding the origin and variability of wetland water sources allows better assessment of wetland type and function (Gibson *et al*., 2005). Therefore isotopic, geochemical and thermal tracers were employed to improve the interpretation and verification of the feedbacks between rainfall, evaporation, groundwater and surface flow through the Mfabeni Mire. In particular this stage of the study seek to establish the source area of the stream flow and the groundwater recharge area for the Mfabeni Mire, as well as investigating the mechanism of maintaining the wetness of the mire's peat.

Isotopic and geochemical analyses support the hydrological evidence that groundwater discharge at the swamp forest along the western margin of the peatland but not at the peatlands eastern margin. Water migrating eastward through the western dune encounters the thick peat layer in the Mfabeni Mire, which acts as a plug, forcing water to discharge at its western margin. From here it flows across the open fen whereupon it becomes enriched and an evaporation signature develops after which it recharges again at the eastern part of the fen towards the eastern dunes and the ocean. Lower concentrations of isotope and cation/anion values below the peat, in the clay layer, suggest the hydrogeological and geochemical exchanges with this layer are limited.

Studying the stable isotope and geochemical composition of various hydrology components of the Mfabeni Mire provided insight into the feedbacks between rainfall, evaporation, groundwater and surface flow through the Mfabeni Mire. The distribution of the geochemical and isotope tracers resulted from the patterns of water flow through the Mfabeni Mire as demonstrated by hydrological flow patterns discussed previously. These tracers are indeed supporting the hydrogeological evidence and illustrate the longer term persistence of the hydrological functions of this wetland ecosystem. The western dune as primary groundwater recharge area of the Mfabeni Mire is emphasised with all tracers supporting flow from these dunes to the mire. Groundwater discharging at the swamp forest, shallow subsurface flows and surface flows across the peatland surface are all mechanisms maintaining the wetness of the mire’s peat and therefore maintaining peatland integrity.

The persistence of peat-accumulating wetlands (mires) in semi-arid environments with strongly seasonal rainfall where evapotranspiration exceeds precipitation requires water inputs from large catchments or sustained local groundwater input (Meadows, 1988; Colvin *et al*., 2007, Ellery *et al.*, 2009) to maintain internal functions and provide ecosystem services. Furthermore, higher water availability during wetter seasons generally promotes large evapotranspiration losses (Penman, 1948) especially in subtropical wetlands, although some wetland plants (including trees) can restrict water losses (Clulow *et al*., 2012). It is therefore important to account for water sources, stores and flows in evaluating a wetland’s ecosystem services, especially where drier climates prevail, since linked ecosystems can be strongly affected by the water relations governed by wetlands. Wetlands in subtropical areas may indeed be a net user of water (McCarthy, 2006; Riddell, 2011) but might still provide downstream ecosystems with a sustained flow in a landscape where seasonal change is a major ecological driver. Therefore, evaluating the functions of wetlands is greatly facilitated if their water balance is defined. Consequently the water balance of the Mfabeni Mire was quantified not only to define its contribution to downstream and adjacent ecosystems, but also to understand the role of the different water sources, stores and flows in the hydrological character of the mire.

Determining and quantifying the contribution of the different components of the water balance enhance not only our understanding of different wetland systems in these climates and their ability to survive climatic instability, but also their role in providing a range of eco-services. Wetlands are an integral part of the hydrological cycle of many catchments, and their position in the landscape determines their role in regulating flow to downstream ecosystems (Ingram, 1983; Joosten and Clark, 2000; Bullock and Acreman, 2003; Maltby, 2009) by influencing basin water storage and flood attenuation (e.g. Siegel, 1988; Brinson, 1993; Smaktin and Bachelor, 2005). Furthermore, wetland hydrological functions that control downstream discharge and water quality (Bullock and Acreman, 2003) are dependent on the type of wetland, relative size and position in the landscape, as well as local climate (Brinson, 1993; Kotze *et al.*, 2008; McCartney and Acreman, 2009). Extensive wetlands such as floodplains can control flood magnitude (Archer, 1989; Kotze *et al.*, 2008), while unchannelled valley-bottom wetlands with thick accumulations of sediment such as peat can sustain baseflow; (Smakhtin and Bachelor, 2005) and are important in sequestering carbon. (Joosten and Clark, 2002)

The Mfabeni Mire, although extensive (1 462 ha) and with an substantial accumulation of peat (11 m) is, based on its water balance, primarily functioning as a control of the regional water table in order to maintain wetness of the accumulated peat within the mire. Groundwater inflow (at 14 mm of the yearly water balance and comprising 64% of the deficit of 22 mm) is therefore an important component not only in developing but also in maintaining peatland integrity by ensuring waterlogged and anaerobic conditions in drier periods. The groundwater outflow is an insignificant component (0.3 mm/year) compared to the other water balance components. It is therefore doubtful if groundwater flows from Mfabeni contribute significantly to adjacent ecosystems such as Lake Bangazi and the smaller eastern wetlands. It seems rather that the internal ecological and peat forming processes of the Mfabeni Mire are sustained by the relatively large (order of magnitude more) groundwater discharge into the wetland compared to the much smaller groundwater efflux, especially in drier periods. The annual outflow through the Nkazana stream (9 mm/year) is more than two orders of magnitudes less than the long-term annual average rainfall (1 200 mm/year) with storage accounting for 3 mm/year. Importantly evapotranspiration losses from the system is the largest component of the Mfabeni Mire water balance (1 053 mm/year) and exceeded rainfall during the period of monitoring by 22 mm (2.1% of the rainfall). The swamp forest evapotranspiration rates were higher than the sedge/reed fen contributing 34% of evapotranspiration whilst only covering 28% of Mfabeni Mire's surface.

The majority of the groundwater discharged into Mfabeni Mire was lost to evapotranspiration, and the surface water in the south was drained by the Nkazana stream to Lake St. Lucia. Consequently the Nkazana stream, although perennial, is characterised with persistently low flows. However, this relatively low flow of surface outflow is still significant in providing refugia at the inflow to Lake St. Lucia during drier periods. However, the value of Mfabeni Mire is more likely in dampening climate turbations thereby contributing to steadier groundwater conditions in a landscape where seasonal change and long-term drier periods are major ecological drivers. This creates a more stable environment for adjacent ecosystems. Consequently peatlands in semi-arid climates should be recognised as an asset in natural resource management and their potential to support adjacent ecosystems should be protected through proper planning and conservation practices.

6.2 MANAGEMENT GUIDELINES

Peatlands are of high regional importance, and require good management, which is challenged by the poor understanding of their ecological and hydrological functions Understanding hydrological flow patterns within a mire provides an unique opportunity in not only understanding their functioning, but also in providing support in management options for their conservation. Wetlands are multifaceted ecosystems with complex mechanisms and often conservation interventions are more appropriate in the surrounding catchment where landscape features such as land cover, slope and soil type control hydrological inputs into the system. Studies of wetland hydrology should therefore take note of the surrounding catchment and its characteristics that could influence water movement. Our ability to manage and conserve such systems in future will depend on the insight we gain in understanding the processes driving formation and evolution during periods of change. Furthermore, given the wide interest in climate change and its expected impact on wetlands (Joosten, 2009; Crooks *et al.*, 2011), it is necessary that management guidelines are based on a sound understanding of the development and functioning of these systems. The extensive conversion of freshwater wetlands for cultivation and adjacent catchments for afforestation in subtropical regions of south eastern Africa should be controlled as these conversions ultimately affect their ability to cope with change and to contribute to ecosystem services.

Management of sensitive landscapes are often hindered due to a lack of scientific supported guidelines often resulting in environmental degradation (du Toit *et al.*, 2003). The results of this hydrogeological research provide researchers and conservation managers which control and manage Mfabeni Mire within iSimangaliso Wetland Park (as well as adjacent wetland areas) with information that will influence their decision making in terms of burning regimes and vegetation changes, groundwater abstraction within the area, and land use zoning (e.g. establishment of timber plantations). The following management aspects need to be considered:

6.2.1 Burning regime

Fire is an important ecological process in grasslands adjacent to Mfabeni and was actively prevented to enter Mfabeni for fear of extensive peat fires during the time when extensive *Pinus* plantations occurred. The peat stratigraphy does indicate the presence of charcoal and ash in the peat as one would expect in a semi-arid landscape. Indeed peat fires were noted twice during the study period when management fires in the dry season spread from the adjacent grasslands into the peatland. It is recommended that based on current understanding of the system that fires as part of ecological processes should not be kept out of a system. However, it should be part of the mosaic burning in the grasslands and only during wet years during wet cycles when it can be ensured that the peat is inundated. The mire must be monitored for a period of at least two to three weeks after fires to detect any peat fires.

6.2.2 Water abstraction

The Eastern Shores, hosting Mfabeni Mire, is a popular tourism destination in iSimangaliso Wetland Park and the pressure to expand existing tourist camps, or develop new ones exists. Groundwater is the most accessible clean drinking water source in the area and is strongly recommend that groundwater abstraction from the western dune recharge area should not be developed. Potentially groundwater resources on the eastern coastal dune component of the Mfabeni Catchment could be considered. However, the development of dewatering cones and saltwater intrusion must be monitored. The groundwater levels must be monitored for any substantial lowering, especially during drier cycles.

6.2.3 Catchment protection

Various landuse changes took place within the catchment of Mfabeni. The most significant of these were the *Pinus* plantations from the 1950 and associated infrastructure during the second half of the 1900's. Most of these were removed during the early 2000's. However, Secondary *Pinus* re-growth as well as the spread of alien invasive species such as guava (*Psidium guajava)* and Triffid weed (*Chromoleana odorata)* remains a problem. Both the hydrological investigation and isotope signature confirm that the source for its sustained base flow is groundwater; therefore reiterating the importance of conserving the western dune as a groundwater recharge area. No development in the western dunes should be allowed and the eradication of *Pinus* regrowth, alien invasive and bush encroachment clearing must be continued to facilitate grassland establishment in former plantation areas. This will encourage former dune formation processes (aeolian movement of sediment amongst others) that will limit transpiration and support recharge of the aquifer feeding the Mfabeni Mire. Furthermore, large tourism development in this part of the catchment should not be encouraged in order to prevent harden surfaces and potential pollution sources.

6.2.4 Research Recommendations

6.2.4.1 Flow patterns

This research has established that groundwater flows in mires in semi-arid regions are an important mechanism in maintaining internal processes. However, further research on surface and subsurface flow patterns within these mires are required to understand the mechanisms that can buffer groundwater fed fens against changes in climate.

6.2.4.2 Peat Surface Oscillation

Peat Surface Oscillation (PSO) is a well-documented peat preservation mechanism in temperate climate peatlands. Although peat surface lowering was noted during this study it only became pronounced as a regional drought intensified in the latter half of 2010. The peat surface reached its lowest point in February 2011 but the recovery of the surface was not documented as the (PSO) monitoring came to an end in April 2011. It remains unclear if PSO is an important peat preservation mechanism in groundwater fed fens in semi-arid regions and further investigations are recommended.

6.2.5 Erosion controls

The Nkazana stream draining Mfabeni Mire only develops towards the narrowing downstream point of the mire where the swamp forest completely covers the lower part of the system. The mire's slope change here from 0.03% to 0.2% and erosion in the channel is noticeable. The role of positive groundwater pressure in balancing downward erosive action of the stream flow should be investigated. This then should be compared to the role of vegetation as an erosion control agent.

6.2.6 Use of fire as a management tool in peatlands

Although fire is an acknowledged ecological management tool in the southern African savanna its role in wetlands and particular mires in this region is poorly researched. The presence of charcoal and ash in the peat profile of Mfabeni is clear evidence of fire in the mire and surrounds. However, the role of fire in contributing to processes within the peatland and how that relates to the adjacent terrestrial uplands/catchment requires further research.

6.2.7 Ecosystem services

A key component in this study of Mfabeni Mire was to determine its hydrological contribution in maintaining downstream and adjacent ecosystems. The hydrological contribution and role of wetlands in semi-arid regions in maintaining linked or downstream ecosystems are poorly researched and quantifying this contribution should be a research priority in motivating their sound management, conservation and to justify costs in their rehabilitation where relevant. Indeed understanding their contribution to ecosystem services should be a requirement in setting management, conservation and rehabilitation objectives.

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APPENDIX 1: MPATE STREAM MEASURING WEIR

Introduction

Discharge of the Nkazana stream (Figure A1) was measured from April 2008 to 2011. The water balance was to be calculated from April 2008 to May 2009 but data was lost for the period mid February 2009 till May 2009. Therefore discharge for this period was inferred for the Nkazana stream by correlation with the discharge pattern of the Mpate stream measuring weir 15 km to the southwest (Figure A1) of the Nkazana measuring weir.

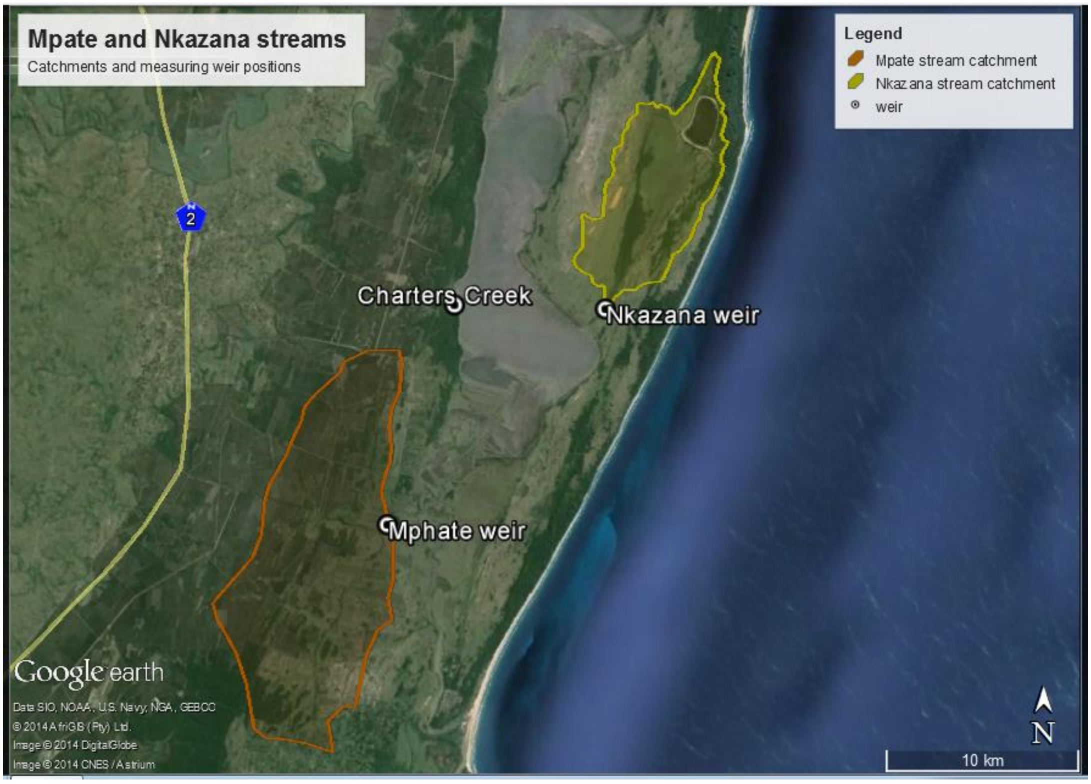


Figure A1: the location of the Nkazana and Mpate measuring weirs.

The Nkazana stream drains a topographically defined catchment of 4456 ha (Figure A1) consisting of highly permeable sand dunes and the Mfabeni Mire as well as small wetlands. Wetlands cover close to 40% of this catchment on the Eastern shores of Lake St. Lucia. The Nkazana stream measuring weir is a compound weir (Figure A2) The Mpate stream measuring weir is rectangular weir (Figure A3) maintained by the Department of Water and Sanitation (DWS), South Africa. It measures stream flow from a 10 300 ha catchment drained by a stream network with less than 20% wetlands in the catchment. The Mpate stream located on the on the Western Shores of Lake St. Lucia is part of the Maputaland primary, aquifer comprising highly permeable sandy soils. The $18x10^6m^3$/year estimated stream flow from the Mpate River is approximately four times the groundwater flow of the Eastern Shores (Nomquphu, 1998).

The objective of this exercise was to infer the discharge for the Nkazana stream by comparing its discharge pattern with that of the Mpate stream.

Figure A2: The Nkazana stream measuring weir – a compound weir. Note the wide angle of the V-notch.

Figure A3: The Mpate stream measuring weir – a rectangular weir (Photo – accessed 22 December 2014: https://www.dwa.gov.za/hydrology/CGI-BIN/HIS/Photos/W3H014.JPG)

Methodology

The discharge data from the Mpathe stream weir was acquired from the DWS website (https://www.dwa.gov.za/hydrology accessed September 2014) and processed in Excel. It was thereafter compared with the Nkazana stream weir data. Ambiguities in the Mpate data, when compared to local rainfall data, were removed.

Results

The Mpate stream measuring weir hydrograph exhibits similar discharge patterns to the Nkazana weir (Figure A4). However, a high flow event (indicated by a red arrow in Figure A4) in December 2008 does not fit the trend, nor does it correlate to the rainfall events at that time and these data points were removed. The correlation between the stream hydrographs for the Nkazana and Mpate measuring weirs for the periods April 2008 to February 2009 is R^2=0.77.

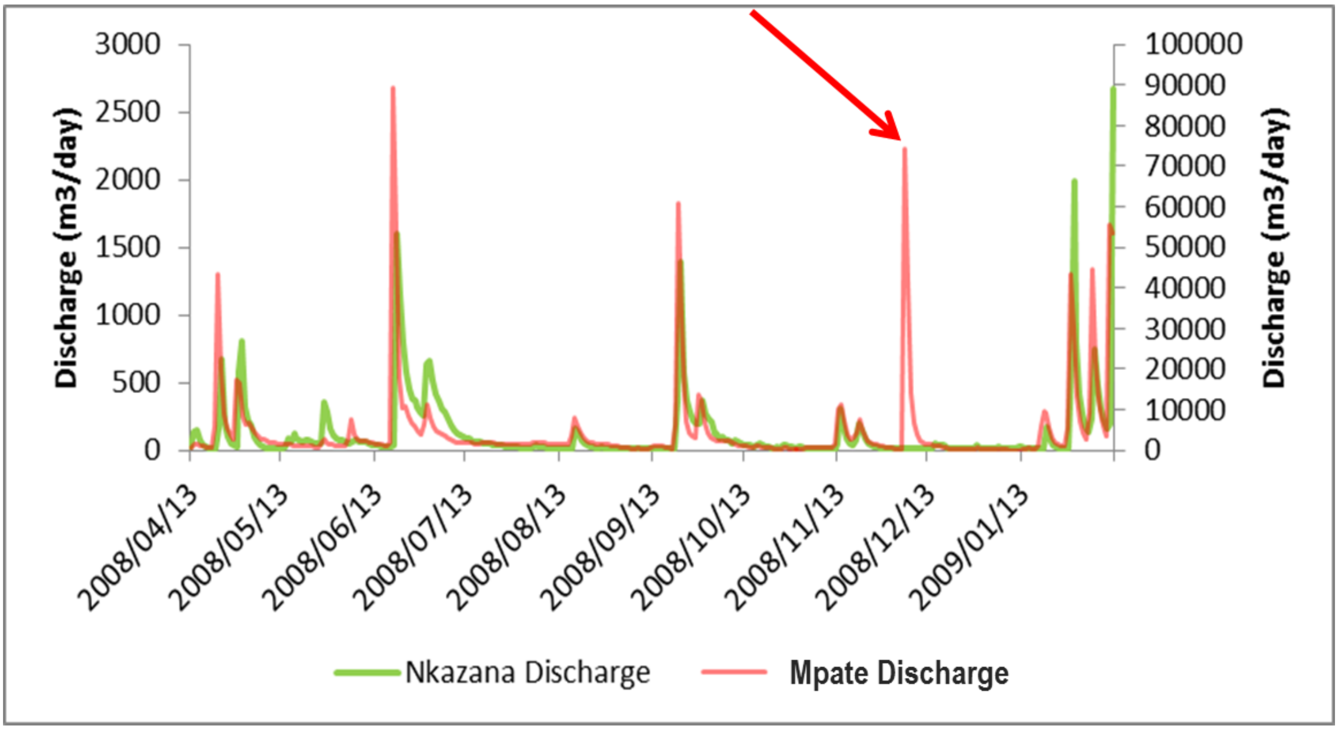


Figure A4: This stream hydrographs for the Nkazana and Mpate measuring weirs. Note the Mpate high flow event in December 2014, indicated by a red arrow.

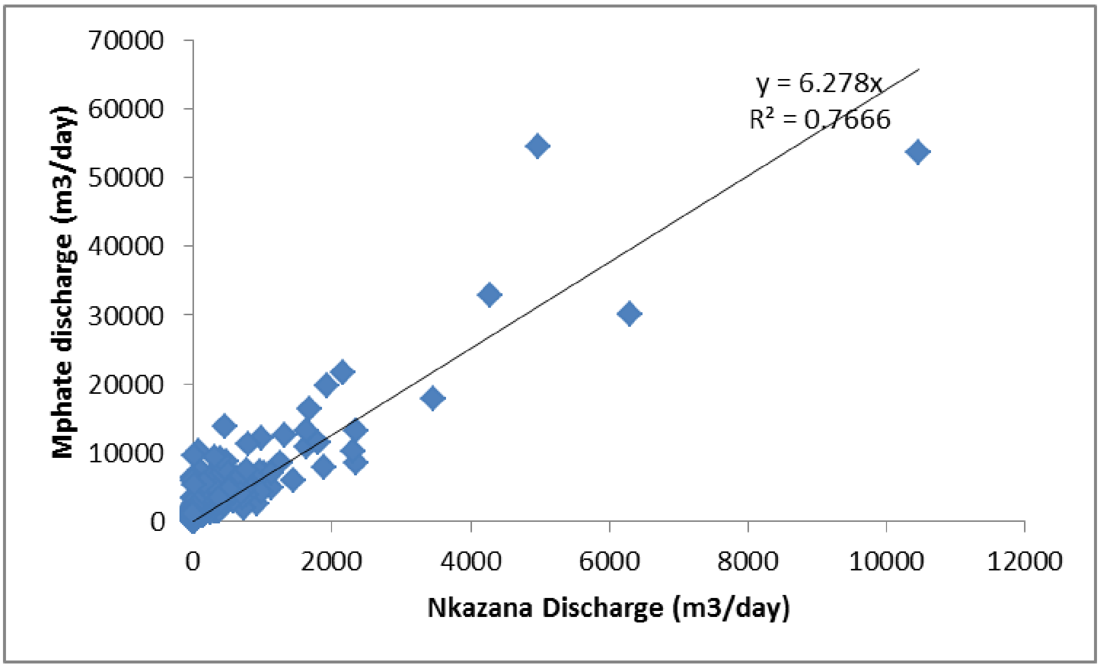


Figure A5: The correlation between the stream hydrographs for the Nkazana and Mpate measuring weirs for the periods April 2008 to February 2009.

Discussion

The Mpate and Nkazana streams both drains catchments located on highly permeable sandy soils. The Nkazana steam catchment receives about 20 % less rainfall than the Mpate stream catchment as rainfall decreases from east to west from the coast (refer to Chapter 1). The Nkazana catchment is about 50% of the Mpate catchment with the Nkazana stream discharge for the period of comparison (April 2008 to February 2009) 10 times less than the Mpate stream discharge.

The Mpate stream measuring weir exhibited similar discharge patterns to the Nkazana weir (correlation of R^2=0.77). This is considered a reasonable correlation and the Mpate stream weir measuring data was therefore used to infer the flow for the Mfabeni stream from February 2009 to May 2009 (Figure A6).

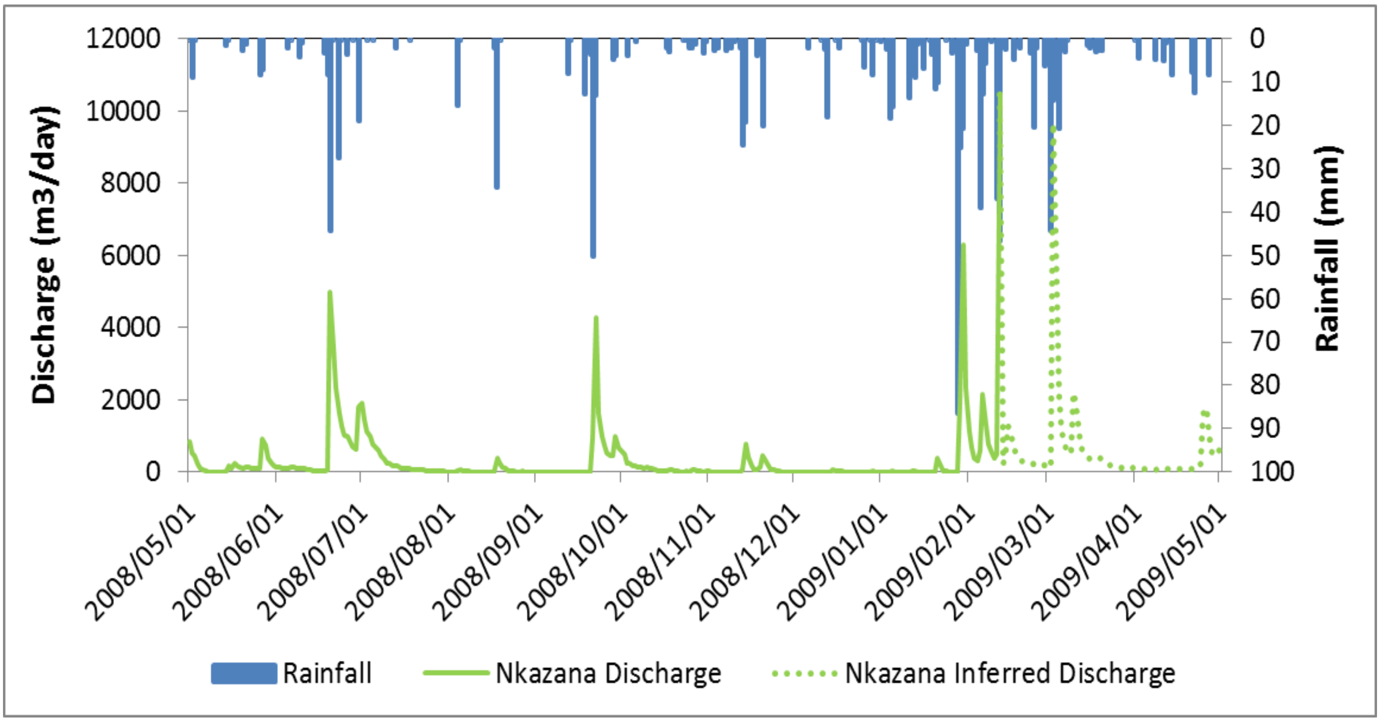


Figure A.6: The hydrograph for the Nkazana stream with the inferred section from February to May 2009.

Conclusion

The inferred hydrograph fits well with the Mfabeni rainfall pattern and exhibits the same stream flow response as the Nkazana stream measuring weir discharge. The period of inferred discharge covers 20% of the monitored period and is considered a reasonable fit.

APPENDIX 2: USGS TOPODRIVE RESULTS

Introduction

In order to characterise the flows of the Mfabeni mire a wells and multi-level piezometer nests at 43 sites were installed at different depths based on the peat or dune stratigraphy; up to depths of ~10 m in the peat, 16 m in the clay beneath the peatland, and to a depth of 30 m in the sandy uplands (24 of the 43 sites were located within Mfabeni Mire). Water levels within the wells and piezometers were monitored manually with an electronic probe on a weekly basis for 4 years from April 2008 to May 2012 (refer to Chapter 3). This resulted in a field based study with a substantially large data set which did not allowed for modelling of the ground water flux given the time constraints of the study.

It was therefore decided to use groundwater software package USGS TopoDrive to guide the final interpretation of the cross-section and depiction of isopotential lines and flow net for the main transect presented in Chapter 3. Hsieh (2001) indicates that TopoDrive is designed to simulate topography-driven groundwater flow by specifying the shape of the water table forming the top of the vertical flow section. The model boundaries are the rectangular extent of the model with two vertical boundaries and the bottom boundary as no flow boundaries which might represent ground-water flow divides or low-permeability bedrock that bounds the model basin. Groundwater flow is simulated under steady state with the distribution of substrates and related hydraulic conductivity and porosity to be specified in the model. The model determines hydraulic head and groundwater flow paths with an interactive visual interface that enables quick and easy evaluation of the modelled system. TopoDrive is therefore "not intended to be a comprehensive modelling tool, but are designed for modelling at the exploratory or conceptual level, for visual demonstration, and for educational purposes" (Hsieh, 2001).

Methodology

The model elements were set up as described by Hsieh (2001) and the input data was based on substrate properties described in Chapter 2 and 3 and included the water table shape and hydraulic conductivity. The modelled results were then used to evaluate an interpretation and depiction of the hand drawn isopotential lines and flow net for the main transect

Results

The model elements included a 5 layered system with the vertical flow boundaries located in the west at the lake interface and the in the west the Indian Ocean, with the bottom no flow boundary represented by Upper Cretaceous siltstones (Figure A2.1). Flows patterns for the larger study area were then generated by the model for a scenario with a canal deposit below Mfabeni Mire (Figure A2.2) and without the canal deposit (Figure A2.3). In Figure A2.3 a close up of the Mfabeni mire is represented (modelled separately with the same parameters).

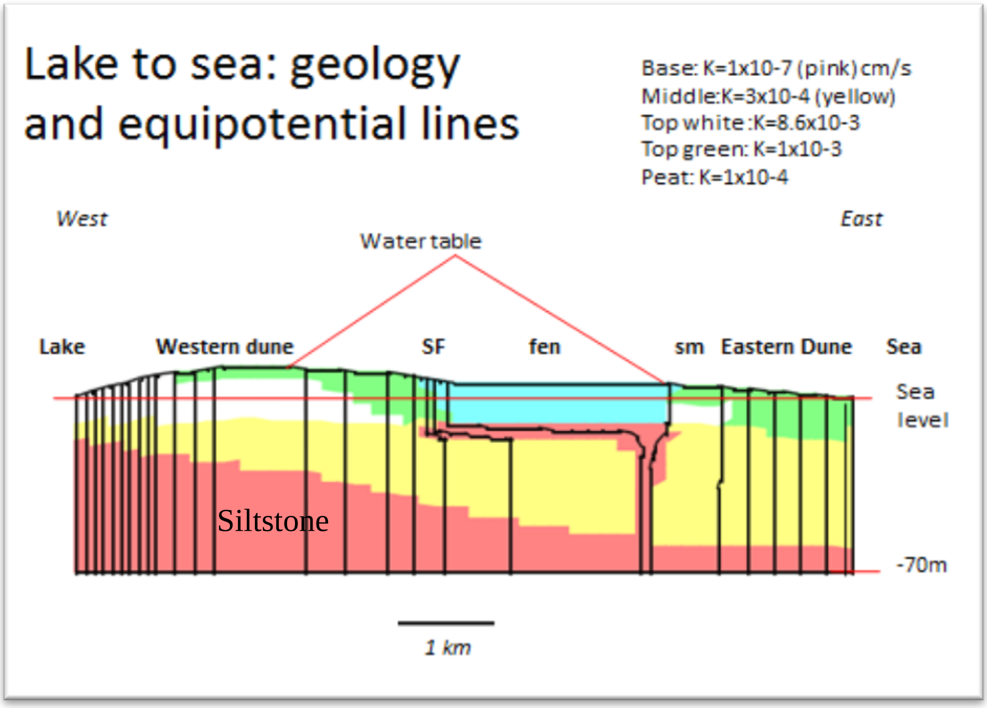


Figure A2.1: This cross section depicts the Mfabeni Mire and the simplified geology from Lake St. Lucia in the west to the Indian Ocean in the east. Hydraulic conductivity and equipotential lines are indicated.

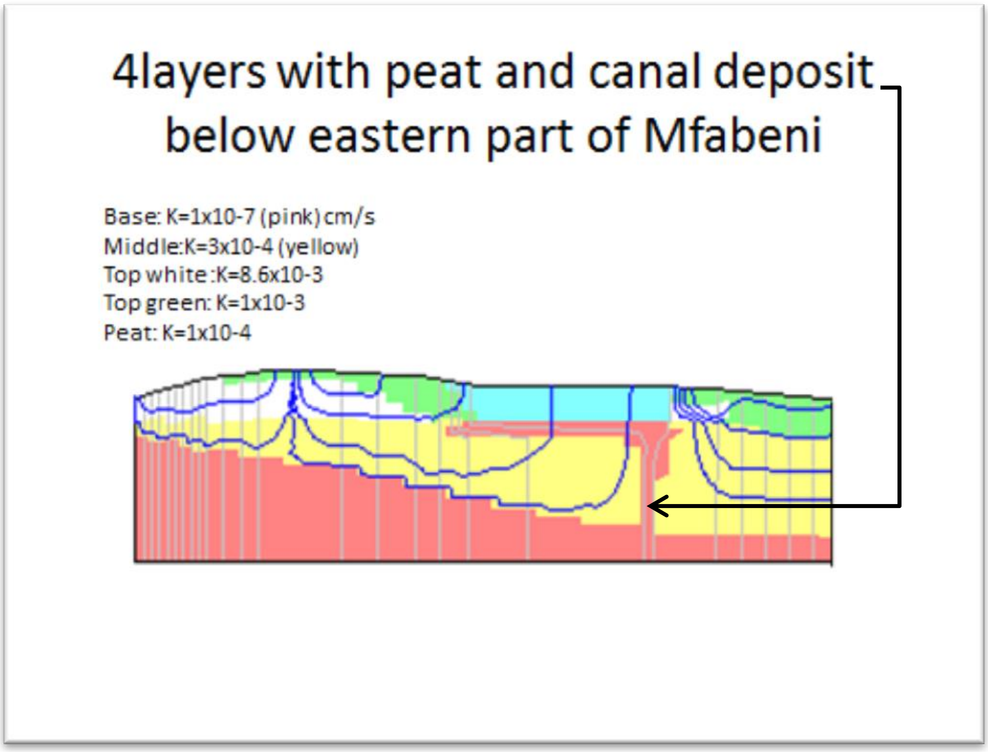
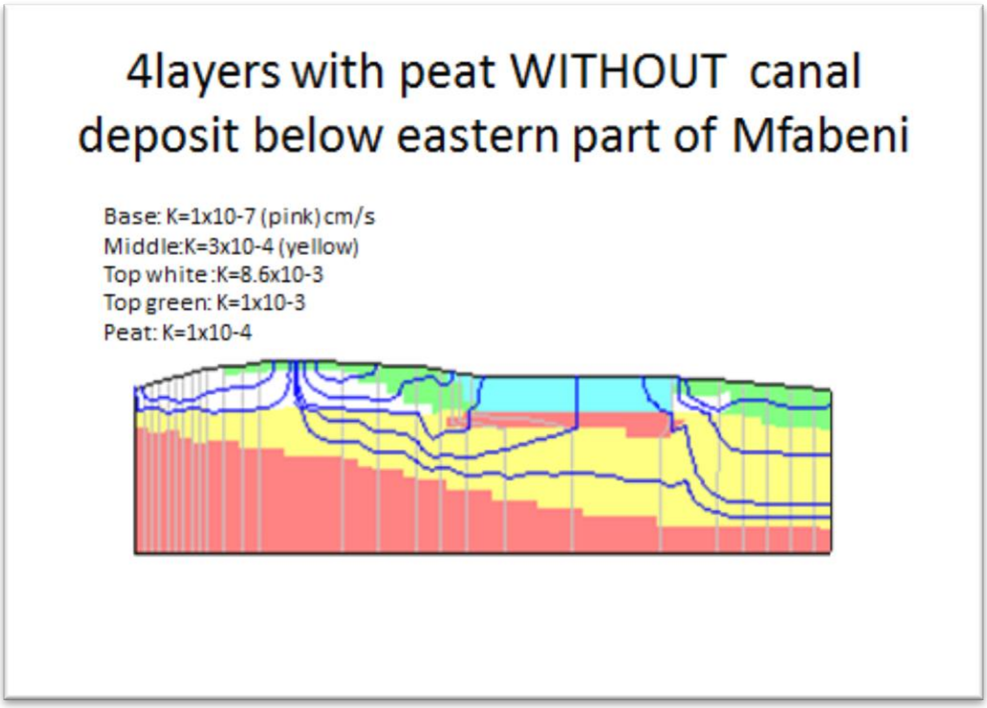


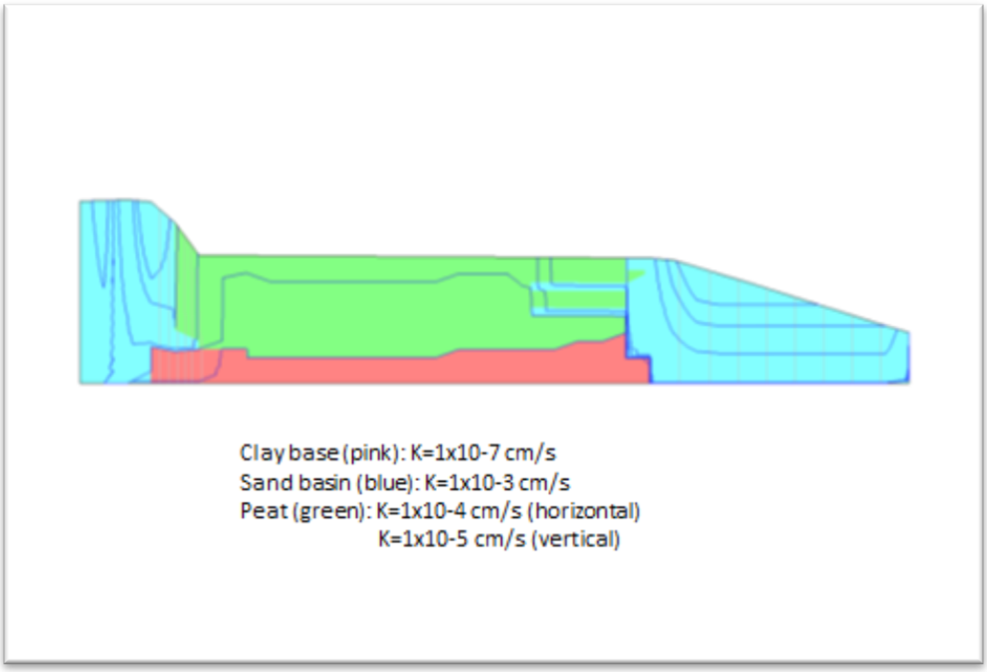
Figure A2.2: Flow pattern generated by USGS Topodrive with a canal deposit in place below the basal Mfabeni Mire clay layer. Note the upward flow indicated at the eastern part of the mire.



4layers with peat WITHOUT canal deposit below eastern part of Mfabeni

Base: K=1x10-7 (pink) cm/s
Middle:K=3x10-4 (yellow)
Top white :K=8.6x10-3
Top green: K=1x10-3
Peat: K=1x10-4

Figure A2.3: Flow pattern generated by USGS Topodrive without a canal deposit in place below the basal Mfabeni Mire clay layer. Note the downward flow indicated at the eastern part of the mire.



Clay base (pink): K=1x10-7 cm/s
Sand basin (blue): K=1x10-3 cm/s
Peat (green): K=1x10-4 cm/s (horizontal)
K=1x10-5 cm/s (vertical)

Figure A4: Flow pattern generated by USGS Topodrive for Mfabeni Mire within an isotropic sand deposit on a basal clay layer setting. The peat is anisotropic with the horizontal K an order of magnitude larger than the vertical K. Note the downward flow indicated at the eastern part of the mire through the interbedded sand layers.

Discussion

The TopoDrive modelled flow confirmed the interpretation that groundwater was migrating from the western dune to Mfabeni Mire, where it discharges at the swamp forest and flows across the fen along the gentle slope to the east (Figure A2.5). Subsurface flow through the peat towards the eastern margin is possible where there are interbedded sand layers with a downward hydraulic gradient. Flow lines turn downward (recharge) at the eastern margin, after which groundwater flows underneath the coastal dune complex towards the ocean. Deeper flow beneath the mire is a possibility depending on the presence or absence of canal deposits below the mire (Figure A2.3).

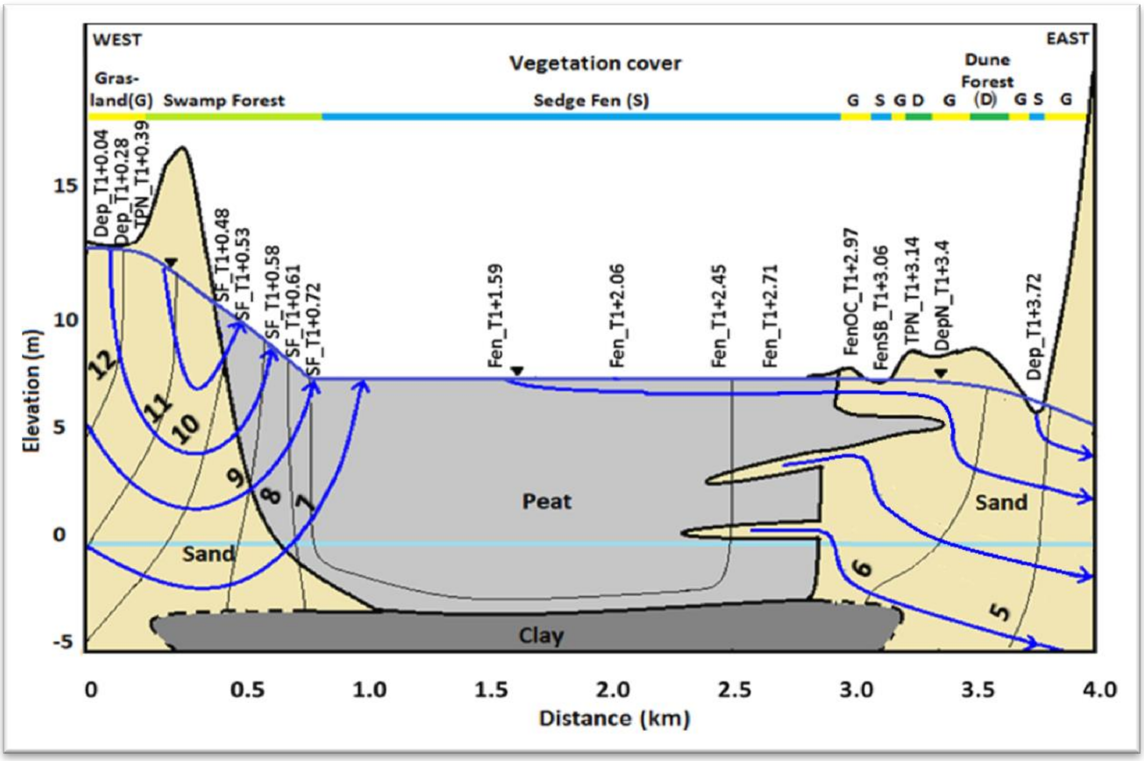


Figure 6.1: A) Measured hydraulic head of the main transect; and B) Flow patterns along the main transect through Mfabeni for the summer, February 2009.

Conclusion

The TopoDrive model results confirmed the flows as shown in the cross-section of the main transect. The differences in localised patterns are due to the inability of the model to accurately define lesser details such as the thin sand layer in the peat or organic layers in the dunes due to the scale of the study area. The hand drawn interpretation is therefore regarded as fair interpretation of the groundwater flow of the main section.

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