Quantification of the water-use dynamics of the dominant plant communities of the Eastern Shores in the iSimangaliso Wetland Park for improved water resource management

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission of South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Colin Everson

Date: November 2015

DECLARATION 1: PLAGIARISM

I, Alistair David Clulow, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles, research reports or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: Alistair Clulow

Date: November 2015

DECLARATION 2: PUBLICATIONS

This thesis is written in manuscript format. Details of my contribution and that of others to each manuscript that form part of this thesis are indicated. Some minor editorial differences may exist between the published papers and the thesis chapters. Some parts are republished in a Water Research Commission report entitled, "Water-use of the dominant natural vegetation types of the Eastern Shores area, Maputaland".

Chapter 2 is published as:
Clulow, A. D., Everson, C. S., Mengistu, M. G., Jarmain, C., Jewitt, G. P. W., Price, J. S., and Grundling, P. L.: Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa, Hydrol. Earth Syst. Sci., 16, 3233-3247, 2012.

The data reported on are based on window period field campaigns as well as long-term monitoring. The window period field campaigns required a team of researchers and technicians to select sites, set up a monitoring infrastructure and maintain the equipment due to the scope of the endeavour and who are co-authors or have been acknowledged in the text. While actively involved in the window period field campaigns, A. D Clulow was solely responsible for maintenance and data collection from the systems that operated over the long-term. The processing, analysis and interpretation of all data were conducted by Alistair Clulow with advice and assistance from C. S. Everson and M. G Mengistu. The manuscript was written in its entirety by A. D. Clulow and all figures and tables were produced by the same. Final editing was provided by the co-authors and anonymous reviewers of the manuscript.

Chapter 3 is published as:
Clulow, A. D., Everson, C. S., Price, J. S., Jewitt, G. P. W., and Scott-Shaw, B. C.: Water-use dynamics of a peat swamp forest and dune forest in Maputaland, South Africa, Hydrol. Earth Syst. Sci., 17, 2053-2067, 2013.

This manuscript is an analysis of tree transpiration within the peat swamp forest and dune forest. A. D. Clulow designed the experiment, selected the sites, wrote the datalogger programs and setup the equipment with assistance from C. Jarmain. A. D Clulow collected and analysed the data and wrote the paper in its entirety, and all figures and tables were produced by the same.

Advice regarding interpretation was provided by C. S Everson. Final editing was provided by the co-authors and anonymous reviewers of the publication.

Chapter 4 was under review when this thesis was submitted for examination. It has subsequently been published with amendments as:
Clulow, A. D., Everson, C. S., Mengistu, M. G., Price, J. S., Nickless, A., and Jewitt, G. P. W.: Extending periodic eddy covariance latent heat fluxes through tree sap-flow measurements to estimate long-term total evaporation in a peat swamp forest, Hydrol. Earth Syst. Sci., 19, 2513-2534, 2015.

Three window period field campaigns to measure above the swamp forest canopy required a team of researchers and technicians due to the scope of the endeavour. The team members contributed to site selection, erection of a telescopic mast with instrumentation and backup power in the swamp forest. The team members assisted with equipment maintenance and are co-authors or have been acknowledged in the text. A. D. Clulow was responsible for processing the data with support from M. G Mengistu. The publication was written by A. D. Clulow and all figures and tables were produced by the same. Advice regarding document layout was provided by C. S. Everson, J. S. Price and G. P. W Jewitt and statistical interpretation was provided by A. Nickless.

Chapter 5 will be submitted for publication to a relevant journal with authors:
Grundling, P. L., Clulow, A. D., and Price, J. S.

This chapter, in which the annual water-balance of the Mfabeni Mire is derived, was conceptualised by P. L. Grundling, but required the evaporation component. A. D. Clulow used the modelling frameworks derived from Chapter 2 (total evaporation of the sedge/reed fen) and Chapter 4 (total evaporation of the swamp forest) to estimate the total evaporation of the Mfabeni Mire. A. D. Clulow compiled the necessary meteorological data and wrote the evaporation section in its entirety. A. D. Clulow contributed to analysis, presentation and interpretation throughout the chapter. Advice on paper structure and content were provided by J. S. Price and C. S. Everson.

Signed: Alistair Clulow

Date: November 2015

EXECUTIVE SUMMARY

The iSimangaliso Wetland Park has UNESCO World Heritage Site status and is therefore of international ecological importance. A diverse mosaic of landscapes and indigenous plant communities co-exist in the Park with the most notable feature being the Lake St. Lucia. The Lake spans 328 km^2, is Africa's largest estuarine system and plays a pivotal role in sustaining plant and animal communities in the Park. However, it falls within an area historically prone to severe droughts and floods and is part of a wider catchment that has undergone, and continues to experience, significant anthropogenic influences. Noteworthy droughts occurred in the 1940s through to 1956 and recently from 2001 to 2011 leading to hypersaline conditions and desiccation to 90% of the Lake by 2006. During this most recent drought it was found that the Eastern Shores area, which lies adjacent to the Lake, provides freshwater through minor tributaries and freshwater seepage zones along its shoreline. This freshwater seepage offers important refugia during hypersaline periods to organisms that would normally not survive the salinity levels and also aids in species recovery following droughts, fulfilling an important role to sustaining the local ecosystem. The Mfabeni Mire is a dominant feature of the Eastern Shores area and one of the oldest peatlands in Africa. Where wetlands and peatlands occur in such areas prone to extended droughts, total evaporation (ET) can exceed precipitation. Sustained groundwater flows are therefore critical to ensure peat accumulation and prevent peat fires with associated carbon releases. However, recent attempts to understand and compute the local water-balance of the Mfabeni Mire revealed that there was insufficient information on the water-use of the indigenous vegetation of the area and ET could not be reliably quantified.

The uniqueness of the Eastern Shores is characterised by the contrasts in vegetation and landscape over a relatively confined area (4 km by 8 km). For example, the swamp forest and dune forest areas are located within close proximity of each other, yet are characterised by different landscape positions in terms of water availability. The coastal dune forest soil profile is generally dry and sandy and the tree roots did not have access to the water table. In contrast the peat swamp forest is located in an inter-dunal wetland where the trees have permanent access to water. Such contrasting environments function differently and have different water requirements and result in different patterns of ET and cannot simply be integrated in terms of water-use.

The purpose of this research was therefore to use the most up-to-date techniques to measure the water-use of the dominant plant communities of the Eastern Shores area (the Mfabeni Mire falls within the Eastern Shores) and to provide a modelling framework for hydrologist, ecologist and/or environmental managers to be able to estimate the ET from the area and derive an accurate water-balance to improve planning and management of the water resources. During the course of this work the contribution of the area to the downstream and adjacent ecosystem was quantified, providing valuable insight into the system's hydrological function and how future anthropogenic and climate change influences should be managed.

The measurements presented in this research provide the first estimates of water-use dynamics and ET of the dominant indigenous plant communities of the iSimangaliso Wetland Park. In water-balance studies, ET is frequently derived as a residual in the mass balance equation. This is one of the few studies in South Africa where all terms of the water-balance equation were based on actual measurements and will be relevant to similar subtropical and coastal environments internationally.

Investigating the four dominant plant communities of the Eastern Shores accounted for approximately 80% of the area. These included peat swamp forest, dune forest, reed/sedge fen and dry grassland. Each plant community provided unique challenges in terms of the most suitable ET measurement approach, due to the different canopy structures and landscape positions. The annual ET for the peat swamp forest, reed/sedge fen and dry grassland were derived, allowing the calculation of ET from the Mfabeni Mire (peat swamp forest and reed/sedge fen). The dune forest areas are commonly found on steep slopes, are species diverse and are interconnected with grassland areas and therefore the water-use dynamics of the dune forest were investigated, but not the overall ET due to fetch limitations.

The surface renewal (SR) method was used to determine the long-term sensible heat flux over the reed/sedge fen (in the Mfabeni Mire) and dry grassland (on the western dunes) with calibration using eddy covariance during two window periods of approximately one week each. The other terms of the shortened energy balance equation (net radiation and soil heat flux) were also measured and the annual ET at a daily interval was derived for these plant communities.

The peat swamp forest and dune forests were challenging environments in which to measure ET. Sapflow systems (heat ratio method) were installed in trees of both forests, which provided information on the water-use dynamics of the trees in terms of their response to atmospheric demand and soil water availability. A dominant species of emergent and understory tree were instrumented in the swamp forest and three dominant species within the dune forest. Both forests are diverse in species and canopy structure and it was not deemed feasible to upscale the sapflow measurements to forest ET; however it was necessary to derive the ET particularly from the swamp forest to be able to quantify the water-balance of the Mfabeni Mire. Eddy covariance measurements are considered the international standard in terms of providing ET estimates over vegetated surface. However, they require frequent maintenance and care, which was not possible over an extended period and in the remote swamp forest of the Mfabeni Mire. Three window periods (between seven and nine days each) of eddy covariance measurement were therefore conducted over the swamp forest in different seasons, two overlapping with the sapflow measurements, in an attempt to understand the ET from the swamp forest. The most suitable models for estimating ET from the swamp forest and sedge/reed fen communities were identified providing hydrologists and ecologist a means to estimate ET using local standard meteorological data.

Volumetric water content was measured at the swamp forest and sedge reed fen as an indicator of the water table level and to confirm adequate water availability to plant roots throughout the study period. In addition, at the drier sites, soil water potential was measured as an indicator of reduced ET as a result of soil water limitations.

The SR method was found to be inexpensive, reliable and with low power requirements for unattended operation over the sedge/reed fen and dry grassland plan communities with calibration periods using eddy covariance. The maximum daily ET from the sedge/reed fen plant community was 6.0 mm day^{-1}, but the average summer (October to March) ET was 3.2 mm day^{-1}. This was attributed to early morning cloud cover that persisted until nearly midday at times and reduced the daily available energy. The ET was therefore lower than expected despite the available water and high average wind speeds. In winter (May to September), there was less cloud but the average ET was only 1.8 mm day^{-1} due to plant senescence. In general ET was also suppressed by the inflow of humid air (low vapour pressure deficit) and the comparatively low leaf area index of the wetland vegetation. Daily ET estimates were compared to the Priestley-Taylor model results and a calibration $\alpha = 1.0$ (R^2=0.96) was obtained for the site. A monthly crop factor (K_c) was determined for the standardised FAO-56 Penman-

Monteith. However, K_c was variable in some months and should be used with caution for daily ET modelling of the sedge/reed fen.

The dry grassland ET was lower than that of the sedge/reed fen with a maximum summer rate of 3.0 mm day^{-1} but averaging only 1.7 mm day^{-1}. In winter the maximum ET was 1.2 mm day^{-1} and averaged only 1.0 mm day^{-1}. Even after rainfall, when soil water was not limited, ET rates were lower than the sedge/reed fen, however soil water was a limitation to ET for extended periods. The accumulated ET from the grassland over the year was 478 mm in comparison to 900 mm from the sedge/reed fen. Seasonal shifts in the energy balance were also noted to be different between the sedge/reed fen and dry grassland communities, explaining the contrasts in seasonal ET.

The challenge of deriving the swamp forest ET from sapflow measurements and three window periods of eddy covariance data was solved by the discovery of a quantifiable relationship between tree sapflow and ET. An empirical model therefore was derived, describing the relationship between the observed ET of the swamp forest, measured during two of the window periods (R^2=0.92 and 0.90), which overlapped with sapflow measurements, thereby providing hourly estimates of predicted ET of the swamp forest for a year, totalling 1125 mm. In building the empirical model, it was found that including the understory tree sapflow provided no benefit to the model performance. In addition, the observed emergent tree sapflow relationship with observed ET between the two field campaigns was consistent and could be represented by a single empirical model (R^2=0.90; RMSE=0.08 mm). The hourly FAO56 Penman-Monteith equation was found to best describe the observed ET from eddy covariance during the three window periods in August 2009 (R^2 = 0.75), November 2009 (R^2 = 0.85) and March 2010 (R^2 = 0.76). From the empirical model of ET and the FAO56 Penman-Monteith equation, a monthly K_c was derived for the swamp forest, providing a method of estimating long-term swamp forest ET from local meteorological data. The monthly crop factor indicated two distinct periods. From February to May, it was between 1.2 and 1.4 compared with June to January, when the crop factor was 0.8 to 1.0. The derived monthly K_c values were verified as accurate (to one significant digit) using historical data measured at the same site, also using eddy covariance from a previous study. It was therefore shown that expensive, high maintenance equipment can be used during manageable window periods in conjunction with low maintenance systems, to derive a model to estimate long-term ET over remote and heterogeneous forests.

The hourly sapflow results over 20 months of measurement indicated critical differences in the water-use dynamics between the swamp forest and dune forest trees. In the swamp forest, the water-use of the emergent *Syzygium cordatum* tree was not strongly seasonal and the daily maximum water-use ranged from approximately 30 L d^{-1} in winter to 45 L d^{-1} in summer whereas the understory *Shirakiopsis elliptica* water-use was more seasonal at 2 L d^{-1} in winter and 12 L d^{-1} in summer. The water-use of the *Syzygium cordatum* was not influenced by seasonal rainfall variations and was actually higher in the drier summer (October 2009 to March 2010) than the wetter summer (October 2010 to March 2011). In contrast, three trees of different heights were monitored in the same way in the dune forest and the water-use found to be highly seasonal. Over the entire measurement period, the water-use was highest for an emergent *Mimusops caffra* (5 to 45 L d^{-1}), whereas the water-use of the *Eugenia natalitia* (2 to 28 L d^{-1}) and *Drypetes natalensis* (1 to 4 L d^{-1}) were lower. At the dune forest, the water-use was highest in the wetter summer due to the reliance of the trees on rainfall. A split-line regression showed that on average, soil water limited tree water-use 64% of the time over the measurement period at the dune forest but when water became available through rainfall events during dry periods (winter), the trees responded rapidly with higher sapflows being recorded until the soil water was depleted. For modeling tree water-use at the dune forest, it was concluded that a two-stage model, taking soil water content into account (from multiple sampling points), is necessary.

The modelling frameworks established for the ET of the swamp forest and reed/sedge fen plant communities enabled the quantification of the annual water-balance of the Mfabeni Mire. Rainfall (1031 mm) and ET (1053 mm) were equally split and dominated the water-balance, which was quantified 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). The seasonal patterns of ET from the two dominant plant communities of the Mfabeni Mire (swamp forest and sedge/reed fen) were noticeably different. This was not surprising considering their significantly different canopy structures.

A compilation of the water-use and ET measurements from the four different plant communities showed the remarkable contrast in water-use dynamics and ET from plant communities within close proximity to each other. Such different plant communities exist due to geohydrological setting. This work shows the importance of acknowledging and understanding the different hydrological roles of these plant communities and how they are interlinked. The critical groundwater recharge into the Mfabeni Mire depends on the low ET rates of the grassland of the western dunes and the water-balance of the Mfabeni Mire, where ET and rainfall are equally balanced and rely on the current distribution of the swamp forest and sedge/reed fen plant communities.

Although the water-balance of Mfabeni Mire is dominated by total 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 persist, lies in its dampening effects of climatic variability. This provides stability for adjacent ecosystems by contributing to steady groundwater conditions. Wetlands, in 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.

The results presented in this thesis show the invaluable contribution that can be gained from field-based measurements. Prior to this study, there was a dearth of information on ET for the dominant plant communities of the Eastern Shores area, which is now provided in this thesis, not simply through modelled estimates but based on actual measurement of the environment concerned and using the most up-to-date techniques available. These results represent not only some of the first long-term measurements of ET from these indigenous plant communities found in Southern Africa, but also one of the few studies of actual ET in a subtropical peatland in the southern hemisphere. The study provides wetland ecologists and hydrologists with guidelines for the use of two internationally applied models for the estimation of wetland ET within a coastal, subtropical environment and showed that wetlands are not necessarily the high water users they are perceived to be. The data captured in this thesis provides a resource of baseline measurements that will be used for future hydrological studies of the area and assist particularly with understanding the consequences of cultivating indigenous areas outside the iSimangaliso Wetland Park and also the importance of restoring them to their natural hydrological function.

A broader implication of this work is that peatlands form where saturated conditions persist and are maintained, they can play an important stabilising role in the hydrology of an area. In southern Africa evaporative demand commonly matches or exceeds rainfall and to maintain a peatland, sustainable groundwater recharge is required from the surrounding catchment. In this thesis it is shown that the water-use of the surrounding plant communities is critical in determining whether groundwater recharge occurs, as plant water-use of different communities varies significantly. With expanding populations and anthropogenic pressures on land and water, in addition to climatic changes, the role of peatlands becomes more essential. However, they too are at risk where unsustainable drainage and cultivation, land-use changes of the surrounding areas or local groundwater abstractions interfere with groundwater inflows and saturation of the peat. The valuable role of peatlands should therefore be carefully considered and protected as a priority for sustainable integrated catchment management.

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The contributions of the WRC project steering committee members as well as the anonymous reviewers of the published papers are thanked for their contributions.

Many thanks to my friends but particularly my parents for their support and assistance in the field, editorial input and child care facilities offered!

To my lovely wife, Suzanne, thank you for your endless support and optimism, always making a plan, enduring the late nights and making me believe this could be achieved. I lack the words to thank you adequately.

To my sons, Noah and Fynn,
who easily create a din.
You are seven and five,
and it's good to be alive.
This one is for you,
as you lads got me through.

In memory of my late father who saw this through to the end. May he rest in peace.

Be still, and know that I am God (Psalm 46:10)

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LIST OF SYMBOLS

Roman symbols:

a	amplitude of air temperature ramps
A	cross-sectional area (m^2)
c	energy balance closure
c_p	specific heat capacity of air (kJ kg^{-1} $^oC^{-1}$)
dh/dl	hydraulic gradient (dimensionless)
e_a	actual vapour pressure (kPa)
e_s	saturated vapour pressure (kPa)
D	energy balance closure discrepancy
ET	total evaporation (mm day^{-1})
ET_c	total evaporation of a crop (mm day^{-1})
ET_{ec}	total evaporation measured using eddy covariance (mm day^{-1})
ET_{EQ}	equilibrium evaporation (mm day^{-1})
ET_p	potential evaporation (mm day^{-1})
ET_{P-T}	total evaporation calculated using the Priestley-Taylor model (mm day^{-1})
ET_r	reference evaporation (mm day^{-1})
ET_{SR}	total evaporation calculated using surface renewal (mm day^{-1})
G	soil heat flux (W m^{-2})
GW_{in}	groundwater seepage influx (mm yr^{-1})
GW_{out}	groundwater seepage outflux (mm yr^{-1})
H	sensible heat flux (W m^{-2})
I_s	solar irradiance (W m^{-2})
K	hydraulic conductivity (m s^{-1})
k	thermal diffusivity (m^2 s^{-1})
K_c	crop factor (fraction)
LAI	leaf area index (m^2 m^{-2})
LE	latent energy (W m^{-2})
$LE_{(P-T)}$	daily latent energy calculated using the Priestley-Taylor model (MJ m^{-2})
L_v	latent heat of vapourisation (2.45 MJ kg^{-1})
MAP	mean annual precipitation (mm)
P	precipitation (mm)
Q	discharge (m^3 s^{-1})

r	stomatal resistance (s m^{-1})
R_n	net radiation (W m^{-2})
R^2	coefficient of determination
RH	relative humidity (%)
s	concentration of a scalar – water vapour in this case (mmol mol^{-1})
S_{in}	diffuse surface inflow and/or open channel inflow (mm yr^{-1})
S_{out}	diffuse surface outflow and/or open channel outflow (mm yr^{-1})
S_y	Specific yield (%)
T_{air}	average air temperature (ºC)
T_{max}	daily maximum temperature (ºC)
T_{min}	daily minimum temperature (ºC)
T_r	tree transpiration (L hr^{-1})
U_2	windspeed at a height of 2 m (m s^{-1})
VPD	vapour pressure deficit (kPa)
V_h	sapflow velocity (cm hr^{-1})
V_{wd}	volume of water drained (mm^3)
V_T	total volume of material (mm^3)
v_1	increase in downstream temperature of sap (ºC)
v_2	increase in upstream temperature of sap (ºC)
w	vertical windspeed (m s^{-1})
x	distance (0.5 cm)
z	measurement height (m)

Greek symbols:

α	Penman aerodynamic term
α	weighting factor for surface renewal and Priestley-Taylor model
β	bowen ratio
Δ	slope of saturated vapour pressure vs. air (kPa $ºC^{-1}$)
Δh	change in watertable elevation (m)
η	error term in the water-balance
θ	volumetric soil water content
θ_{PT}	total profile water content
$\theta_{7.5}$	profile water content at 0.075 m
ρ_a	density of air (kg m^{-2})

ρ_d	density of dry air (kg m^{-2})
γ	psychometric constant (kPa ºC^{-1})
σ	standard deviation
τ	ramping period

LIST OF ABBREVIATIONS

ARC	Agricultural Research Council
ATI	Applied Technologies, Inc.
BLS	Boundary layer scintillometer
DF	Dune forest
DWAF	Department of Water Affairs and Forestry (South Africa)
HPV	Heat pulse velocity
ISCW	Institute for Soil, Climate and Water
EC	Eddy covariance
LT	Local time
MCP	Maputaland Coastal Plain
MS	Meteorological station
PSF	Peat swamp forest
PSO	Peat surface oscillation
RMSE	Root mean square error
SFW	Subtropicial freshwater wetland
SR	Surface renewal
TC	Thermocouple
TDR	Time domain reflectometry
UK	United Kingdom
UNESCO	United Nations Educational, Scientific and Cultural Organisiation
USA	United States of America
WRC	Water Research Commission

CHAPTER 1: INTRODUCTION

1.1 Rationale for the research

1.1.1 Background

Wetlands have been recognised for their high biodiversity value and for the important hydrological function they perform (Mitsch and Gosselink, 2007). In South Africa there are a number of wetlands recognised as being of international importance under the Ramsar convention (Ramsar Convention Secretariat, 2006). After the Ukhahlamba Drakensberg Park, the St Lucia system is the second largest Ramsar site with an area of 1555 km^2. The St Lucia system was also established as South Africa's first World Heritage site in 1999 and is managed by the iSimangaliso Wetland Park Authority. It is the largest estuarine system in Africa and received World Heritage status due to the variety of landforms and critical habitats it provides to wetland, marine and savanna species. Amongst other notable features, it includes one of the last remaining swamp forest areas and oldest peatlands in the world (Grundling et al., 1998). Adjacent to these threatened wetlands, exists a mosaic of seasonally inundated areas, dry grasslands and dune forests.

1.1.2 Anthropogenic influences

In the case of the iSimangaliso Wetland Park, the ecological significance and international acknowledgement of the area does not exclude it from the anthropogenic influences of the past century. These include catchment land-use changes (increased areas under commercial forestry and sugarcane in particular), inlet modifications and water diversions and abstractions. Arguably the most significant influence being the diversion of the Mfolozi River from Lake St. Lucia at the mouth of the estuary in 1952, which is well described by Whitfield and Taylor (2009). Since this alteration, salinity levels of the lake have fluctuated reaching levels threatening the survival of many species to the extent that Cyrus et al. (2011) describe the Lake as being in crisis due to the combined effects of mouth closure, low water levels and hypersalinity. These fluctuations have been amplified by prolonged droughts and extreme floods (Mucina and Rutherford, 2006; Taylor et al., 2006; Chrystal, 2013). The most recent drought in the area has been severe, lasting from 2002 to 2009 (Whitfield and Taylor, 2009), and resulted in widespread desiccation of the Lake, particularly in 2006 (Chrystal, 2013). Clearly the hydrological function of the area warrants further investigation.

With duration and the severity of droughts, there has been a gradual shift in the priority of research areas over the past 50 years from mainly species-specific investigations (of which there are many) to those dealing with salinity (Taylor, 1993), the importance of groundwater (Kelbe and Rawlins, 1992) and the freshwater inflows and groundwater recharge (Taylor at al., 2006; Vrdoljak and Hart, 2007). Currently, the most recent research coming from the area has focussed almost exclusively on the deleterious influence of the high salinity levels on certain species (Jerling at al., 2010, Vivier et al., 2010) but even more so on physically reshaping the flow dynamics of the estuary mouth through engineering solutions with most authors concluding that some form of reconnection between the Mfolozi River and Lake St. Lucia would be the most viable solution (Cyrus et al., 2011 ; Whitfield and Taylor, 2009; Cyrus et al., 2011; Lawrie and Stretch, 2011; Chrystal, 2013; Whitfield et al., 2013). It is evident that these engineering interventions are highly necessary but complex. For example, anthropogenic changes have occurred and continue to occur in the Mfolozi catchment and the quality and quantity of the flows may not be as expected. In addition, the uncertainties of climate change remain a formidable threat to the system (Vaeret et al., 2009).

1.1.3 Motivation

Since the separation of the Mfolozi River from the mouth of the estuary, the majority of the freshwater to the Lake has been supplied by several rivers to the west including the Mkuze, Mzinene, Hluhluwe and Nyalazi (see Figure 2.2 for further clarification). However, during drought periods these rivers provide limited flow and freshwater seepage from the Mfabeni Mire in the Eastern Shores area into the Nkazana and Tewate Rivers and other seepage zones along the shoreline become the most important contribution to the lake (Taylor et al., 2006; Vrdoljak and Hart, 2007). This groundwater seepage from the Eastern Shores area has significant ecological importance and provides refugia where localised freshwater inflows enable many species to survive during periods of high salinity, preventing extinction and loss of biodiversity. However, the availability of seepage water depends largely on the magnitude of water loss by evaporation from the adjacent wetland system and surrounding areas. These wetlands have a high water availability, creating the potential for high evaporative losses. However, total evaporation (ET*)* estimates from wetlands have frequently relied on indirect

methods based on estimates of potential evaporation and its calculation as a residual in the water-balance (LaBaugh, 1986).
Where past studies have addressed the hydrology of Maputaland (Taylor et al., 2006; Vaeret et al., 2009; Kelbe and Germishuyse, 2010; Chrystal 2013) and ET estimates have been required for modelling or water-balance studies, the best information has been obtained from the Water Resources of South Africa study by Midgley et al. (1994) or from the published maps of the region by Schulze et al. (1997). However, this information is based on regional estimates of potential evaporation which is inadequate for detailed studies addressing water-balance, land management, environmental reserve and climate change studies. To further confound the current situation, meteorologically based models can be highly variable with large degrees of error and have utility only for certain vegetation types or during certain periods of the year (Drexler et al*.,* 2004). For instance, in the hydraulic modelling of the Nylsvlei floodplain, the discrepancy between the traditional ET models compared to energy balance and Class A-pan evaporation techniques were up to 4 mm day^{-1} in winter and 6 mm day^{-1} in summer (Birkhead et al, 2007). Drexler et al. (2004) leads one to conclude that, due to the variability and complexity of wetlands, there is no single method (technique or model) that is best for estimating wetland ET. This leaves wetland ecologists and hydrologists with some uncertainty regarding the most appropriate methods for estimating wetland ET in water-balance studies or environmental water requirement assessments.

The specific need to determine ET from the Eastern Shores area arose during the course of WRC funded project K5/1857 by Grundling et al. (2013) titled “The capability of the Mfabeni Mire to respond to climatic and land-use stresses, and its role in sustaining discharge to downstream and adjacent ecosystems”. An accurate water-balance study was required but was impossible without reliable estimates of ET. In addition, it became apparent that the Mfabeni Mire is a groundwater dependent ecosystem, with groundwater supplied from the surrounding dunes, however there was no information on the water-use dynamics of these surrounding plant communities.

It remains clear, that in addition to the current engineering solutions proposed to bring additional freshwater into the Lake from the Mfolozi River, ecophysiological and hydrological studies such as those reported in this thesis are necessary and should continue to focus on such aspects as plant water-use and the ET of the Eastern Shores area, which has been identified as a critical freshwater seepage zone.

1.1.4 The research approach

The solution was to apply the most appropriate and up-to-date methods to determine the long-term ET for the dominant plant communities of this key strategic wetland and surrounding areas and to use these results to verify existing meteorologically based models to assist in determining the annual water-balance of the Mfabeni Mire. These results of ET over pristine areas is expected to serve as an invaluable benchmark or baseline for future studies of degraded areas beyond the boundaries of the iSimangaliso Wetland Park.

1.2 Research question

Do existing meteorological measurement and modelling techniques sufficiently capture the complex nature of vegetated surfaces and hydrological conditions found in plant communities of the Maputaland Coastal Plain and can modern measurement techniques improve our long-term estimates of ET to determine the water-balance of the Mfabeni Mire for improved water resource management?

1.3 Aims and objectives

The overall aim of the research described in this thesis was to provide new knowledge and advance our understanding of the plant water-use dynamics and ET over the indigenous plant communities of the St. Lucia Eastern Shores area and also to empower decision-makers in terms of the future hydrological function of the Eastern Shores area and ultimately the greater Maputaland Coastal Plain.

The objectives of the research were to:

a) Quantify the ET losses from the swamp forest and sedge/reed fen plant communities of the Mfabeni Mire.
b) Differentiate the ET losses of the Mfabeni Mire from those of their contributing catchment.
c) Improve our understanding of the dominant processes controlling ET in the Mfabeni Mire.
d) Assess and validate the most suitable meteorological models to estimate ET for the plant communities of the Mfabeni Mire.

e) Determine the seasonal trends in ET losses from the Mfabeni Mire and their proportional loss from the wetland water-balance.

The tasks undertaken to achieve these objectives were to:

a. Identify the dominant plant communities of the Eastern Shores area.
b. Apply suitable measurement techniques, while considering their limitations, together with the topography and vegetation structure, which could be used to measure the ET losses from these plant communities, and where necessary, the soil water content or water potential.
c. Perform calibrations of the surface renewal system against eddy covariance during manageable window periods.
d. Install sapflow/transpiration measurement systems at the forested sites.
e. Collect meteorological data and apply suitable atmospheric models to estimate long-term ET.
f. Compare measured ET to modelled ET and analyse their appropriate use over the different vegetation types.
g. Compute the annual water-balance for the Mfabeni Mire using the ET models and their derived parameters.

1.4 Outline of thesis structure

Following the "acceptable formats for a thesis" as outlined by the University of KwaZulu-Natal (UKZN), this thesis is structured, "as a set of papers which are published, in press, submitted, or intended for submission". Chapters 2 to 5 are written for publication, including relevant literature, materials and methods, results, discussion, and conclusions and are briefly outlined below.

The thesis structure "as a set of papers" inevitably includes some overlap between chapters, primarily in the description of the study area, which they have in common, and the description of the meteorological models used to estimate total evaporation. The focus of each chapter however, differs significantly either in terms of canopy structure addressed, plant community or measurement strategy employed and therefore the aims and outcomes. In combination they contribute towards an improved understanding of appropriate measurement and modelling techniques (and implementation) to determine the water-use of the Eastern Shores area. As recommended by the UKZN "acceptable formats for a thesis", the references have been included at the end of each Chapter in a style that conforms to the journal in which that paper was published, to which it has been submitted, or will be submitted.

The approach taken in structuring the chapters of this thesis was to compare plant communities with similar vegetation heights but in contrasting landscape positions. The sedge/reed fen and dry grassland were compared as well as the swamp forest and dune forest. This strategy clearly emphasised the significant differences in the ET and plant water-use dynamics of the different plant communities.

Some changes in naming conventions between chapters have been retained to stay true to the published papers. These often came about through the need to emphasise certain features. The swamp forest for example, is referred to as the Nkazana Peat Swamp Forest to emphasise the peat in Chapters 3 and 4. The sedge/reed fen was not a key component of Chapter 4 and was generally referred to as a subtropical freshwater wetland according to the Mucina and Rutherford (2006) vegetation map of South Africa. However, in Chapter 2 it is simply referred to as the Mfabeni Mire. The dry grasslands of the western dunes were also referred to as the Embomveni Dunes. The naming convention within each chapter is clearly defined in the study site description.

Chapter 2 focuses on the measurement of total evaporation over the course of a year using the surface renewal and eddy covariance techniques over the short vegetation (< 1.2 m) types of the Eastern Shores. It provides an understanding of the evaporation dynamics of the sedge/reed fen portion of the Mfabeni Mire which are highlighted through comparison with a nearby dry grassland on the Embomveni Dunes. The surface renewal technique was evaluated for long-term use over a wetland with calibration. The long-term measurements of total evaporation were used to identify the most suitable model for estimating long-term total evaporation over the sedge/reed fen plant community.

Chapter 3 provides insight into the differences in water-use dynamics between the indigenous forests of the Eastern Shores over a period of 20 months through the measurement of transpiration using a sapflow technique. The peat swamp forest and the dune forest plant communities are located in significantly different topographic positions in the landscape, with the water-logged swamp forest and elevated dune forests responding differently to seasonal climatic changes and experiencing different limits to transpiration.

Chapter 4 is devoted to deriving the long-term total evaporation from the swamp forest and providing a modelling framework to estimate total evaporation of the forest from meteorological data. It addresses the problems associated with measurement of total evaporation in remote sites and provides a strategy towards deriving total evaporation using a combination of measurement techniques. Some were operated during intensive window periods while others, which require less maintenance, over extended periods.

In Chapter 5, all components required to derive the annual water-balance of the Mfabeni Mire were quantified. These components were measured using standard techniques without too much difficulty, except for total evaporation. From the modelling frameworks established in chapters 2 and 4, the total evaporation from the swamp forest and sedge/reed fen were modelled and water-balance closure assessed. This chapter demonstrates an applied application using the new contributions acquired in chapters 2 to 4 and indicates the hydrological role of the Mfabeni Mire and potential threats to its function.

The final chapter, Chapter 6, integrates the work and emphasises the elements that emerge. The implications of the results are interpreted and gaps and future research possibilities are identified.

The structure of the chapters is shown against the cross-sectional profile (Fig. 1.1), which runs through the study site in a WNW-ESE direction (see Fig. 3.1 for details of the transect location). It was derived from a 50 x 50 m digital elevation model (Armstrong et al., 2002) and created by using the Spatial Analyst 2.0 and Profile Extractor 6.0 extensions in ESRI ArcView 3.2. It shows the focus areas and location of the comparative plant communities studied in each chapter, but most importantly how they combine to achieve the overall research aim. The Fig. 1.1 also shows that the Mfabeni Mire contains the swamp forest (also known as the Nkazana Peat Swamp Forest) and sedge/reed fen plant communities. The Embomveni dunes to the west are dominated by dry grassland and the coastal dunes to the east by dune forest vegetation. These regions combine to form an area known as the Eastern Shores of the iSimangaliso Wetland Park.

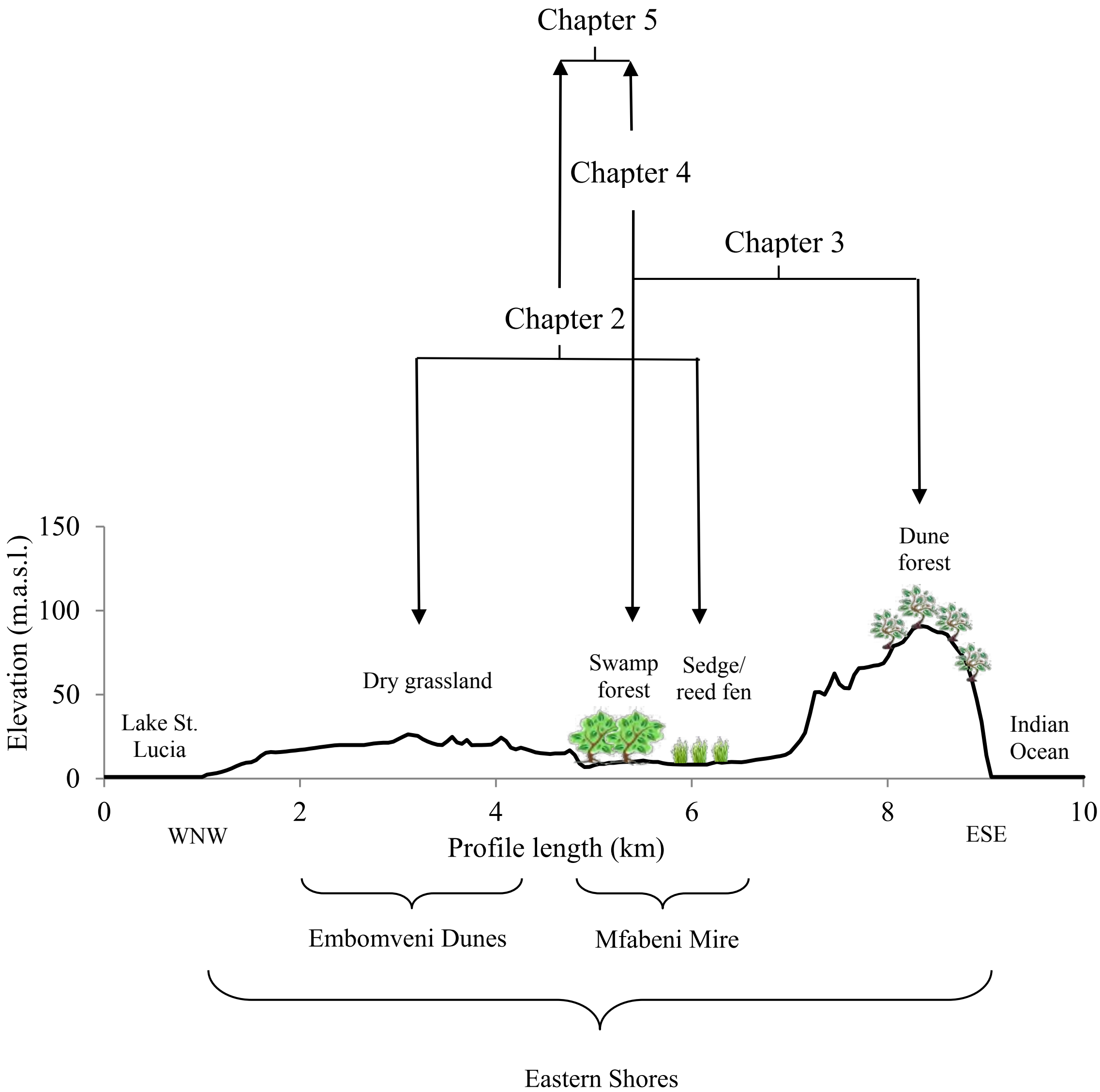

Figure 1.1 Structure of Chapters 2 to 5 showing the areas of focus and approach used to achieve the overall objectives of the research

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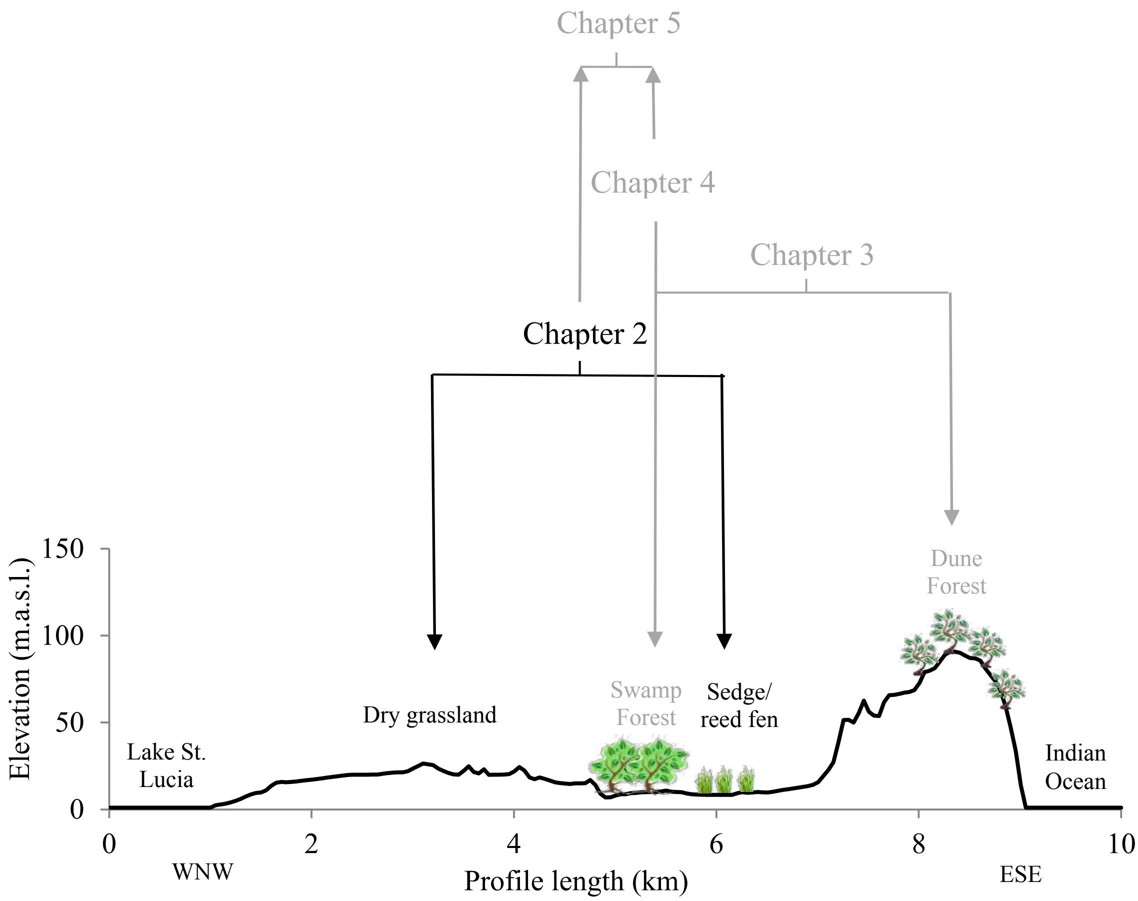
Lead into Chapter 2

The sedge/reed fen is the dominant plant community of the Mfabeni Mire while the dry grassland exists on elevated sand dunes where groundwater recharge of the Mfabeni Mire accumulates. Chapter 2 provides an annual cycle of ET for these two plant communities, which are both relatively short canopies (<1.2 m), but, despite their close proximity to each other, dissimilar in terms of plant available water. This was clearly observed in the differences found in the seasonal pattern of ET between the sites and the applicability of meteorological models to estimate ET over the two plant communities. Differences in the energy balance between the sites were noted. Figure 1.1 has been reproduced below but modified to show the plant communities investigated in Chapter 2.



CHAPTER 2: MEASUREMENT AND MODELLING OF EVAPORATION FROM A COASTAL WETLAND IN MAPUTALAND, SOUTH AFRICA

2.1 Abstract

The surface renewal (SR) method was used to determine the long-term (12 months) total evaporation (ET) from the Mfabeni Mire with calibration using eddy covariance during two window periods of approximately one week each. The SR method was found to be inexpensive, reliable and with low power requirements for unattended operation.

Despite maximum ET rates of up to 6.0 mm day^{-1}, the average summer (October to March) ET was lower (3.2 mm day^{-1}) due to early morning cloud cover that persisted until nearly midday at times. This reduced the daily available energy and the ET was lower than expected despite the available water and high average wind speeds. In winter (May to September), there was less cloud but the average ET was only 1.8 mm day^{-1} due to plant senescence. In general ET was suppressed by the inflow of humid air (low vapour pressure deficit) and the comparatively low leaf area index of the wetland vegetation. The accumulated ET over 12 months was 900 mm. Daily ET estimates were compared to the Priestley-Taylor model results and a calibration α = 1.0 (R^2=0.96) was obtained for the site. A monthly crop factor (K_c) was determined for the standardised FAO-56 Penman-Monteith. However, K_c was variable in some months and should be used with caution for daily ET modelling.

These results represent not only some of the first long-term measurements of ET from a wetland in Southern Africa, but also one of the few studies of actual ET in a subtropical peatland in the southern hemisphere. The study provides wetland ecologists and hydrologists with guidelines for the use of two internationally applied models for the estimation of wetland ET within a coastal, subtropical environment and shows that wetlands are not necessarily high water users.

Keywords: *fen, peat, surface renewal, eddy covariance, Priestley-Taylor, FAO-56 Penman-Monteith.*

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Reference style according to the journal Hydrology and Earth System Sciences

2.2 Introduction

The Maputaland coastal plain (MCP) is an ecologically important area on the east coast of South Africa prone to prolonged droughts and floods (Mucina and Rutherford, 2006; Taylor et al., 2006b). It is essential in such areas to accurately determine the water-balance for the effective management of the water resource. The MCP has extensive wetland areas, from which, total evaporation (ET) is likely to be the dominant loss from the system (Drexler et al., 2004). Where ET estimates have been required for studies in the past, the best information has been obtained from the Water Resources of South Africa 1990 study by Midgley et al. (1994) or the published maps of the region by Schulze et al. (1997). However, this information was based on regional estimates of potential evaporation and is inadequate for detailed, long-term studies, addressing water-balance, land management, environmental reserve and climate change studies.

Internationally, Souch et al. (1996) concluded that our understanding of ET and the related physical processes are not well characterized for many wetland types. Drexler et al. (2004) state that despite the numerous methods available to quantify wetland ET, it remains insufficiently characterized due to the diversity and complexity of wetland types and that no single model or measurement technique can be universally applied. Goulden et al. (2007) note the high variation in ET between wetlands and that different measurement techniques are likely to produce widely divergent measures of ET. This leaves wetland ecologists and hydrologists with some uncertainty regarding the most appropriate methods for measuring and modeling wetland ET.

Despite the lack of a definitive conclusion above, the eddy covariance technique has probably been recognised as the most accepted method for measuring wetland ET (Souch et al., 1996; Acreman et al., 2003; Goulden et al., 2007). Recent advances have further improved the reliability of eddy covariance systems, yet there are still restrictions to their long-term deployment. The MCP study site, for example, is remote, surrounded by African wildlife, and with a high risk of theft from surrounding rural communities. An expensive eddy covariance system, requiring frequent maintenance due to high power requirements, is therefore, not practical in the long-term. Damage by wildlife or runaway fires, and theft of batteries (or solar panels) has financial implications but is particularly costly in terms of lost data; preventing an assessment of inter-seasonal variability. To obtain long-term estimates of ET in South Africa, the current *modus operandi* has become to adopt short-term (one week) deployment of eddy covariance, in two or three different seasons over a year, to gain representative measurements of a site such as in Everson et al. (2009) and Jarmain et al. (2009). The difficulty becomes infilling these window periods and the question of how representative a window period is of a seasons ET. Drexler et al., (2004) however, found the more recently developed surface renewal (SR) to hold promise as a suitable technique for the measurement of wetland ET. In addition, the SR technique is much cheaper than an eddy covariance system, has a low power requirement, is easily maintained and can typically include multiple measurements from one system if there is a likelihood of damage (Mengistu and Savage, 2010). It therefore holds potential at sites such as the MCP, for long-term deployment to compliment the short-term, window period measurements, using eddy covariance.

Meteorological models that calculate estimates of ET such as the Penman-Monteith model have gained popularity due to their relatively low data requirements and have been incorporated into numerous hydrological and crop-growth models such as CANEGRO (Inman-Bamber, 1991), ACRU (Schulze, 1995), SWB (Annandale et al., 2003) and SAPWAT (van Heerden et al., 2009) amongst others. These formulations are most suitable for uniform agricultural crops and have not been tested for many natural vegetation types and in particular wetlands with heterogeneous vegetation including sedges and reeds often growing in saturated or flooded conditions. For instance, the way some ET models have been applied (e.g. Penman-Monteith) has resulted in some doubt in the use of published vegetation specific parameters such as the crop factor (Drexler, et al., 2004). Much of this doubt has been removed since the standardization of the Penman-Monteith formulation by the Food and Agriculture Organization (Allen et al., 1998). Despite the value in meteorological models in estimating ET, it has long been accepted that they require vegetation or location specific parameters that change seasonally (Monteith, 1981; Ingram, 1983; Mao et al., 2002).

There was therefore a need to apply the most appropriate and up-to-date methods to determine the long-term ET for key strategic wetlands and to use these results to verify existing meteorologically based models. This will not only reduce uncertainty, but will also provide some guidance in terms of wetland ET rates and thus, lead to a better understanding of the processes that define the partitioning of the surface energy balance in wetlands. In this study SR was therefore applied over a period of one year (September 2009-August 2010) to determine the ET from the Mfabeni Mire in the iSimangaliso Wetland Park. These results were compared to ET estimates from two well-known meteorological models, namely, the Priestley-Taylor and FAO-56 Penman-Monteith models to provide wetland ecologists and hydrologists with an indication of their suitability to ET estimation in subtropical coastal wetlands of the MCP. This work represents one of the few ET studies in a subtropical peatland of the southern hemisphere. It therefore provides critical new insights into the process of ET, which may differ, from the commonly studied northern hemisphere boreal and arctic tundra peatlands.

2.3 Study sites

The study area is located in the Eastern Shores section of the iSimangaliso Wetland Park, which was declared South Africa's first UNESCO World Heritage Site in 1999. The study area lies adjacent to Lake St Lucia and within the St Lucia Ramsar Site designated in 1986. The iSimangaliso Wetland Park is a premier tourist destination contributing to the economy of the surrounding communities and the town of St Lucia (Fig. 2.1).

The health and future conservation of Lake St. Lucia is strongly dependent on the water level and salinity of the water within the Lake, which is controlled in part by freshwater inflows (Whitfield and Taylor, 2009). The groundwater contribution to the water-balance of Lake St Lucia is negligible except in extreme prolonged drought periods when the main rivers to the west (Mkuze, Mzinene, Hluhluwe and Nyalazi) can cease to flow and groundwater and direct rainfall are the only source of freshwater for the lake (Taylor et al., 2006a). Freshwater seepage from the groundwater mound of the Embomveni ridge on the Eastern Shores area into the Nkazana and Tewate Rivers and other seepage zones along the shoreline therefore become the most important contribution to the lake (Bjørkenes et al., 2006; Taylor et al., 2006b). This groundwater seepage from the Eastern Shores area has significant ecological importance as it provides refuge sites where localised freshwater inflows enable many species to survive during periods of high salinity, reducing the risk of extinction and loss of biodiversity (Vrdoljak and Hart, 2007).

The Eastern Shores is bordered by the Indian Ocean to the east and Lake St Lucia to the west (Fig. 2.1). High coastal dunes form a barrier to the east, and to the west the slightly lower, undulating Embomveni Dunes flank Lake St Lucia. Between these dunes lies an interdunal drainage line that forms the Mfabeni Mire. The Mire is drained by the Nkazana Stream, which flows along the eastern border of the Swamp Forest, feeding Lake St. Lucia and is a critical freshwater source during severe drought periods (Vrdoljak and Hart, 2007). Peat has accumulated in the Mfabeni Mire over the past 45 000 years, forming one of the largest peatlands in South Africa and one of the oldest active peatlands in the world (Grundling et al., 1998). The Mire is 8 km long in a north-south direction and 3 km at its widest point. It has an overall extent of 1047 ha providing more than adequate fetch for the micrometeorological techniques used.

Detailed vegetation studies were completed in and around the Mfabeni Mire by Lubke et al. (1992), Sokolic (2006) and Vaeret and Sokolic (2008). The dominant species in the immediate vicinity of the Mfabeni Mire study site (28º9.007'S, 32º31.492'E) were the sedges *Rhynchospora holoschoenoide* and *Fimbristylis bivalvis*, and the grasses *Panicum glandulopaniculatum* and *Ischaemum fasciculatum.* The vegetation in the vicinity of the site had an average height of 0.8 m. The canopy cover was full, homogenous and with no areas of fully exposed peat or water. The leaf area index (LAI) was between ~1.7 in winter and ~2.8 in summer. The plant roots had permanent access to the water table at this site.

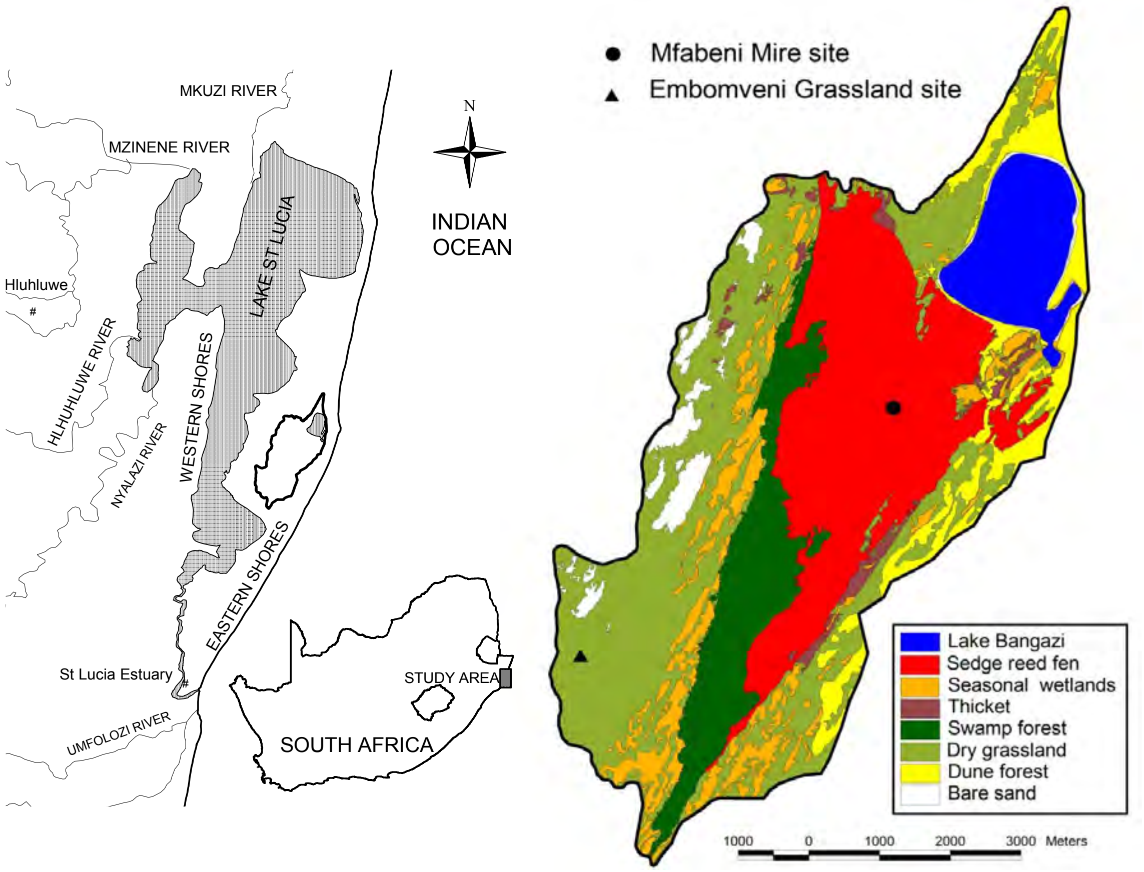

Figure 2.1 The location of the Mfabeni Mire and Embomveni Dune sites on the Maputaland coastal plain. The Mfabeni Mire is represented by the sedge reed fen vegetation unit

The Mfabeni Mire is a subtropical freshwater fen surrounded by Maputaland Coastal Belt vegetation, which is a mixed, seasonal grassland community (Mucina and Rutherford, 2006). Therefore, for purposes of comparison, ET was also measured over a terrestrial grassland on the western Embomveni Dunes (28º11.549'S, 32º28.807'E), over the same period as the Mfabeni Mire, using the same techniques. The Embomveni Dune site was 6 km from the measurement station in the Mfabeni Mire and therefore experienced similar climatic conditions but represented a significantly different landscape position. The dunes have an elevation of approximately 30 m above mean sea level. The grass roots were confined to the upper 1 m of the sandy soil profile and were not in contact with the watertable. During the summer growing season the grassland vegetation was therefore dependent on soil water stores and rainfall. The vegetation was mixed but the dominant plants were the grasses *Trachypogon spicatus, Imperata cylindrica*, the herb *Helichrysum kraussii*, the sedge *Cyperus obtusiflorus*, the succulent *Crassula alba*, and the shrub *Parinari capensis.* The average vegetation height was typically 0.4 m and the LAI between ~0.85 in winter and ~1.2 in summer.

The iSimangaliso Wetland Park is situated in the Indian Ocean Coastal Belt Biome (Mucina and Rutherford, 2006). It has a subtropical climate and lies in a summer rainfall area. There is a steep rainfall gradient from east to west and at the coastline, the mean annual precipitation exceeds 1200 mm yr^{-1} but only 900 mm yr^{-1} at Fanies Island, just 10 km to the west. Taylor et al, (2006b) indicated that the temporal variability of the rainfall gives rise to severe wet and dry periods in Maputaland and during this study there was a well reported drought in the region.

2.4 Materials and methods

The shortened energy balance equation is used in evaporation studies to describe energy partitioning at the earth's surface (Eq. 1). The "shortened" version ignores the energy associated with photosynthesis, respiration and energy stored in plant canopies, which are small when compared with the other terms (Thom, 1975). The net irradiance (R_n) equates to the sum of the sensible heat flux (H), the ground heat flux (G) and the latent energy flux (LE):

$$R_n = LE + H + G \tag{2.1}$$

where, all components except LE are measured, the energy balance equation may be used to determine LE as the residual term in Eq. 2.1, which is then converted into ET (Savage et al., 2004)

Net irradiance and ground heat flux were measured at both the Mfabeni Mire and Embomveni Dune sites from October 2009 to September 2010. A net radiometer (NRLite, Kipp and Zonen, Delft, The Netherlands) was used to measure R_n at 2.0 m above the canopy and G was measured using two soil heat flux plates (HFT-3, REBS, Seattle, WA, USA). The plates were placed at a depth of 80 mm below the soil surface. A system of parallel thermocouples at depths of 20 and 60 mm were used for measuring the soil heat stored above the soil heat flux plates and volumetric soil water content (CS615, Campbell Scientific Inc., Logan, Utah, USA) was measured in the upper 60 mm. At the Mfabeni Mire, the groundwater level at its highest was 0.1 m below the surface and therefore, the total *G* was determined using the methodology described by Tanner (1960) at both sites. The measurements were sampled every 10 s with a CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) and 30-minute averages were computed.

Over the corresponding time period, H was calculated using the SR technique at both the Mfabeni Mire and Embomveni Dunes. Air temperature was measured using two unshielded type-E (chromel/constantan) fine-wire thermocouples (76 µm diameter) placed at heights of 1.00 m and 1.40 m above the ground surface. Data were recorded with a datalogger (CR3000, Campbell Scientific Inc., Logan, Utah, USA) powered by two 100 Ah batteries and two 20 W solar panels. Data was recorded onto a 2 GB compact flash card with the capacity to store up to six weeks of high frequency (10 Hz) data. The SR technique is based on the principle that an air parcel near the surface is renewed by an air parcel from above (Paw U et al., 1995). This process involves ramp like structures (rapid increase and decrease of a scalar, such as air temperature in this study), which are the result of turbulent coherent structures that are known to exhibit ejections and sweeps under shear conditions (Gao et al., 1989; Raupach et al., 1996; Paw U et al., 1992). The theory of heat exchange between a surface and the atmosphere using the SR method is described in detail by Paw U et al. (1995), Snyder et al., (1996), Paw U et al. (2005) and Mengistu and Savage (2010). The exchange of sensible heat energy between a surface and the atmosphere is expressed as:

$$H = \alpha \rho_a c_p z \frac{a}{\tau} \tag{2.2}$$

where, α is a weighting factor, ρ_a is the density of air, c_p is the specific heat capacity of air, z is the measurement height, a is the amplitude of the air temperature ramps and τ is the total ramping period.

The amplitude and the ramping period were deduced using analytical solutions of Van Atta (1977) for air temperature structure function ($S^n(r)$). This is calculated for each averaging period (2 min) from high frequency (10 Hz) air-temperature measurements using:

$$S^n(r) = \frac{1}{\tau - j}\sum_{i=1+j}^{m}(T_i - T_{i-j})^n \quad (2.3)$$

where, n is the power of the function, m is the number of data points in the time interval measured at frequency f (Hz), and j is the sample lag between data points corresponding to a time lag, T_i is the ith temperature sample. The Van Atta (1977) method then involves estimating, for each time lag, in this case 0.4 and 0.8 s (Mengistu and Savage, 2010), the mean value for amplitude a during the time interval, by solving the following equation for the second, third and fifth order roots:

$$a^3 + pa + q = 0 \quad (2.4)$$

where:

$$p = 10S^r(r) - \frac{S^5(r)}{S^3(r)} \quad (2.5)$$

and

$$q = 10S^3(r) \quad (2.6)$$

The ramp period τ is then finally calculated using:

$$\tau = -\frac{a^3 r}{S^3(r)} \quad (2.7)$$

The 2 min H was calculated using Quick Basic 4.0 software, under MS-DOS and the data then averaged to 30 min. The weighting factor α is required to determine the final H using the surface renewal technique (Eq. 2.2). It depends on the measurement height, canopy architecture (due to changes in heat exchange between the plant canopy and air parcels) and thermocouple size (due to changes in sensor response time). Once determined by calibration, it is fairly stable and does not change regardless of weather conditions unless the surface roughness changes (Snyder et al., 1996; Spano et al., 2000; Paw U et al., 2005). An extended Campbell Scientific Open

Path Eddy Covariance system (Campbell Scientific Inc., Logan, Utah, USA) was therefore deployed at the Mfabeni Mire to determine the weighting factor α during two window periods of measurement in November 2009 and March 2010. An "Sx" style ATI, Inc. sonic anemometer (Longmont, Colorado, USA) was used at the Embomveni Dune site during the same window periods. The sensors were mounted on 3 m lattice towers at a height of 2.5 to 3.0 m above the ground level or 2.0 to 2.5 m above the vegetation cover. They were orientated into the direction of the prevailing wind to minimize flow distortion effects. At both sites, water vapour corrections as proposed by Webb et al. (1980) and coordinate rotation following Kaimal and Finnigan (1994) and Tanner and Thurtell (1969) were performed using EdiRe software (R. Clement, University of Edinburgh, UK) to determine the eddy covariance derived H. The weighting factor α (Eq. 2.1) was finally obtained from the slope of the least-squares regression (forced through the origin) of the eddy covariance H versus the uncalibrated surface renewal H (Paw u et al., 1995). At the Mfabeni Mire and Embomveni Dunes, an α of 0.8 and 1.0 respectively were determined (at a measurement height of 1.0 m above ground surface).

Finally, LE was determined every 30 min as a residual in Eq. 2.1. The product of LE and specific heat capacity of water (Savage et al., 2004) provided the final estimate of total evaporation where H was derived by surface renewal (ET_{SR}). During stable night-time conditions, the analysis failed to resolve the ramp characteristic and while $R_n < 0$, ET_{SR} was reduced to zero (Monteith, 1957; Baldocchi, 1994). Daily ET_{SR} was then used to verify the Priestley-Taylor and FAO-56 Penman-Monteith models described in the results section and simple linear regression was used to assess whether ET could be accurately predicted from these models. Polynomial regression quantiles (95th quantile) were fitted in GenStat (VSN International, 2011) to determine the general seasonal course of the modelled results in the Mfabeni Mire and Embomveni Dunes. Regression quantiles are useful for describing the upper 'edge' of a cloud of heterogeneous data to identify the pattern of constraint imposed by the independent on the dependent variable (Cade et al. 1999). Net irradiance was used in the derivation of measured and modelled results and therefore auto self-correlation was minimized by using independently collocated measurements.

An automatic weather station providing supporting climatic data in the Mfabeni Mire measured rainfall, air temperature and relative humidity, solar irradiance, wind speed and direction. Solar irradiance was measured using an LI-200X pyranometer (LI-COR, Lincoln, Nebraska, USA). Wind speed and direction were measured using a wind sentry (Model 03002, R.M. Young, Traverse city, Michigan, USA). The raingauge (TE525, Texas Electronics Inc., Dallas, Texas, USA) was mounted at 1.2 m and the remaining sensors 2 m above the ground. Vapour pressure deficit (VPD) was calculated from the air temperature and relative humidity sensor (HMP45C, Vaisala Inc., Helsinki, Finland) according to Savage et al. (1997). The climatic data were averaged over 30-minute intervals from observations made every 10 s and stored on a data logger (CR3000, Campbell Scientific Inc., Logan, Utah, USA).

To understand potential constraints to ET, volumetric soil water content was determined using CS615 time domain reflectometers (Campbell Scientific Inc., Logan, Utah, USA) at the Mfabeni Mire (0.100 m, 0.200 m, 0.400 m) and at the Embomveni Dunes (0.025 m, 0.075 m, 0.125 m, 0.250 m, 0.500 m, 1.000 m). At the Dune site, soil water potential was measured using Watermark 200 sensors (Irrometer Company, Riverside, California, USA) at the same depths. Soil water data was measured hourly and stored on a data logger (CR10X, Campbell Scientific Inc., Logan, Utah, USA).

LAI is the surface area on one side of the leaf material (m2) per unit area of ground (m2). It is a biophysical property closely linked to plant ET (Allen et al., 1998). The average LAI of the vegetation at the Mfabeni Mire and Embomveni Dunes was measured at monthly intervals across each site using an LAI-2000 (LI-COR Inc., Lincoln, Nebraska, USA).

2.5 Results

2.5.1 Weather conditions during the study period

Over the study period most of the rainfall occurred during the summer months from October through to March, although there was some rainfall experienced in winter (May to August) associated with frontal conditions (Fig. 2.2). At the research site in the Mfabeni Mire the precipitation over the 12-month measurement period was 650 mm (Fig. 2.2). This was significantly below the annual average (1200 mm) but in agreement with the well-reported drought in the region. The groundwater level at the beginning (October 2009) of the study period at Mfabeni was 0.1 m below the surface and by the end of August 2010 was 0.3 m below the surface, confirming the prevailing drought conditions. In normal rainfall years, Mfabeni Mire is often flooded in summer with water depths of ~0.3 m.

Daily solar radiant density fluctuated seasonally, peaking at 12 MJ m^{-2} in winter and 27 MJ m^{-2} in summer (Fig. 2.2), but was more variable in summer due to cloud cover, which was particularly prevalent during the mornings until 11:00 a.m. LT. Maximum temperatures in the Mfabeni Mire were frequently above 30 °C in summer and generally below 30 °C in winter. The average daily minimum temperature was 20 °C in summer and rarely below 5 °C in winter, although on 17 June 2010 the temperature dropped to -1.2˚C. The humid coastal conditions are best described by the average daytime (R_n>0) VPD of 0.79 kPa indicating a low atmospheric evaporative demand generally. The monthly average daytime VPD was between 0.56 kPa and 0.96 kPa (Fig. 2.3) with October experiencing the lowest and February the highest VPD. The average daytime (R_n>0) windspeed was 4 m s^{-1} (Fig. 2.3). The highest monthly average was measured in October (5.4 m s^{-1}) and the lowest in May (3.2 m s^{-1}). The dominant wind direction was north-easterly (onshore) in summer and with southerly winds during cold frontal conditions in winter (not shown).

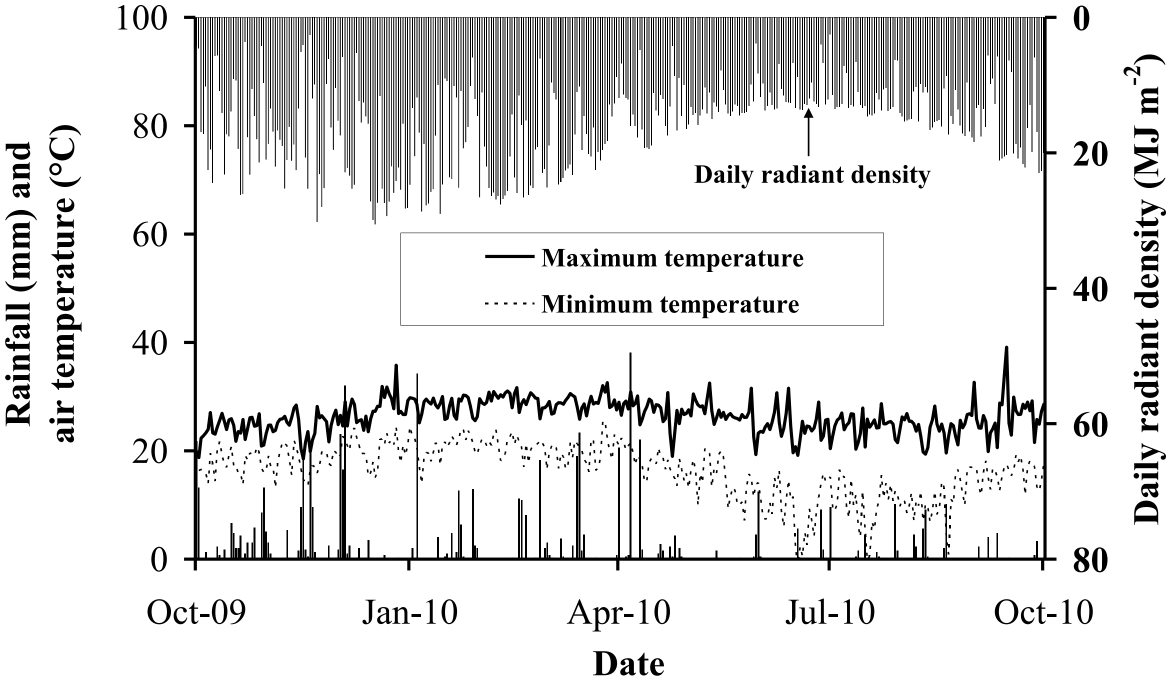

Figure 2.2 Climatic conditions at the Mfabeni Mire including maximum and minimum air temperature (˚C), rainfall (mm) and daily solar radiant density (MJ m^{-2}) from October 2009 to September 2010

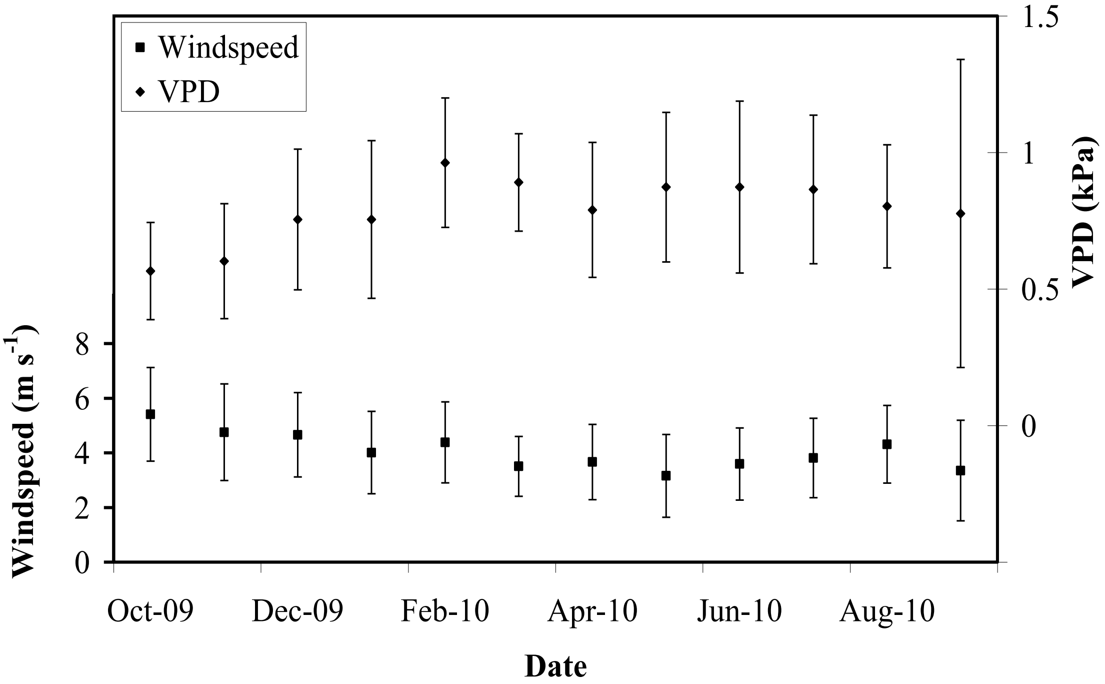

Figure 2.3 Monthly average windspeed and VPD (with standard deviation error bars) at the Mfabeni Mire from October 2009 to September 2010

Fires are a common occurrence in South African wetlands (Cowan, 1995). A runaway fire burned through the Mfabeni Mire just before measurements commenced in September 2009. It spread from dry peat that smoldered for weeks in the northeast corner of the Mfabeni Mire and was rekindled by a change in wind direction. Despite high windspeeds during the fire, the burn was patchy due to low fuel load densities and some of the actively growing vegetation such as the reeds and sedges were undamaged. The burn however, provided an opportunity to investigate the ET directly after a fire, followed by natural spring re-growth.

Albedo (ratio of reflected irradiance from the surface to incident irradiance upon it) increased after the fire in September 2009 from 0.10 to 0.22 in April 2010 due to vegetative re-growth (Fig. 2.4) and then gradually decreased again to approximately 0.17 due to plant senescence and winter conditions.

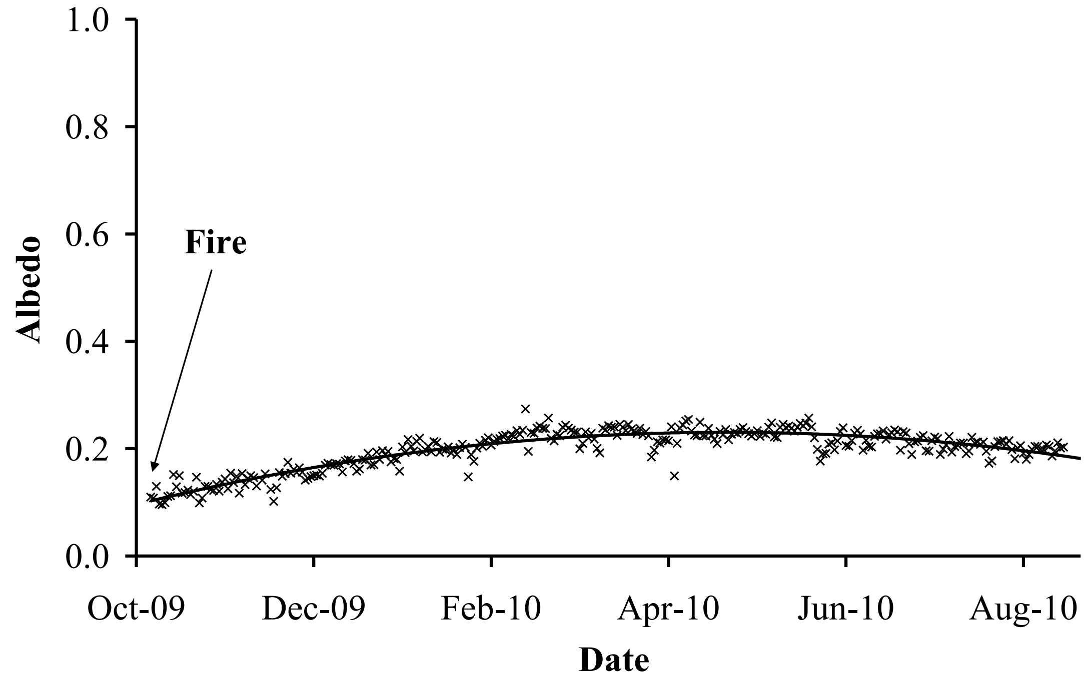

Figure 2.4 The change in albedo of the Mfabeni Mire following the recovery of vegetation after a fire in September 2009

2.5.2 Measured energy balance and total evaporation

During winter, there was noticeably less variation in R_n due to the dominance of clear skies (Fig. 2.5a). For example, in August 2010, four of the days (18, 21, 22 and 23) showed complete cloudless conditions, which were never observed during the summer period. Net irradiance at the Mfabeni Mire in summer (up to 800 W m^{-2}) was variable due to intermittent cloud cover (Fig. 2.5b). Cloudy mornings, with some clearing between 10h00 and 11h00 were common.

At the Embomveni Dunes, the peak daily R_n in winter was similar to that at the Mfabeni Mire (Fig. 2.5c), but in summer (Fig. 2.5d) R_n was ~100 W m^{-2} lower than at the Mfabeni Mire. This is a function of the albedo and indicated that there was more irradiance reflected from the Dunes than the Mire in summer. Where exposed, the dark surface of the peat at the Mfabeni Mire was in contrast to the off-white sand of the Embomveni Dunes. However, plant senescence in winter reduced the difference in the reflected irradiance between the sites. This is shown by the slope of the linear regression of R_n at the Mfabeni Mire on the R_n at the Embomveni Dunes of 0.84 in summer (Fig. 2.6a) whereas in winter the slope was 0.97 (Fig. 2.6b). In addition, the lower co-efficient of determination during summer ($R^2 = 0.90$) over winter ($R^2 = 0.99$), supports the cloudiness noted in the paper, which, despite the close proximity of the sites (6 km), introduced differences in half hourly solar radiation results between the sites (Figs. 2.6a and 2.6b).

There was a marked dominance of *H* over LE at the Embomveni Dunes, where the Bowen ratio (β) was > 1 in summer and winter (Table 2.1; Figs. 2.5c and 2.5d). The exception was when rainfall increased the soil water content. For example, 12 mm of rain on 19 and 20 August 2010 increased the near surface volumetric soil water content from 6.2% to 8.7%. On the 21 and 22 August the LE was similar to the *H* but by 23 August, ET had depleted the soil water to 7.0% and *H* dominated the energy balance again. This showed the dependence of the grassland ET_{SR} on soil water and identified it as a limiting factor for growth.

There was a shift in the distribution of the energy balance at the Mfabeni Mire between summer and winter (Table 2.1). At the Mfabeni Mire, in summer, the ratio LE:R_n (0.61) was almost twice H:R_n (0.31), while G:R_n made up the remainder (0.08). The pattern shifted in winter to an equal split between LE:R_n and H:R_n (0.46) while G:R_n was again 0.08. The reduced dominance of LE:R_n was likely due to plant senescence in winter and was typical of a surface with full canopy cover. At the Embomveni Dunes there was little change in the energy partitioning between seasons. This indicated that the limiting factors controlling the partitioning of the energy balance remained consistent between seasons. The exception was after rainfall at the Embomveni Dunes where a change in water availability altered the partitioning of the energy balance as discussed above. At both sites there was little change in the ratio G:R_n between seasons as the reduced LAI in winter (described above) was likely offset by a lower sun angle.

The ET_{SR} at the Mfabeni Mire varied seasonally (Fig. 2.7). Intermittent cloud during the summer period (October to March) resulted in large daily fluctuations in ET_{SR}. This was also evident in the high variability of R_n in summer in comparison to the winter period, which the meteorological data (Fig. 2.2) showed to be characteristic of the coastal weather patterns for the area. In the Mfabeni Mire, the average summer ET_{SR} was 3.2 mm day^{-1} (σ = 1.4 mm day^{-1}). The fitted 95% regression quantile ($p < 0.001$) indicated potential maximum daily rates in summer to be approximately 6.0 mm day^{-1}. During the winter months (April to September) the average daily ET_{SR} was 1.8 mm day^{-1} (σ = 0.8 mm day^{-1}) with an estimated potential maximum around the winter solstice of 1.3 mm day^{-1}. The accumulated ET_{SR} over 12 months was 900 mm (Table 2.2) of which 64% occurred in the summer months (October to March).

At the Embomveni Dune site (Fig. 2.7), as with the Mfabeni Mire, there were many cloudy days in summer. The average summer ET_{SR} (October to March) was 1.7 mm day^{-1} (σ = 0.8 mm day^{-1}) with the maximum rate estimated by the 95% regression quantile of approximately 3.0 mm day^{-1}. The average daily ET_{SR} during the winter months (April to August) was 1.0 mm day^{-1} (σ = 0.8 mm day^{-1}) with an estimated maximum around the winter solstice of 1.2 mm day^{-1}. The accumulated ET_{SR} over 12 months was 478 mm (Table 2.2) of which approximately 63% occurred in the summer months (October to March).

Despite the close proximity of the two sites (6 km), ET_{SR} at the Mfabeni Mire (900mm) was almost double the ET_{SR} at the Embomveni Dune site (478mm). This difference was due to the freely available water at the Mfabeni Mire and the different vegetation types found between the sites. The dominant limitations to transpiration and surface evaporation at the Mfabeni Mire were likely to have been available energy, low atmospheric demand (noted above) and some stomatal control (mainly of the grasses) due to plant senescence in winter. The ET_{SR} at the Embomveni Dunes was limited by soil water content and the low water-use requirements of the dune vegetation, an adaptation to survive prolonged dry conditions. Even for brief periods after rainfall when soil water was not limiting, the daily ET_{SR} was still lower than the Mfabeni Mire. However, soil water availability was generally low with volumetric water content of ~6% and frequently below −800 kPa at a depth of 0.075m (measured continuously but not shown).

The SR method was found to be reliable, easy to operate in the field and suitable for long-term, unattended use over wetlands with calibration using eddy covariance. However, the fine-wire thermocouples are fragile and easily broken by animals, hail or contact with fast growing vegetation, and at least one backup thermocouple was used.

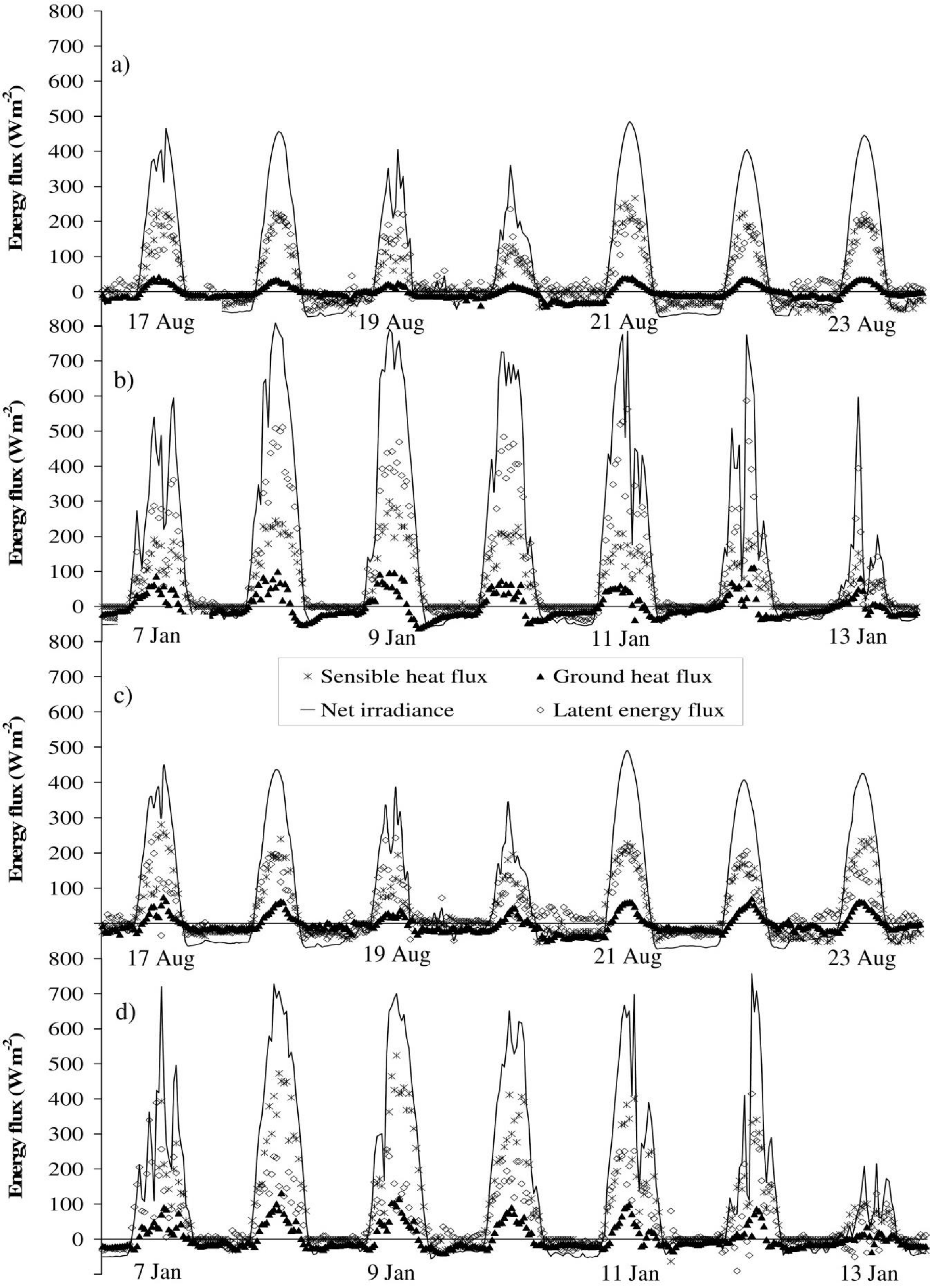

Figure 2.5 Diurnal energy fluxes at Mfabeni Mire on (a) 17 to 23 August 2009 and (b) 7 to 13 January 2010 and on corresponding days at the Embomveni Dunes in (c) August 2009 and (d) January 2010

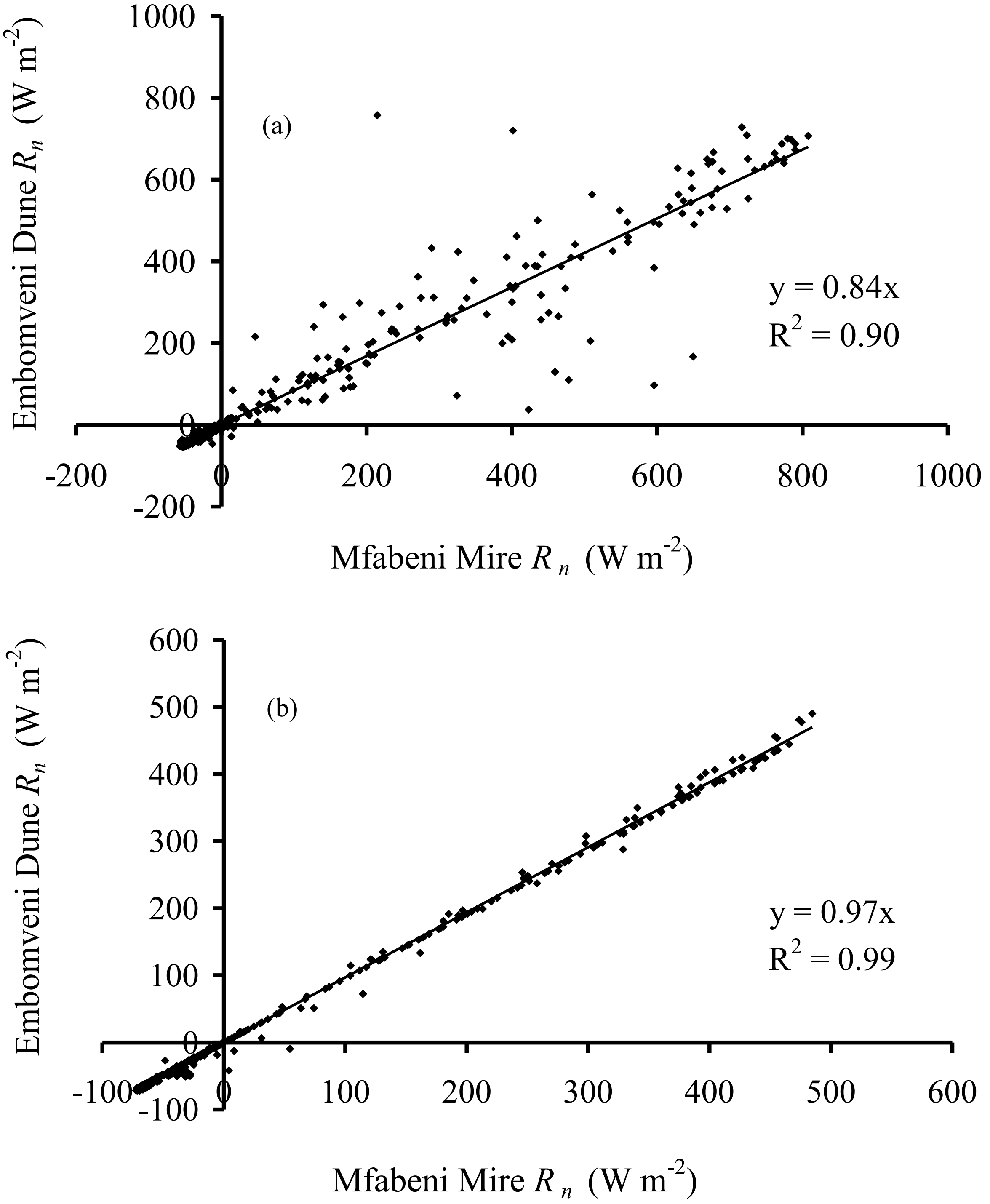

Figure 2.6 The difference in summer (a) and winter (b) net radiation R_n (half hourly) between the Mfabeni Mire and Embomveni Dune sites shown by the slope of the least squares linear regression

Table 2.1 Distribution of the average daily energy balance as fractions of R_n, as well as the Bowen ratio (β), at the Mfabeni Mire and Embomveni Dune sites

Site	Summer				Winter			
	$LE:R_n$	$H:R_n$	$G:R_n$	β	$LE:R_n$	$H:R_n$	$G:R_n$	β
Mfabeni Mire	0.61	0.31	0.08	0.51	0.46	0.46	0.08	1.00
Embomveni Dunes	0.36	0.55	0.09	1.53	0.37	0.53	0.10	1.43

Table 2.2 Summary of seasonal and annual total evaporation derived using a surface renewal system to calculate the sensible heat flux with standard deviations (σ) in brackets

Site	Summer (mm)	Winter (mm)	Total (mm)
Mfabeni Mire	575 (σ = 1.4)	325 (σ = 0.8)	900 (σ = 1.4)
Embomveni Dunes	303 (σ = 0.8)	175 (σ = 0.4)	478 (σ = 0.7)

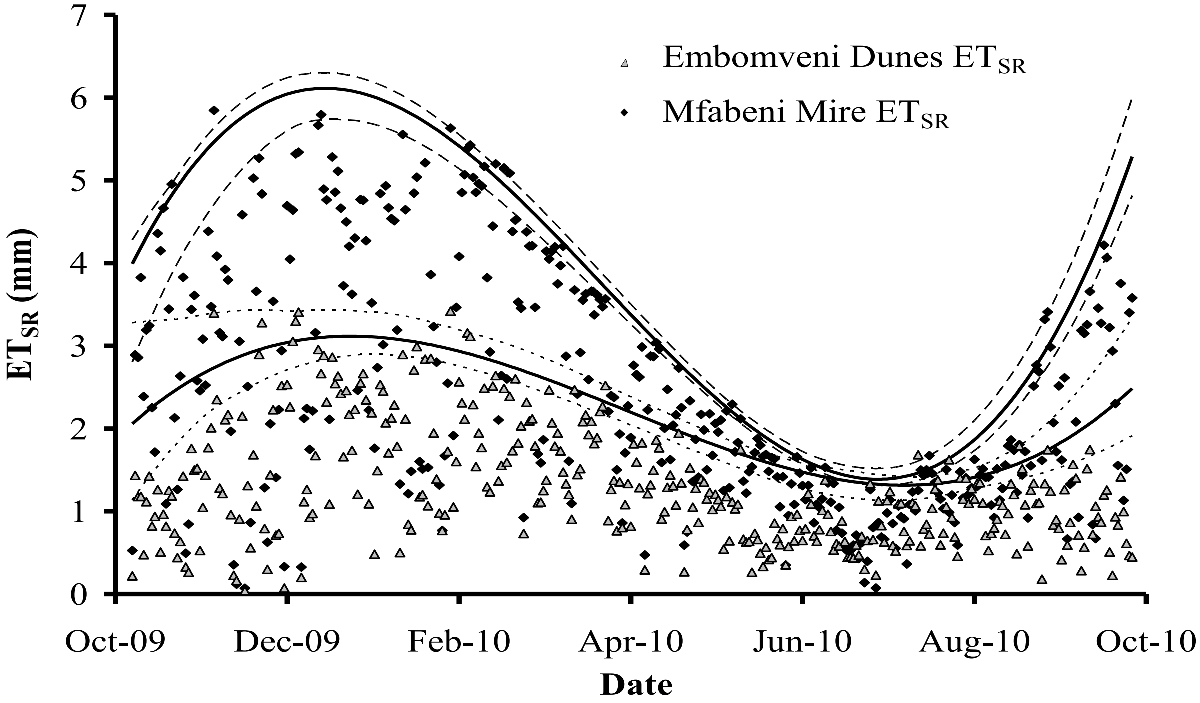

Figure 2.7 Daily total evaporation at the Mfabeni Mire (upper line) and Embomveni Dunes (lower line) from October 2009 to September 2010 using the surface renewal technique. Solid lines represent fitted 95% regression quantiles and dashed lines their 95% confidence intervals

2.5.3 Modelling total evaporation

Evaporation measurement is complex and in most studies of wetland hydrology is modelled using weather data collected from a nearby automatic weather station. Two methods used widely for wetland applications are the FAO-56 Penman-Monteith method (Allen et al., 1998) and the Priestley-Taylor method (Priestley and Taylor, 1972). These models are relatively simple and suitable for use by hydrologists or wetland ecologists to determine wetland ET. They are also well suited to wetland applications as water availability does not limit transpiration.

FAO-56 Penman-Monteith: The original Penman model (Penman, 1948) is frequently cited and was a significant contribution to evaporation modelling. It was improved by Monteith (1965) by incorporating surface and aerodynamic resistance functions and was widely used in this form as the Penman-Monteith equation. It is still commonly applied but is highly data intensive (Moa et al., 2002; Drexler et al., 2004). The equation was later standardised by the Food and Agriculture Organisation (Allen et al., 1998) into a form known as the FAO-56 Penman-Monteith model. The standardisation includes the definition of a reference crop as "a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 ms^{-1} and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered" (Allen et al., 1998).

The FAO-56 Penman-Monteith model provides an estimate of ET from a hypothetical grass reference surface (ET_r). It can be universally applied as it provides a standard to which ET at different times of the year or in other regions can be compared and to which the ET from other crops can be related. It is used internationally to estimate crop ET using the crop factor (K_c) approach in the form:

$$K_c = \frac{ET}{ET_r} \tag{3.8}$$

where, the crop is not water stressed. In Allen et al., (1998) numerous values of K_c have been compiled for different vegetation types and the different stages in crop development.

The ET_r was calculated hourly and summed each day. The daily results of ET_r (Fig. 2.8) reflected a similar seasonal trend to that shown by the ET_{SR} (Fig. 2.7) at the Mfabeni Mire. The standard deviation (σ) in summer was higher (1.3 mm) than in winter (0.7 mm). Monthly K_c averages (Fig. 2.9) reflect the need to accommodate seasonal changes in K_c at times. The monthly 95% confidence intervals indicate a higher variability of daily K_c from June to January compared to February through to May. From October to January there was no significant difference between mean monthly K_c and a single mean over this period would be suitable. However, from February to September all but two of the monthly K_c's are significantly different and a monthly K_c should be used over these months. Over the 12 months of measurement the average K_c was 0.80 indicating that the ET_{SR} was on average 20% less than ET_r. This K_c result was low for a wetland, particularly considering the freely available water in the Mfabeni Mire. Although the linear regression of ET_{SR} on ET_r was significant ($F_{1, 355} = 1640$, $p < 0.001$) and accounted for 82% of the variation in ET_{SR}, residual variation about the regression was not constant (hetroscedastic), even under various data transformations. This suggests that the crop factor approach was not suited to estimating ET for the Mfabeni Mire.

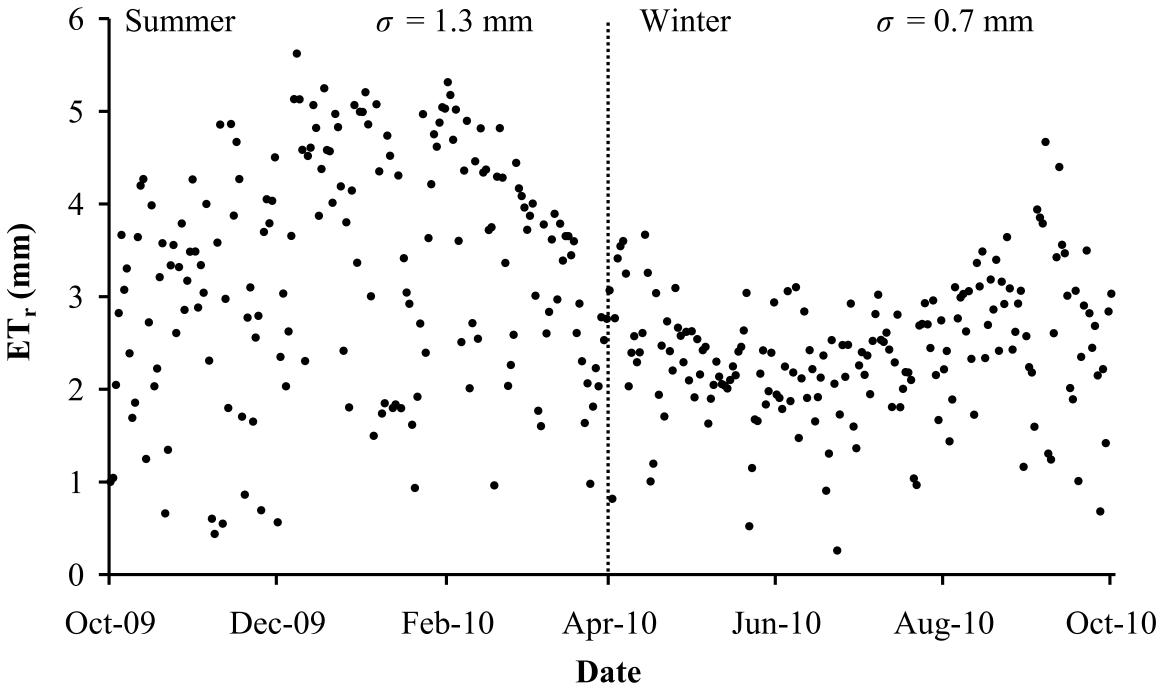

Figure 2.8 The short grass reference evaporation (ET_r) from October 2009 to September 2010 in the Mfabeni Mire

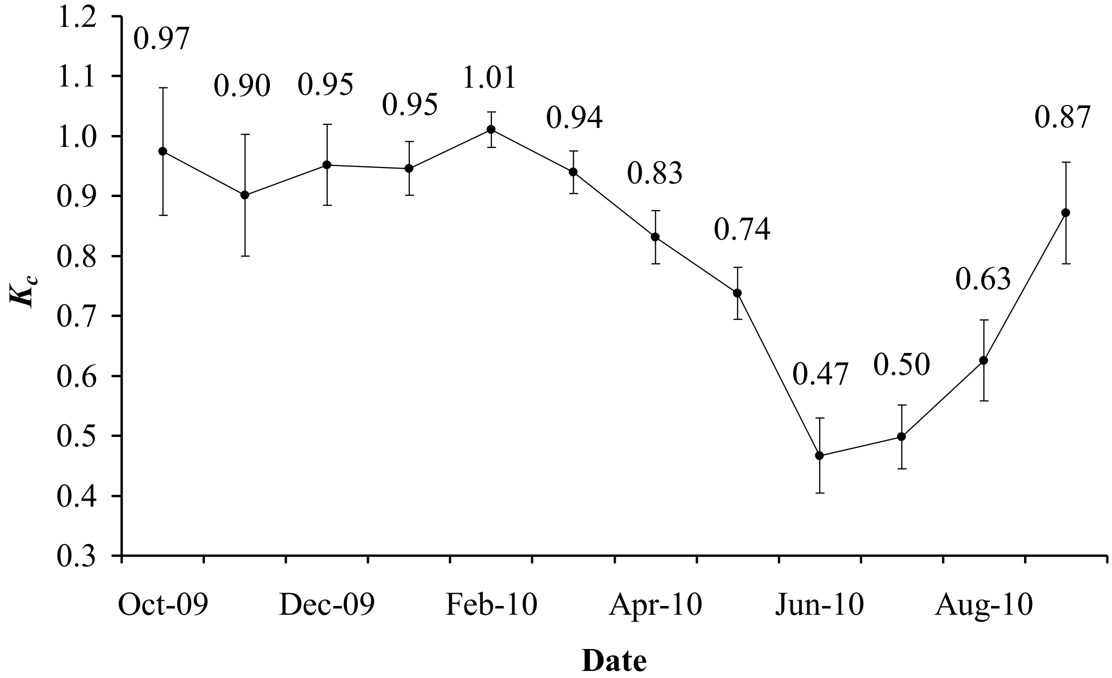

Figure 2.9 Mean monthly crop factor (K_c) for the Mfabeni Mire from October 2009 to September 2010 with 95% confidence intervals

Priestley-Taylor: The Priestley-Taylor model (Priestley and Taylor, 1972) is a simplified version of the more theoretical Penman model. The aerodynamic terms of the Penman model are replaced by an empirical and constant α known as the advective term. It is reasoned that as an air mass moves over an expansive, short, well-watered canopy, ET would eventually reach a rate of equilibrium when the air is saturated and the actual rate of ET would be equal to the Penman rate of potential evapotranspiration. This is referred to as equilibrium evaporation (ET_{EQ}). Under these conditions the aerodynamic term of the Penman equation approaches zero and irradiance dominates. The Priestley-Taylor model is therefore commonly used to estimate evaporation from wetlands (Price, 1992; Souch et al., 1996; Mao et al., 2002) and was applied in this study in the form described by Savage et al. (1997).

At the Mfabeni Mire, ET_{EQ} (α=1, Fig. 2.10) reflected the seasonality observed in ET_{SR} (Fig. 2.7). The fitted 95% regression quantile ($p < 0.001$) indicates maximum rates on clear days. In summer the maximum rates were higher (6.0 mm day^{-1}) but more variable (σ = 1.5 mm day^{-1}) and in winter, lower (1.7 mm day^{-1}) and less variable (0.8 mm day^{-1}). A linear regression of ET_{SR} on ET_{EQ} ($F_{1, 355} = 7553$, $p < 0.001$) over the 12 months of measurement indicated that ET can be accurately predicted (R^2 = 0.96) by the Priestley-Taylor equilibrium model at the Mfabeni Mire. The Priestley-Taylor α represented by the slope of the linear regression in Fig. 2.11 and is equal to 1 (intercept of -0.3).

The dry conditions of the Embomveni Dune site violate the ‘well watered’ assumptions of the Priestley-Taylor model however it was used at this site for comparison with the Mfabeni Mire. As with the Mfabeni Mire, the ET_{EQ} at the Embomveni Dune site reflected the seasonality of ET_{SR} with summertime highs of 5 mm day^{-1} (σ = 0.8 mm day^{-1}) and wintertime lows of 1.8 mm day^{-1} (σ = 0.4 mm day^{-1}). An acceptable linear regression of ET_{SR} on ET_{EQ} was found with square-root transformed data to ensure a constant and approximately normally distributed residual. However, the confidence with which ET_{EQ} can be used to estimate ET_{SR} was lower (R^2=0.71) than at the Mfabeni Mire (R^2=0.96). In summer for example, the 95% regression quantile of ET_{SR} was only 3.0 mm day^{-1} whereas ET_{EQ} was 5 mm day^{-1}. This indicated that a severe constraint was imposed by low soil water availability (measured but not shown). For example, on the days of 21 and 22 August (following 12 mm of rain on 19 and 20 August) the near surface volumetric water content increased from 6.2 % to 8.7 % and the Priestley-Taylor α was 0.8 and 0.81 respectively. However by the 23 August the surface soil water was depleted to 7.0 % and the Priestley-Taylor α was restricted to 0.52 by the soil water limitation.

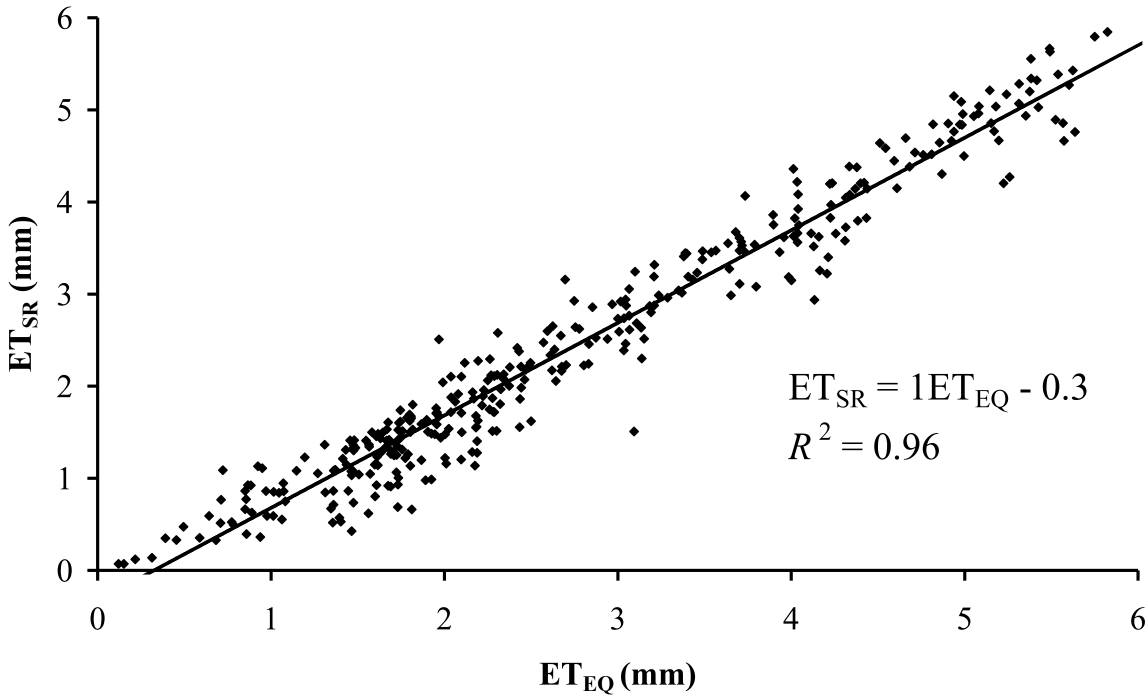

Figure 2.10 The advective term (α) at the Mfabeni Mire determined as the slope of the least squares linear regression of ET_{EQ} *vs* ET_{SR} from October 2009 to September 2010

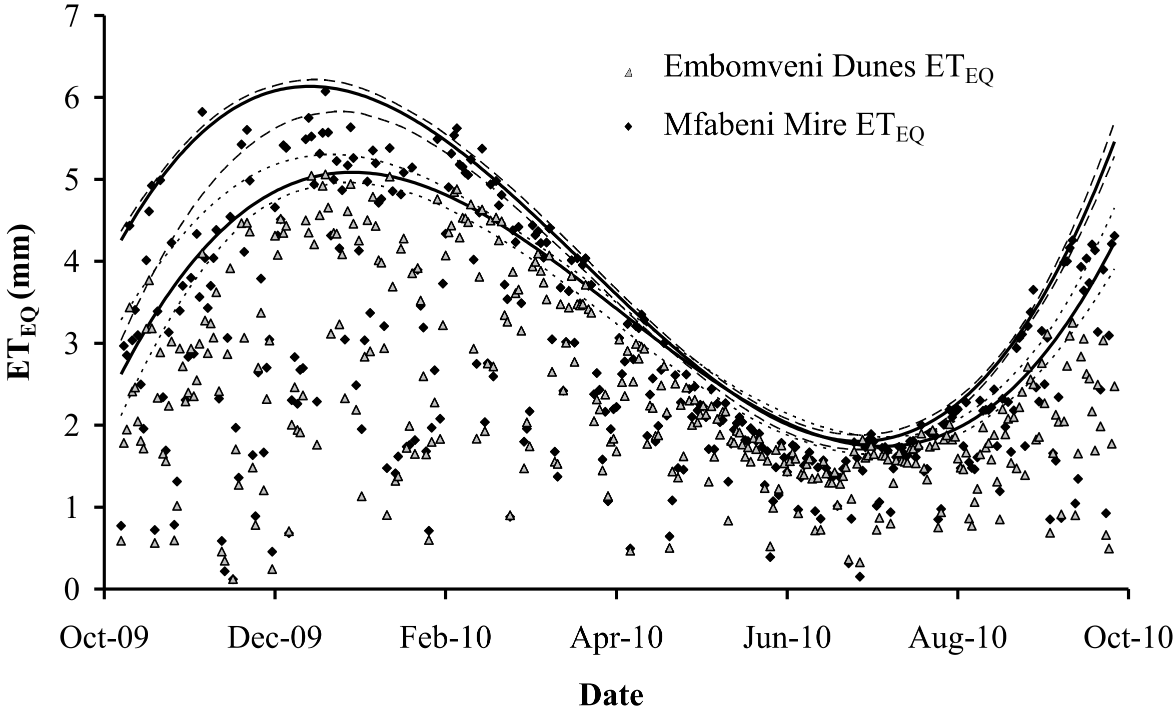

Figure 2.11 The equilibrium evaporation (ET_{EQ}) from October 2009 to September 2010 at the Mfabeni Mire (upper line) and Embomveni Dunes (lower line). Solid lines represent fitted 95% regression quantiles and dashed lines their 95% confidence intervals

2.6 Discussion

The SR method, used to estimate *H* in this study, was found to be reliable for long-term, unattended use over the Mfabeni Mire with periodic calibration using eddy covariance. Once determined, a re-calibration is only required if there are significant changes in the vegetation canopy (Snyder et al., 1996; Spano et al., 2000; Paw U et al., 2005). Further advantages found to be significant in this study included the relatively low cost of the system, the low power consumption and the simple and basic maintenance requirements in comparison to alternative methods available for estimating *H*. This was particularly important as it reduced the cost and time resources required for field visits, as the site was remote and the study was long-term. In addition, Drexler et al., (2004) comment that the SR method is less dependent on fetch than other methods (eddy covariance). Therefore, in wetlands with complex surfaces with areas of open water, soil and vegetation, the number of measurements can be replicated at a low cost by including additional fine-wire thermocouples offering a better spatial representation of ET.

The site specific calibration required by the SR method is however a disadvantage as an independent measure of H is required over a suitable calibration period. In addition, the SR method was introduced by Paw U and Brunet (1991) and is still relatively new in terms of measurement systems. As a result there are no complete SR systems available commercially as there are with other methods (eddy covariance). This introduces a significant barrier to entry for wetland hydrologists or ecologist as expertise in logger programming, data processing and an understanding of micrometeorological measurement is required. The fine-wire thermocouples (76 μm diameter), although not prohibitively expensive, are fragile and breakage can result in data loss if backup thermocouples are not installed.

Despite improvements to measurement techniques and the dominant role of ET in wetland water-balances, there are few studies in Southern Africa with actual measurements of ET from wetlands. Wetland ET has been estimated in the Ntabamhlope research catchment in the foothills of the Drakensberg using diurnal fluctuations in the water table levels (Smithers et al., 1995) with significant residuals and deficiencies identified in the technique. Also at Ntabamhlope, an evaporimeter was used together with the Penman (1948) method and the complementary relationship concept of Bouchet (1963) but problems with instrumentation drift compromised the results (Chapman, 1990). The Nylsvlei floodplain is a seasonal wetland of the semi-arid Limpopo Province in the north of South Africa. Total evaporation was estimated in the Nylsvlei wetland using a combination of meteorological models, pan evaporation and a few days of energy balance measurements (ignoring sensible heat flux) to derive monthly means of ET (Birkhead et al., 2007).

A more comprehensive wetland ET study in South Africa was performed by Dye et al. (2008) near Orkney (27.02° S, 26.68° E) in the Dry Highveld Grassland Bioregion of central South Africa. The Bowen ratio technique and eddy covariance were used intermittently over a *Phragmites communis* dominated marsh over one year. The ET in summer in the marsh peaked at 6.0 mm day^{-1} (Mfabeni = 6.0 mm day^{-1}) and averaged approximately 3 mm day^{-1} (Mfabeni = 3.2 mm day^{-1}). Around the winter solstice, peak rates of 1.6 mm day^{-1} (Mfabeni = 1.3 mm day^{-1}) were measured. Dye et al*.,* (2008) also noted the summertime variation in daily ET rates depended on cloud and humidity. These results from Orkney compared favourably with the results from Mfabeni and indicated that despite the geographically distinct location and altitude the ET estimates were similar.

Also inland but further to the north, ET was measured in a riparian area of the Sabie River in the Kruger National Park, South Africa (Everson et al., 2001). The Bowen ratio technique was applied over a *Phragmites mauritianus* dominated marsh in a riparian wetland. Maximum ET rates were 9 mm day^{-1} in summer and 4 mm day^{-1} in winter. These rates are higher than at the Mfabeni Mire due to the higher available energy but most significantly the daily average VDP's were higher (mostly between 1 and 3 kPa) and therefore the sites are not comparable.

The ET_{SR} results from the Embomveni Dunes (terrestrial grassland) serve as an interesting contrast to the Mfabeni Mire ET_{SR}. The 12 month accumulated ET_{SR} at the Mfabeni Mire was 900 mm in contrast to 478 mm at the Embomveni Dune site. The soil water content at the grassland was low (~6% volumetric and frequently below -800 kPa at a depth of 0.075 m) during the measurement period due to the prevailing drought conditions. The ET_{SR} at the Embomveni Dunes was therefore limited by soil water availability rather than energy. A similar result was observed by Jacobs et al., (2002) in a wet prairie under drought conditions in Central Florida, USA. They found that the fraction of available energy used in the evaporation and transpiration of water depended on soil water content and that a two-stage model with a reduction coefficient under dry conditions was appropriate. The soil water content in the Mfabeni Mire was by comparison much higher (>85%) and the ET_{SR} was energy limited.

In South Africa, two comparative long-term studies of ET over grasslands have been performed. Everson et al. (1998) estimated ET over *Themeda triandra* grasslands of the Drakensberg escarpment near Cathedral Peak (28.95˚ S, 29.20˚ E). Cathedral Peak lies approximately 250 km inland of the coast with altitudes of 2000 m and falls within the Grassland Biome. They found maximum daily ET to be as high as 7 mm day^{-1} in summer (Embomveni = 3.0 mm day^{-1}) and < 1 mm day^{-1} in winter (Embomveni < 1.2 mm day^{-1}). The high summer rates of the Drakensberg are likely to contrast with the Embomveni Dunes for a number of reasons. The high summer rainfall (long-term average = 1299 mm) of the Drakensberg area (compared to 650 mm measured in the Mfabeni Mire) sustained an adequate soil water content (generally > 43 % and < 80 kPa) in comparison to the rapidly draining drier soils of the Embomveni Dune site (generally < 7% and > 200 kPa), which limited ET. In addition, the summer VPD of the Drakensberg (Everson et al., 2012) is higher (mostly between 1.5 and 2.5 kPa) than at the Embomveni Dunes (mostly between 0.5 to 1.5 kPa). The lower atmospheric demand together with the lower soil water content explains the lower summertime ET rates of the Embomveni Dunes and brings into question a quantitative comparison between these sites. The second study was performed by Savage et al. (2004) in the KwaZulu-Natal Midlands near Pietermaritzburg (24.63˚ S, 30.43˚ E) approximately 100 km from the coast in a mixed grassland community during a dry period. They reported average daily summer ET rates to be approximately 3 mm day^{-1} and daily winter ET, 1 mm day^{-1}. These results are closer to the ET_{SR} in the Embomveni Dune site possibly due to the similar drought conditions and a water limiting environment reported during their study.

Internationally, there are no comparable ET studies in the southern hemisphere to those at the Mfabeni Mire. In Australia, the subtropical wetland studies focus on water treatment wetlands where the 'clothesline effect' is noted (Headley et al., 2012) and in South America the focus is forest wetlands (Fujieda et al., 1997). In the northern hemisphere however, the Florida (USA) Everglades wetland region has been studied intensively and the results at Mfabeni Mire can be compared with studies by Mao et al. (2002) and Abtew (1996) who found ET rates slightly higher than those measured at the Mfabeni Mire over cattail and saw-grass vegetation. Abtew (1996) found annual average rates of ET over mixed marsh of 3.5 mm day^{-1} (Mfabeni = 2.5 mm day^{-1}). Mao et al. (2002) measured growing season rates for cattail and saw-grass of 4.1 and 5.9 mm day^{-1} (Mfabeni = 3.2 mm day^{-1}) and non-growing season rates of 2.2 and 2.0 mm day^{-1} (Mfabeni = 1.8 mm day $^{-1}$). The Mfabeni Mire ET is generally lower than at these other comparable wetland sites. This is likely due to the low leaf area, vapour pressure deficit and a net irradiance, which was suppressed at the Mfabeni Mire due to prevailing cloudy conditions especially during the summer (Fig. 2.5b and 2.6a).

The Priestley-Taylor model was originally derived for use over extensive, saturated surfaces. When α=1, the equation represents the equilibrium model, which occurs when the gradient of VPD approaches zero and ET_{EQ} equals potential evaporation. During unstable daytime conditions, this is mostly not the case. Priestley and Taylor (1972) found an average α over oceans and saturated land of 1.26. This implies that additional energy increases the ET by a factor of 1.26 over ET_{EQ}. This has been explained by some as a result of entrainment of warm, dry air, down through the convective boundary layer (Lhomme, 1997). Numerous studies have determined other values for α (Monteith, 1981; Paw and Gao, 1988; Clulow et al., 2012). Ingram (1983) found the value of α to be dependent on vegetation cover and that for treeless bogs α lay between 1 and 1.1 and for fens approximately 1.4. Moa et al., (2002) derived values for α in a subtropical region of Florida (USA) over sawgrass and cattail communities interspersed with open water areas of between 1.12 and 0.90. Most available literature regarding suitable α values, are however derived from studies in subarctic regions (Eaton et al., 2001), arid areas (Bidlake, 2000), over lakes (Rosenberry et al., 2007) or boreal aspen forest (Krishnan et al., 2006). The Priestley-Taylor α is site specific and these estimates from the Mfabeni Mire for Southern African vegetation and climatic conditions are valuable.

The α estimate of 1.0 (with an offset of −0.3 mm) calculated for the Mfabeni Mire is low in comparison with results from much of the international literature. However, it agrees well with those of Moa et al. (2002), German et al. (2000) and Abtew (1996) derived from the Florida (USA) Everglade wetlands, and very well with the estimate of 1.035 of Souch et al. (1996) during the warm summer climate of the Indiana Dunes National Lakeshore Great Marsh. In this study it was also noted that a flow of humid air off the nearby Lake Michigan suppressed evaporation from the marsh. Equilibrium evaporation clearly describes the evaporation rate in the Mfabeni Mire and other wetlands of subtropical climates surrounded by open water or other wetland types.

The standardized FAO-56 Penman-Monteith model together with a K_c was developed to be applied internationally allowing comparison between different sites in different locations (Allen et al., 1998, 2006). It has, in some respects, become the industry standard in terms of ET estimation from different land-uses and is incorporated into numerous hydrological models (ACRU, SWAT, SWAP) and would be a popular solution for a wetland ecologist or hydrologist seeking to characterize the ET from a wetland using meteorological inputs. The report by Allen et al. (1998) is comprehensive and provides solutions for different time steps and levels of data, increasing the accessibility of the method. The relatively poor relationship between ET_{SR} and ET_r (R^2=0.82), for the Mfabeni Mire, showed that despite attempts to create a universal solution, it should be used with caution when applied to natural vegetation. An alternative to the K_c method is to estimate the ET using the Penman-Monteith method but Drexel et al. (2004) found the lack of information on aerodynamic and surface resistances limiting.

The Priestley-Taylor model is a simplification of the FAO-56 Penman-Monteith model in which the mass transfer term is reasoned to be close to zero over a wet expansive surface and is ignored. The residual variation around the regression between ET_{SR} on ET_r (R^2=0.82) was higher than between ET_{SR} and ET_{EQ} (R^2=0.94). This difference must therefore be introduced from within the mass transfer term of the FAO-56 Penman-Monteith model, which is a function of wind speed and VPD (or air temperature and relative humidity). This relationship between

ET_{SR} and ET_r is described by K_c (Eq. 2.4), which was most variable in October when the highest daily average wind speeds and lowest daily average VPD's were measured (Fig. 2.3). In contrast, the daily variability of K_c was lowest in February, which corresponded to the month with the lowest windspeed and highest VPD. The high wind speeds, possibly combined with low VPD's, reduced the confidence with which the FAO-56 Penman-Monteith model can be used to predict ET_{SR} at the Mfabeni Mire.

Leaf area index and albedo are important descriptors of a site in terms of ET. The albedo data are useful for future solar irradiance modelling studies and for remote sensing energy balance models such as the Surface Energy Balance Algorithm for Land model SEBAL, which has been used successfully in wetland areas (Bastiaanssen et al., 1998; Mohamed et al., 2006). Asner et al., (2003), in their global synthesis of LAI observations concluded that the leaf area index of the wetland biome is not well represented internationally but that it is a key descriptor of vegetation. They document the results from six wetland studies resulting in a mean wetland LAI of 6.3 with a minimum of 2.5 and a maximum of 8.4. In comparison, the LAI of the Mfabeni Mire was lower, between ~1.7 in winter and ~2.8 in summer due to the narrow leaves of the vegetation. This result is of importance where site specific parameters (such as the Priestley-Taylor α factor) are transferred to similar or nearby wetlands. Knowles (1996) for example, applied a correction to K_c based on an LAI that is lower than full canopy cover. The LAI is therefore an important determinant of ET_{SR} and the relatively low ET_{SR} in contrast to the ET_r of the Mfabeni Mire could therefore partly be explained by the low LAI of the Mfabeni Mire.

2.7 Conclusion

The contribution of freshwater supply from the Mfabeni Mire to Lake St. Lucia during dry periods is important to the survival of certain plant and animal species in the iSimangaliso Wetland Park. This freshwater supply is mainly dependent on the variability of the major components of the water-balance, namely rainfall and total evaporation (ET). Attempts to quantify the water-balance have been limited through uncertainties in quantifying ET from the Mfabeni Mire. There are few measurements of ET from comparable wetlands in South Africa and despite advances in evaporation measurement and modelling from wetlands, there still exists some doubt as to which methods are best suited to characterise wetland ET, with most authors suggesting a combination of methods.

The SR method was successfully used to estimate H and was found to be suitable for long-term, unattended use over a subtropical wetland with periodic calibration using eddy covariance. It therefore has the potential to become more accessible to wetland researchers but the method is still relatively new and complete SR systems are not commercially available. Due to system complexity it currently remains the domain of micrometeorologist.

Despite plentiful water and a subtropical environment, wetlands are not necessarily the high water users they are frequently perceived to be (Bullock and Acreman, 2003). Even high wind speeds characteristic of the site did not raise the ET due to the low evaporative demand (or VPD) of the air. Despite maximum ET rates of up to 6.0 mm day^{-1}, the average summer (October to March) ET_{SR} was lower (3.2 mm day^{-1}) due to intermittent cloud cover, which reduced the available energy. In winter (May to September), there was less cloud but the average ET_{SR} was only 1.8 mm day^{-1} due to plant senescence and the accumulated ET_{SR} over 12 months was 900 mm. The results compared well with studies in similar subtropical wetlands of the northern hemisphere although are slightly lower due to lower leaf areas.

The Embomveni Dune (terrestrial grassland) measurements of ET_{SR} provided a useful contrast to the Mfabeni Mire (fen). The ET_{SR} was seasonal at both sites yet only 478 mm over 12 months. Even for brief periods after rainfall when the soil water was not limited, the ET_{SR} was lower at the Embomveni Dune site. The vegetation is therefore adapted to dry conditions and has a low water-use requirement even with higher soil water availability. However, for the majority of the measurement period, the ET_{SR} was limited by soil water availability. The drought conditions (650 mm of rainfall versus a mean annual precipitation of 1200 mm yr^{-1}) therefore contributed to the low summer ET_{SR} at the Embomveni Dunes, which is expected to be higher in a normal to high rainfall year.

A comparison of ET_{SR} with ET_r suggests that the crop factor approach was not suited to estimating ET_{SR} for the Mfabeni Mire. The Priestley-Taylor model however, closely reflected the daily changes in ET_{SR} at the Mfabeni Mire and $\alpha = 1$ (intercept of -0.3) can be used with confidence to estimate daily ET (R^2=0.96) throughout the year. This relationship between ET_{SR} and ET_{EQ} showed that ET from the Mfabeni Mire was largely dependent on energy and was at the equilibrium (or potential) rate. Including the mass transfer term, as is the case in the FAO-56 Penman-Monteith model, was of no benefit due to the complexity of the high wind speeds and low VPD at the site.

The significant advantage of the Priestley-Taylor method for use by wetland hydrologists and ecologists is the low data requirement. If R_n and G are measured or estimated (Drexler et al., 2004) from a nearby weather station then only T_{max} and T_{min} are required to estimate the wetland daily ET. In addition, the Priestley-Taylor model has been internationally accepted and tested since 1972 although the extent to which it can be applied beyond the Mfabeni Mire to other South African wetlands under equilibrium conditions requires further investigation.

The ET measurements and modelling guidelines for the Mfabeni Mire and Embomveni Dunes will assist in determining a more accurate water-balance, which was previously impossible without reliable estimates of ET. This will not only reduce uncertainty in water-balance studies and environmental flow determinations but provide better insight into the resilience of the system to droughts and the pressures of climate change.

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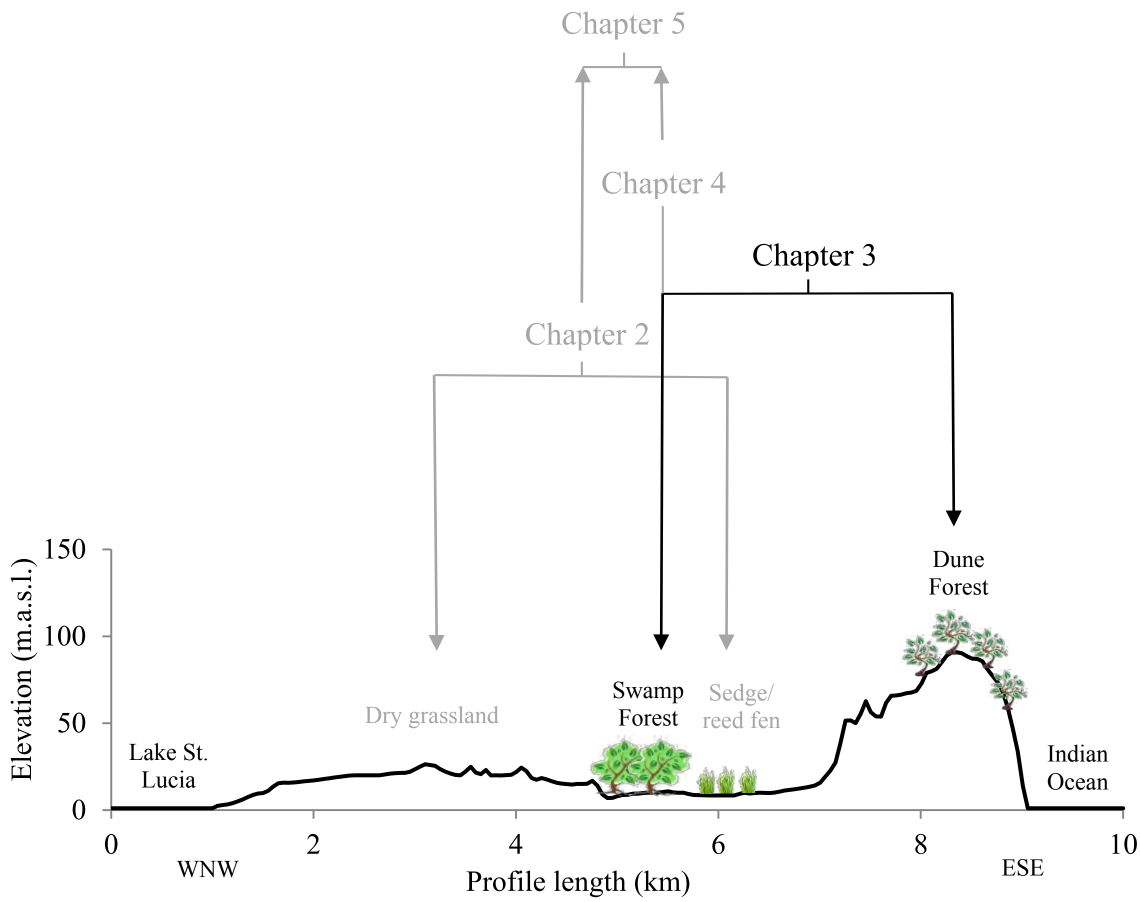
Lead into Chapter 3

The swamp forest plant community runs down the western side of the Mfabeni Mire a few meters above sea-level while the dune forest plant community grows on the coastal dunes that rise up to over 80 m.a.s.l., only 3 km to the east. This chapter describes the water-use dynamics of the forested plant communities investigated in this thesis. Sapflow techniques, reference evaporation and soil water measurements were used over a period of approximately 20 months to understand seasonal tree water-use patterns and responses to rainfall as well as factors limiting individual tree transpiration. Total evaporation for the two forested plant communities was not derived in this chapter. Figure 1.1 has been reproduced below but modified to show the plant communities investigated and compared in Chapter 3.



CHAPTER 3: WATER-USE DYNAMICS OF A PEAT SWAMP FOREST AND A DUNE FOREST IN MAPUTALAND, SOUTH AFRICA

3.1 Abstract

Peat swamp forests are the second rarest forest type found in South Africa while dune forests have been under severe threat through mining and agriculture. Both forest types exist in the conservation area, and World Heritage site, known as the iSimangaliso Wetland Park on the East coast of South Africa. The area is prone to severe droughts (Taylor et al., 2006) and recent attempts to understand the local water-balance revealed that there was insufficient information on the water-use of the indigenous forests of the area. The Peat Swamp Forest and Dune Forest sites studied in this research were located within close proximity to each other, yet, are characterised by different landscape positions in terms of water availability. The coastal dune forest soil profile was generally dry and sandy and the tree roots did not have access to the water table. In contrast the peat swamp forest is located in an interdunal wetland where the trees have permanent access to water. The climate at both sites is subtropical with a mean annual precipitation of 1200 mm year^{-1}. However, over 20 months of measurement, the first summer (October 2009 to March 2010) was drier (424 versus 735 mm) than the second summer (October 2010 to March 2011) emphasising the variability of the rainfall in the area and providing a wide range of conditions measured.

The sapflow of an evergreen, overstory *Syzygium cordatum* and a semi-deciduous, understory *Shirakiopsis elliptica* were measured in the peat swamp forest using the heat ratio method. The *Syzygium cordatum* water-use was not highly seasonal and the daily maximum water-use ranged from approximately 30 L d^{-1} in winter to 45 L d^{-1} in summer whereas the *Shirakiopsis elliptica* water-use was more seasonal at 2 L d^{-1} in winter and 12 L d^{-1} in summer. The water-use of the *Syzygium cordatum* was not influenced by seasonal rainfall variations and was actually higher in the drier summer (October 2009 to March 2010). Three trees of different heights were monitored in the same way in the dune forest and the water-use found to be highly seasonal. Over the entire measurement period, the water-use was highest for an emergent *Mimusops caffra* (5 to 45 L d^{-1}), whereas the water-use of the *Eugenia natalitia* (2 to 28 L d^{-1})

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and *Drypetes natalensis* (1 to 4 L d^{-1}) was lower. At the dune forest, the water-use was highest in the wetter summer due to the reliance of the trees on rainfall to recharge the soil water. A split-line regression showed that on average, soil water limited tree water-use 64% of the time over the measurement period at the dune forest. For modeling tree water-use at the dune forest, it was concluded that a two-stage model, taking soil water content into account (from multiple sampling points), would be necessary.

Keywords: *sapflow, transpiration, soil water, split-line regression*

3.2 Introduction

There has been extensive research on the comparative water-use of introduced trees and the indigenous vegetation they replace in South Africa (Dye, 2001; Everson et al., 2008; Gush and Dye, 2006; Gush and Dye, 2009). However, most of the work does not extend to indigenous tree water-use and there is a general dearth of information around the subject (Dye et al., 2008). Where information is available, climatic means, geographic location and soil water availability introduce doubt as to the transferability of results from one area to the next. Peat swamp forest (PSF) and dune forest (DF) transpiration rates measured in this research are the first of their kind in South Africa and form a valuable contribution to the existing indigenous tree water-use information. Indeed, the authors are unaware of any comparable water-use estimates from either of these vegetation types internationally.

The recent drive in South Africa to understand indigenous water-use stems primarily from the hydrologically extreme change in land use that has taken place in South Africa since the early 1900s. The result of this change has brought about a shift in the water-balance (Dye et al., 2008). For example, in some areas shallow rooted, seasonally dormant grasslands were replaced by deep rooted, evergreen forest plantations with high leaf areas. Commercial forestry plantations of exotic species have been associated with increasing the green water (water lost by evaporation) and decreasing the blue water (water in rivers and dams) in areas across South Africa (Calder, 1999; Jewitt, 2006). The first forest plantations were established in 1875 in the high rainfall areas of the country (Gush et al., 2002). During the course of the 1900s, the area under forestry grew to 1.5 million hectares, approximately 1.5% of the country's land cover, as the demand for wood increased. It was realised that forestry posed a threat to the availability of blue water, and since 1968 there have been recommendations and legal requirements associated with forestry as a result of its water-use (Dye and Versfeld, 2007). Water use licenses and monthly water costs associated with forestry (DWAF, 2004) and strict environmental legislation associated with riparian zones have been implemented (FIEC, 1995).

The Eastern Shores area of the St. Lucia estuary, in the Maputaland area of KwaZulu-Natal, was planted to exotic commercial pine plantations in the 1950s (Dominy, 1992). However, since the avulsion of the Umfolozi River from Lake St Lucia in 1952, the importance of groundwater recharge and the dependence of the Lake water levels and wetland areas on groundwater became critical (Taylor et al., 2006). With a growing understanding of the importance of the regional ecology and the potential for tourism, the Greater St. Lucia Wetland Park (the iSimangaliso Wetland Park since 2007 and a RAMSAR and World Heritage Site) was protected from dune mining proposals in the 1990s. However, the negative impact of commercial forestry on water resources and specifically the potential of the trees to deplete groundwater resulted in a decision to remove the plantations from the Eastern Shores area. This was successfully undertaken between 1991 and 2004 and the only evidence of commercial forestry across the dunes and around wetlands are the remaining tree stumps.

However, despite the removal of the commercial plantations, lower than average rainfall near the lake exacerbated the wider drought conditions since 2001, and salinity levels in the Lake have been critically high at times and have threatened species survival (Mackay et al., 2010). Cyrus et al. (2010) stated that remedial action is required to enable the proper functioning of the estuary and therefore proposed the establishment of a permanent link between the Umfolozi River and the Lake to supply fresh water and reduce salinity levels. The healthy functioning of the estuary is clearly in the balance due to anthropogenic influences that have severely affected the water-balance of the system. A water management strategy is therefore critical to the future health of the estuary. In addition, of the indigenous forests in KwaZulu-Natal, Eeley et al. (1999) particularly include swamp and dune forests as being those most at risk due to climate change. Even more so, peat swamp forests are at risk of invasion or succession by upland species in response to lowering of the water table, the drying out of peat and the increased potential for peat fires. It was during the course of a recent research project (Water Research Commission Project K5/1704) to address the water management of the Eastern Shores area and the implications of climate change to the area, that it was necessary to determine the water-balance. However, it was apparent that there is little or no information on the actual water-use from the natural vegetation types of the area. Total evaporation (ET), which includes transpiration and soil water evaporation, is a dominant component of the water-balance in South

Africa (Linacre, 1976; Everson et al., 2001; Everson et al., 2011). It was therefore determined that there is a need to measure the tree transpiration, which dominates in forests (Bosch and Hewlett, 1982), to better understand the dynamics of these two important forest types found within the area.

In terms of contribution to water-balance modeling, an improved understanding of tree transpiration dynamics and limits of individual (and dominant) species, was considered more useful than an overall ET estimate of each forest type, which is the sum of the water-use from the trees, undergrowth and soil. The dynamics of the tree transpiration (which dominates in forests) can be lost in a single measurement of ET due to the inclusion of the other components with their particular dynamics (undergrowth and soil). In addition, the absolute results of ET from each forest type are site specific and therefore not necessarily transferable to other forest areas, whereas an understanding of dynamics and limits of individual tree transpiration (hereafter referred to as water-use) provide concepts transferable to PSFs and DFs in other areas. Therefore, the aim of this research was to determine daily tree water-use in a PSF and a nearby DF, to understand the water-use dynamics in response to seasonal changes with additional measurements of soil water fluctuations within each forest type.

3.2.1 Study area

The study area (Fig. 3.1) was located in the Eastern Shores area of the iSimangaliso Wetland Park, which was declared South Africa's first UNESCO World Heritage Site in 1999 (Taylor et al., 2006). It lies adjacent to Lake St. Lucia and within the St Lucia Ramsar Site designated in 1986 (Taylor, 1991). It is a premier tourist destination contributing to the economy of the surrounding communities and the town of St Lucia (Whitfield and Taylor, 2009).

The iSimangaliso Wetland Park has a subtropical climate and lies in a summer rainfall area (Schulze et al., 2008). There is a steep rainfall gradient from east to west and at the coastline the mean annual precipitation exceeds 1200 mm yr-1 but drops to only 900 mm yr-1 10 km to the west at Fanies Island (Taylor et al., 2006). Taylor et al. (2006) further reported that the temporal variability of the rainfall gives rise to severe wet and dry periods in Maputaland and during this study there was a well reported drought in the region.

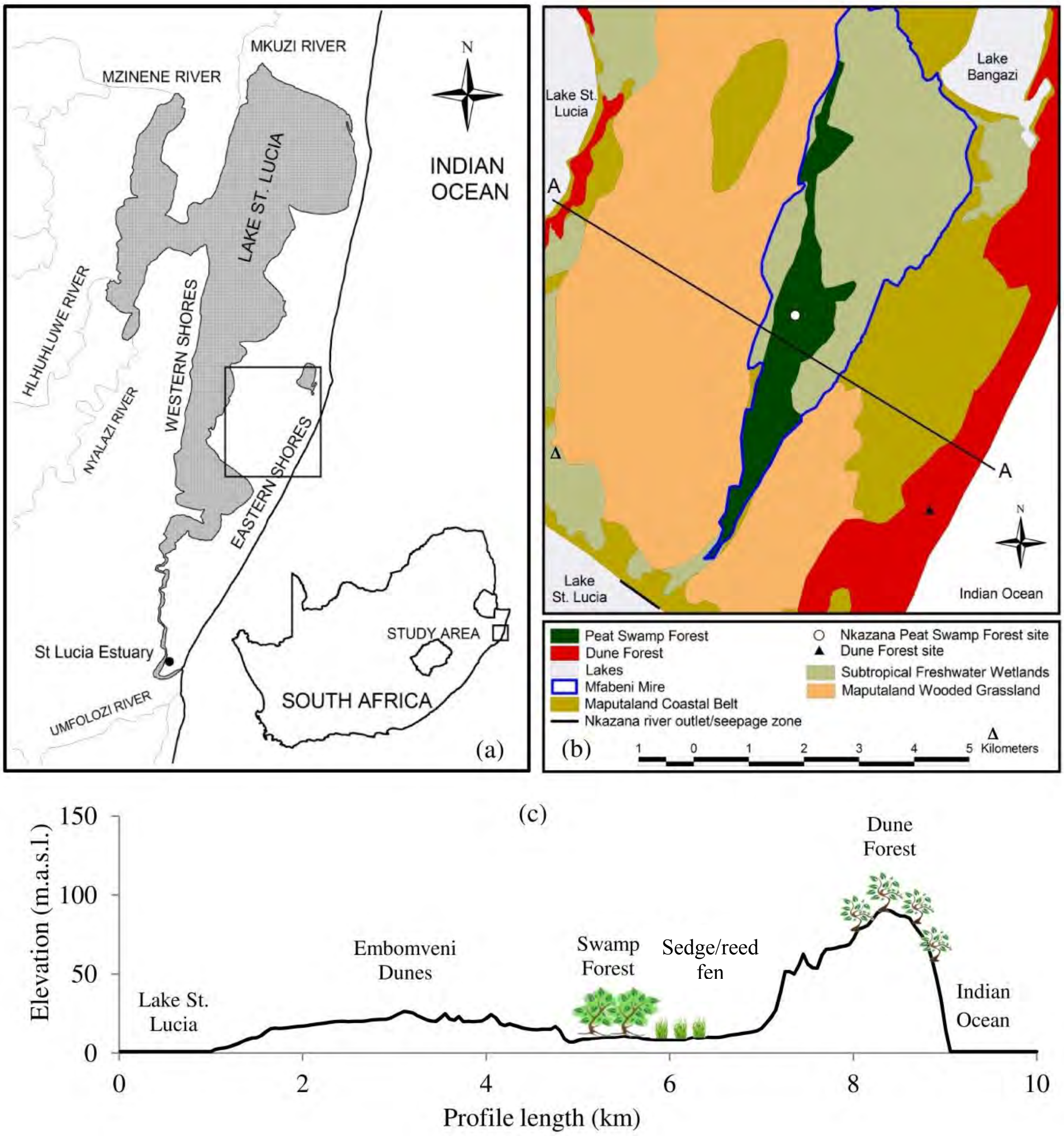

Figure 3.1 (a) Location of Lake St. Lucia and research area in South Africa, (b) the Nkazana Peat Swamp Forest site and the Dune Forest site with the distribution of the vegetation on the Eastern Shores and (c) a cross-sectional profile of transect A-A in Fig. 1b derived from 50 m digital elevation model.

The Eastern Shores area is flanked by Lake St. Lucia to the west and the Indian Ocean to the east (Fig. 3.1b). The coastal dunes, where the DF site is situated, are among the tallest forested coastal sand dunes in the world (Pooley, 2003); to the west the lower, undulating Embomveni Dunes border Lake St Lucia. An ancient interdunal drainage line that forms the Mfabeni Mire lies between these two dune areas (Fig. 3.1c). The Mfabeni Mire is drained by the perennial Nkazana Stream which flows freshwater into Lake St. Lucia and is an important source during droughts (Vrdoljak and Hart, 2007). Organic matter and sediment at times has accumulated in the Mfabeni Mire over the past 45 000 years, forming one of South Africa's largest peatlands and one of the oldest active peatlands in the world (Grundling et al., 1998). The Mfabeni Mire is approximately 8 km long (north-south direction) and 4 km at its widest point (east-west direction). The Nkazana PSF forms part of the Mfabeni Mire and runs down the western side of the Mire (Fig. 3.1b). The Nkazana PSF and the DF fall within the Indian Ocean Coastal Belt Biome, described as being a mixed, seasonal grassland community (Mucina and Rutherford, 2006). The former is further classified by von Maltitz et al., (2003) and Mucina and Rutherford (2006) as an Azonal Forest (AII: Swamp Forest) and the latter a Northern Coastal Forest (VII1: KwaZulu-Natal Coastal Forest).

3.2.2 Study sites

The Nkazana PSF site (28º 10.176' S, 32º 30.070' E) lies on the western boundary of the Mfabeni Mire and runs in a north-south direction for approximately 7 km. A detailed vegetation survey of the PSF has been described by Venter (2003). Wessels (1997) classified the swamp forests of the area into three logical subgroupings based on dominant species, stand density and basal areas. The *Syzygium cordatum* subgroup is characterised by an irregular, broken canopy of predominantly *Syzygium cordatum* trees (known locally as the Water Berry) of up to 30 m, emerging above an intermediate canopy of approximately 6-15 m. The Nkazana PSF site posed several challenges due to general inaccessibility as well as the dense *Nephrolepis biserrata* fern that covers the forest floor to a height of 2.5 m and the *Stenochlaena tenuifolia* (Blechnaceae) fern that festoons the tree stems. The ground at the PSF site was wet and soft with a 0.3 m layer of peat over sand. However, the peat is over 2 m thick in places within the Nkazana PSF (hereafter referred to as PSF only). The two trees instrumented for monitoring sapflow were located within this widely spread *Syzygium cordatum* subgroup of the PSF at its broadest point (approximately 1 km) to minimise edge effects. An overstory tree (*Syzygium cordatum*) and a mid-canopy tree (*Shirakiopsis elliptica*) were instrumented. *Syzygium cordatum* is the most common swamp forest tree across Maputaland, likely due to its fire and hydroperiod tolerance (Wessels, 1997). Other tree species found in the immediate vicinity of the monitored trees included: *Macaranga capensis*, *Bridelia micrantha*, *Tarenna pavettoides* and *Stenochlaena tenuifoli*. The leaf area index (LAI) beneath the ferns and trees was approximately 7.2 and below the trees approximately 3.3 (suggesting a near closed canopy) throughout the year (Fig. 3.2). The depth to water table was < 1.0 m and the trees had permanent access to groundwater.

The coastal dunes are flanked to the east by the Indian Ocean and to the west by the Mfabeni Mire. The dunes rise steeply from the beach to an elevation of up to 80 m.a.s.l and drop-off gradually to the Mfabeni Mire to the West (Fig. 3.1c). The vegetation is mainly a mixed species DF with isolated areas of grassland. The DF site (28º 12.017'S, 32º 31.633'E) has a rich diversity of tree species. Three different tree species (*Drypetes natalensis*, *Eugenia natalitia* and *Mimusops caffra*) were instrumented for monitoring of sapflow. These trees were selected because they are common DF trees representative of the coastal dune forests of Maputaland and due to their proximity to each other, which was a limitation of the sapflow system installed. They also represented different height categories within the DF with the *Drypetes natalensis* being the shortest and therefore mainly shaded within the canopy (understory), the *Eugenia natalitia* partly shaded (mid-canopy), and the *Mimusops caffra* emergent or fully exposed to solar irradiance (overstorey). Other dominant tree species found around those instrumented include *Strychnos gerrardii*, *Garcinia livingstonei*, and *Casearia gladiiformis*. The LAI was between 2.3 in winter and 4.3 in summer (Fig. 3.2). The DF soils are well drained and the tree roots did not have access to the water table.

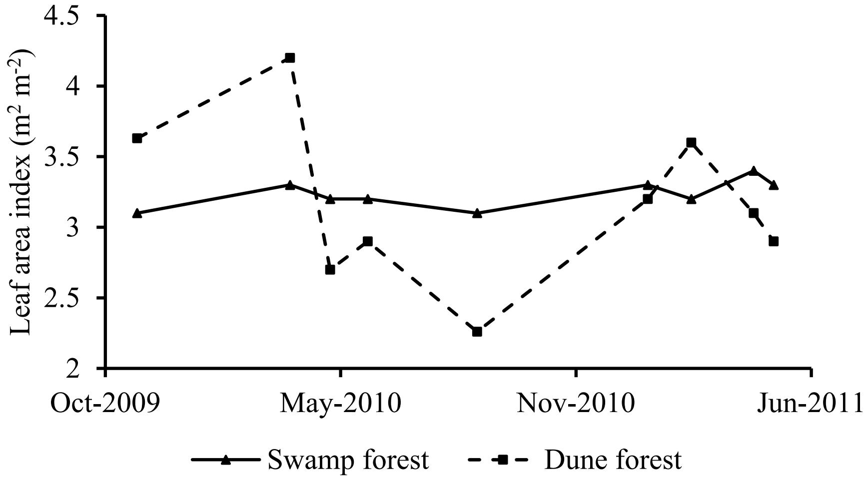

Figure 3.2 Leaf area index measured at the Swamp Forest (above the ferns) and Dune Forest sites.

3.3 Methodology

An automatic weather station provided climatic data from the nearby (3 km from the PSF site, 5 km from the DF site) Mfabeni Mire where rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA), air temperature (HMP45C, Vaisala Inc., Helsinki, Finland), relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp & Zonen, Delft, The Netherlands) wind speed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA) were measured. The raingauge was mounted so that the orifice was at a height of 1.2 m above the ground and the remaining sensors 2 m above ground level. Vapour pressure deficit (VPD) was calculated from the air temperature and relative humidity according to Savage et al. (1997). The climatic data were averaged over 30-minute intervals from observations made every 10 s and stored on a data logger (CR1000, Campbell Scientific Inc., Logan, Utah, USA). The FAO-56 grass reference evaporation (ET_r) was calculated from the climatic data according to Allen et al. (2006) at an hourly interval and summed to a daily level.

A Heat Pulse Velocity system (HPV) using the heat ratio method as described by Burgess et al. (2001), was used to estimate sapflow at various depths across the sapwood of selected trees over 20 months from September 2009 to early May 2011. The site for measurement in each forest was selected based on trees that were representative in terms of species, size, canopy height as well as proximity to each other due to cable length limitations of the HPV system. Tree species instrumented at each site are representative of either PSF's or DF's in Maputaland (Boon, 2010). An assessment of bark and cambium depth were made and suitable insertion depths (Table 3.1) selected for optimal measurement within the sapwood of the trees using an increment borer and Methyl Orange. A line-heater probe, (8 cm long and of 0.18 cm outside-diameter stainless steel tubing) enclosed a constantan filament that, when powered from a 100 Ah, deep cycle battery for 0.5 s provided a heat source. A pair of thermocouple (TC) probes (consisting of type T copper-constantan thermocouples embedded in 0.2 cm outside-diameter PTFE tubing) was used to measure temperatures 0.5 cm upstream and downstream of the heater probe. Hourly measurements (CR1000, Campbell Scientific Inc., Logan, Utah, USA) were recorded from 4 September 2009 to 4 May 2011. Up to 24 TC's were multiplexed (AM16/32, Campbell Scientific Inc., Logan, Utah, USA) allowing 12 measurements at various sapwood depths and across tree species. The number of trees monitored was limited due to equipment costs but a full sapflow system allowing 12 measurement pairs was available for each forest type. At the DF the tree stem diameters were all < 0.17 m and four TC pairs in each tree was suitable to measure sapflow at different depths across the sapwood. However, at the PSF, the *Syzigium cordatum* stem diameter was 0.43 m and sapflow was measured at four depths across the sapwood on the eastern side of the stem and at four depths across the sapwood on the western side of the stem in case of differences in the thick stem of the tree. The remaining four pairs were installed in a nearby mid-canopy tree (*Shirakiopsis elliptica*) which has a smaller stem diameter (0.081 m).

The automated hourly measurement sequence began by measuring each thermocouple 10 times to provide an accurate initial temperature. Following the release of a pulse of heat, the downstream and upstream temperatures were measured 60 times between 60 and 100s (Burgess et al., 2001). The heat pulse velocity (V_h) was calculated from:

$$V_h = \frac{k}{x} ln\left(\frac{v_1}{v_2}\right) 3600 \quad (3.1)$$

where, k is the thermal diffusivity of green (fresh) wood, x is the distance (0.5 cm) between the heater and either upstream or downstream thermocouple, and v_1 and v_2 are increases in the downstream and upstream temperatures (from initial average temperatures) respectively, x cm from the heater. A thermal diffusivity (k) of 2.5×10^{-3} cm^2 s^{-1} (Marshall 1958) was used.

Table 3.1 Tree sizes and probe measurement depths

Nkazana Peat Swamp Forest site	Overbark diameter (m)	Bark (m)	Sapwood depth (m)	Probe depths below outer bark surface (m)	Tree height (m)
Syzygium cordatum	0.430	0.008	0.055	1=0.020, 2=0.035, 3=0.040, 4=0.060 5=0.020, 6=0.035, 7=0.040, 8=0.060	22.5
Shirakiopsis elliptica	0.081	0.003	0.033	1=0.006, 2=0.012, 3=0.020, 4=0.030	6.8
Dune Forest site					
Drypetes natalensis	0.069	0.002	0.030	1=0.005, 2=0.010, 3=0.015, 4=0.025	4.5
Eugenia natalitia	0.132	0.002	0.047	1=0.010, 2=0.020, 3=0.030, 4=0.045	7.5
Mimusops caffra	0.161	0.005	0.060	1=0.010, 2=0.020, 3=0.030, 4=0.045	7.2

Probes were inserted into trees with single stems and at a height of between 0.5 m and 1.4 m above the ground and below any branches. A drill guide was strapped firmly to the stem to ensure that holes were drilled with the correct spacing and parallel alignment. However, slight misalignment was assessed by checking for inconsistencies in the zero flux values. This was done by examining periods during which zero sap flow ($V_h = 0$) was most likely to occur - such as pre-dawn, rainfall periods, high relative humidity and low soil moisture periods. The V_h values at these times may subsequently be adjusted to zero, and the average of these adjustments provided the offset value applied to the whole data set. For all probe pairs, the offset was < 5% of the midday sapflow rates.

Wounding or non-functional xylem around the TC's (Table 3.2) was accounted for using wound correction coefficients described by Swanson and Whitfield (1981). Sap velocities were then calculated by accounting for wood density and sapwood moisture content (Table 3.2) as described by (Marshall, 1958). Finally, sap velocities were converted to tree water-use or sap flow (L hr^{-1}) by calculating the sum of the products of sap velocity and cross-sectional area for individual tree stem annuli (determined by below-bark individual probe insertion depths and sapwood depth). In this way, point measurements of sap velocity were weighted according to the amount of conducting sapwood they represent in the annulus.

Table 3.2 Tree specific data required for calculation of sap flow

Peat Swamp Forest site	**Wood density (m^3 kg^{-1})**	**Moisture fraction**	**Average wounding (mm)**
Syzygium cordatum	0.56	0.83	3.4
Shirakiopsis elliptica	0.53	0.73	3.7
Dune Forest site			
Drypetes natalensis	0.54	0.89	3.2
Eugenia natalitia	0.73	0.47	3.2
Mimusops caffra	0.61	0.71	3.0

Stem diameters were monitored at the probe installation height of the tree trunk at monthly intervals to determine sapwood area. A corer was used to determine the interfaces between the bark, sapwood and heartwood (Table 3.1). These were distinguished by colour, wood hardness and in some cases Methyl Orange was used to identify tyloses (Blanche et al., 1984). Tree height was also measured monthly using a tree height rod at the DF and hypsometer (VL402, Haglöf, Sweden) at the PSF. The LAI was measured (LAI 2200, LI-COR Inc., Lincoln, Nebraska, USA) at monthly intervals at both sites. The measurement sequence of an above canopy, four below canopy and an above canopy reading were performed at each site in triplicate. However, due to the dense ferns at the PSF, the LAI of the ferns and trees was measured separately to the LAI of only the trees by measuring above the ferns.

Soil profile water content at both sites was measured (CR1000, Campbell Scientific Inc., Logan, Utah, USA) every hour to be in sync with the sapflow measurements. A time domain reflectometry system (TDR100, Campbell Scientific Inc., Logan, Utah, USA) with multiplexer (SDMX50, Campbell Scientific Inc., Logan, Utah, USA) and probes with three waveguides (CS605, Campbell Scientific Inc., Logan, Utah, USA) were installed at depths of 0.025 m, 0.075 m, 0.125 m, 0.250 m, 0.500 m and 1.000 m. The determination of volumetric water content by time domain reflectometry (TDR) has been well established by Topp et al. (1980) and Ledieu et al. (1986). The linear Ledieu conversion coefficients were used to convert the apparent probe length (measured by the TDR100) over the real probe length (known) to volumetric water content. Probe cable lengths were kept to a minimum to avoid distortion of the waveform caused by cable (RG58) impedance. The soils do not have high electro-conductivities which can cause signal attenuation due to ionic conduction and were therefore suitable for measurement with TDR methodology.

At the DF site, soil water potential sensors (Model 253, Irrometer Company, Riverside, California, USA) were installed with the CS605 sensors. The data was also recorded hourly using the same logger described above but a multiplexer (Am16/32, Campbell Scientific Inc., Logan, Utah, USA) was used to extend the number of measurement channels. These sensors were included at the DF due to the dry nature of the soils and a hypothesis that water was likely to be a limiting factor at this site. The soil water potential against which the trees extract water was therefore of interest at the drier site. At the PSF site, the water table was close to the surface (0.5 – 1.0 m) and it was unlikely that water would be a limiting factor and therefore water potentials would be permanently low.

The watermark sensors used to measure water potential at the DF site have a range of 0 to 125 kPa beyond which the linear calibration has not been verified (Thompson and Armstrong, 1987). Unfortunately, the conditions at the DF were drier than expected and frequently out of this range. Therefore, the water retention characteristics of the soils were determined for the PSF and DF sites using undisturbed cores analysed in the laboratory at pressures between 0 and

-1500 kPa following the methods and procedures of Klute and Dirksen (1986). Particle size distribution was also determined in the laboratory using the methods described by Gee and Bauder (1986).

The groundwater level (Solinst levelogger 3001, Ontario, Canada) at the PSF was measured at hourly intervals to coincide with the sapflow measurements. A perforated PVC access tube, lined with a geotextile was installed at the site for the monitoring of groundwater levels to approximately 1.8 m. The DF groundwater level was measured (Solinst levelogger, Ontario, Canada) approximately 3 km to the north (28˚10.407′ S 32˚32.115′ E) near the top of the dunes, also at hourly intervals in a steel cased borehole.

Soil samples were collected (approximately 2 kg per sample) for the determination of root distribution at each site using an Eijkelkamp Edelman Extendible Auger for sand. Samples were collected from three different locations around the sites from soil pits. The samples were oven dried (105˚C) and weighed. The roots were separated from the soil with a 0.002 m sieve, oven dried and weighed again to determine the mass of roots per mass of dry soil. All root sizes were included in the measurement, which at the PSF included tree and fern roots. At the DF, only trees were present as there was very little undergrowth around the measurement site.

3.4 Results

3.4.1 Weather conditions during the study period

The annual precipitation measured over the 2009-2010 hydrological year (October 2009 to September 2010) was 650 mm, well below the long-term average of 1200 mm yr^{-1}. The summer rainfall over the 2009-2010 period was particularly low (424 mm), contributing to the dry conditions. The 2010 winter rainfall was characteristically low but was augmented by frontal conditions in July and August providing 30 and 34 mm $month^{-1}$ of rainfall, respectively (Fig. 3.3a). The summer rains of 2010-2011 improved (735 mm) and were evident from October onwards, with December and January experiencing 191 and 202 mm $month^{-1}$, respectively, compared with 84 and 85 mm $month^{-1}$ in the previous year (Fig. 3.3a). The long-term summer average at the nearby South African Weather Services station (0339756W) was 738 mm (Kunz, 2004; Lynch, 2004) showing that the 2009-2010 summer was drier and the 2010-2011 summer close to the long-term summer average rainfall.

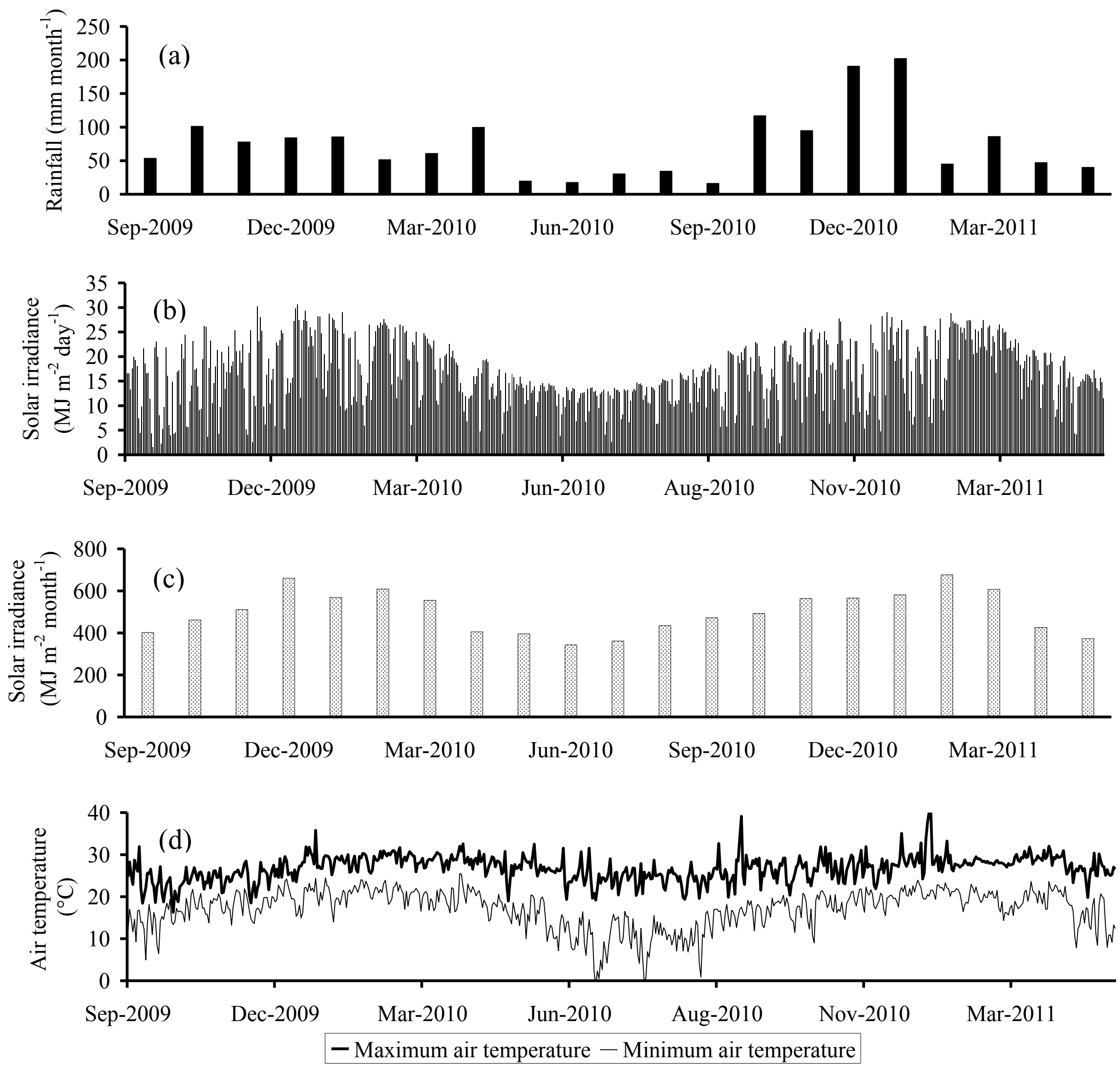

Figure 3.3 The (a) monthly rainfall, (b) daily solar radiant density, (c) monthly solar radiant density, and (d) daily maximum and minimum air temperatures at the Mfabeni Mire

Daily solar radiant density was seasonal, peaking at 30 MJ m^{-2} in summer and 12 MJ m^{-2} in winter on clear days (Fig. 3.3b). The daily solar radiant density was more variable in summer due to cloud cover, which was particularly prevalent during the mornings until 11:00 a.m. local time. This cloud cover effect during summer is clear from the differences in the year on year monthly solar radiant densities (Fig. 3.3c). During the summer of 2009-2010, December (661 MJ) had the highest solar radiant density whereas in 2010-2011 February (676 MJ) had the highest. This variability in cloud cover, which is able to influence monthly solar radiation totals in summer, is important to note as tree sapflow response to energy is well documented

(Landsberg and Waring, 1997; Meiresonne et al.,1999; Granier et al., 2001; Williams et al., 2001; Wullschleger et al., 2001; Meinzer et al., 2004).

The warm Mozambique Current from the north exerts a warming influence on the coastal areas. Temperatures are warm to hot in summer with maximums frequently above 30 °C (Fig. 3.3d). Winter months are mild to warm and maximum temperatures were generally around 25 °C. The average daily minimum temperatures were around 20 °C in summer and rarely below 5 °C in winter, although on 17 June 2010 the temperature dropped to -1.2˚C indicating frost conditions, which are considered extremely rare in the area (Meadows, 1985).

The humid and subtropical coastal conditions over the period of measurement are best described by the average daytime (R_n>0) VPD of 0.80 kPa (Fig. 3.4), which is low, indicating a low atmospheric evaporative demand generally. The monthly average VPD was lowest in October and highest in February during both 2010 and 2011. The daytime standard deviations were mostly below 0.30 kPa except in September when the standard deviation of the VPD was >0.38 during both 2010 and 2011.

The wind in the research area was seasonal with the highest monthly average wind speeds experienced in October to December and the lower wind speeds in winter (April to July). The dominant wind direction was north-easterly (onshore) in summer and with southerly winds during cold frontal conditions in winter (not shown).The average daytime (R_n>0) windspeed was 3.9 m s^{-1} over the measurement period (Fig. 3.4). The highest monthly average was measured in October (5.4 m s^{-1}) and the lowest in May (3.2 m s^{-1}).

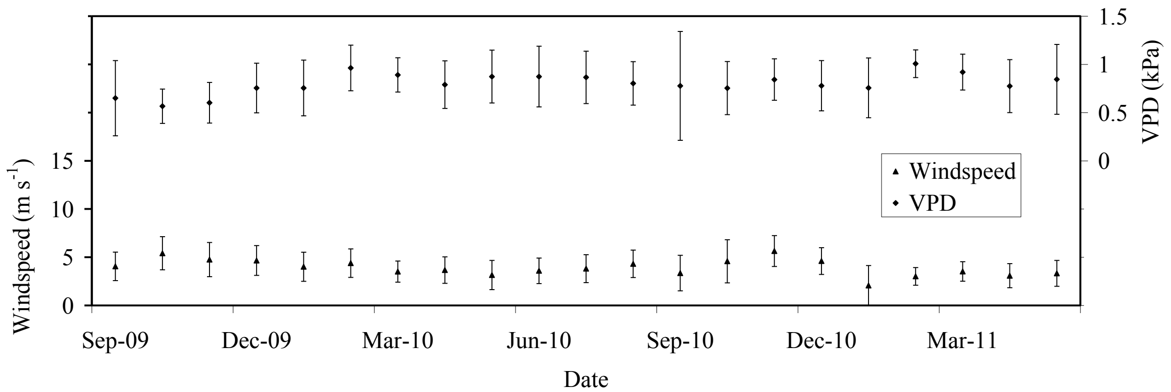

Figure 3.4 Monthly average vapour pressure deficit and windspeed with standard deviation error bars measured at the Mfabeni Mire during daylight hours

3.4.2 Soil profile and water content

A surface organic horizon (peat) at the PSF site was approximately 0.3 m deep and the roots were concentrated in this horizon (Table 3). There was a sharp transition below the organic horizon to a coarse (11%), medium (36%) and fine (42%) sand profile (by mass - the remainder being silt and clay) that contained less root material but with some roots extending below 1 m. The volumetric water content (θ) was generally high at the PSF site. The incremental measurements down the profile (data not shown) indicated that the profile was drier near the surface (15 to 20%) and wetter at depth (40 to 50 %). At 0.5 m, θ only responded to rainfall events over 15 mm (over a few h) while at 1.0 m, θ remained unchanged between September 2009 and August 2010, when the water table was above the soil water measurement probe. From the beginning of September 2010 to mid-October 2010, θ dropped 17% from 39% to 22% indicating that the water table had moved below the probe at 1 m. Following spring rains (117 mm in October 2010), θ increased first rapidly and later more slowly for the remainder of the measurement period to levels (38%) close to previous values (39%). After rainfall, the surface drained rapidly indicating low water retention, characteristic of sandy soils. The total soil profile volumetric water content (θ_{PT}) at the PSF site fluctuated between 30% and 42 % over the 1.5 m depth profile (Fig. 3.5). Despite the differences in the PSF site water retention characteristic down the soil profile (Fig. 3.6a), it was clear that the -1500 kPa wilting points (10% at 0.8 m, and 30% at 0.4 m) were both below the driest limits reached in θ_{PT} (30%). This indicated that soil water was not a limit to tree water-use, particularly considering that the water table level was generally between 0.5 m and 1.0 m. Rainfall interception was likely to have been relatively high (due to the high LAI) but was unlikely to have been an important process in terms of limiting water-use as the vegetation had constant access to water at this site.

Table 3.3 Dry root mass per unit volume of soil along a 1.0 m soil profile at the Peat Swamp Forest and Dune Forest sites

Depth (m)	Dune Forest site ($g\ m^{-3}$)	Peat Swamp Forest site ($g\ m^{-3}$)
0.005	18.7	7.5
0.250	2.6	1.3
0.500	0.3	1.2
1.000	0.1	0.6

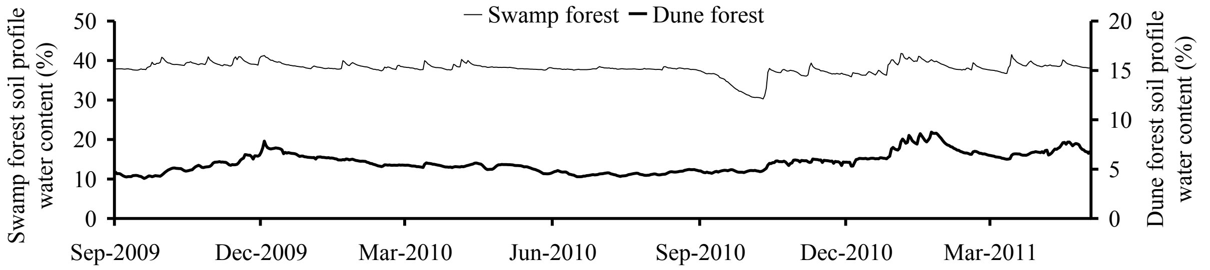

Figure 3.5 Total volumetric water content in the upper 1.5 m of the soil profile at the Dune Forest and Peat Swamp Forest sites

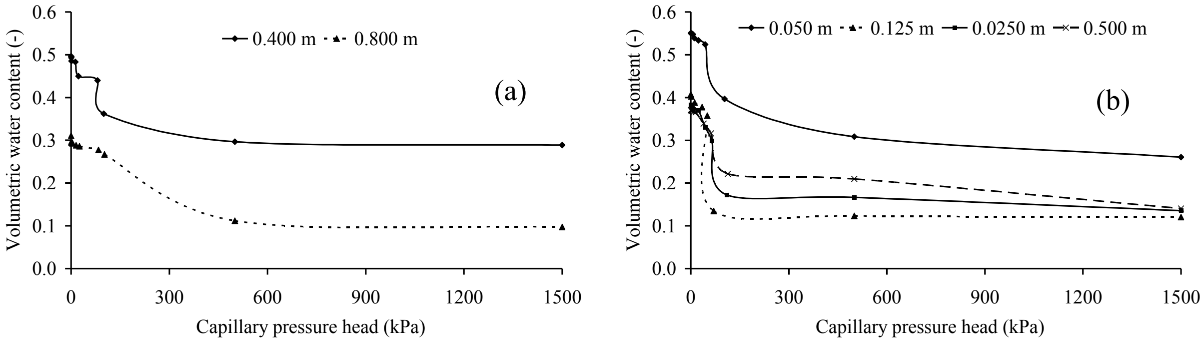

Figure 3.6 Water retention characteristics of the (a) Peat Swamp Forest and (b) Dune Forest sites

At the DF site, there was a high root density near the surface (Table 3.3) that decreased (8% to 1% root mass per soil mass) from 0.1 m to 0.2 m. The surface sands were water repellant as determined by the Water Drop Penetration Time test, as described by Dekker et al. (2001). The soil texture did not change down the profile and was mainly medium (46%) and fine (45%) sands (0 to 0.350 m). Rainfall interception was likely to have been an important process at the DF as only rainfall events (over a few h) >10 mm (or rainfall on consecutive days) affected the upper soil water profile (0 to 0.125 m). Smaller rainfall events (<4 mm) during the beginning of December 2009 had no impact on the surface θ. In some cases, rainfall events of approximately 10 mm (over a few h) resulted in small changes in surface θ, yet large changes in soil water potential. For example, from May 2010 to July 2010, θ at 0.075 m decreased from 8% to 7% (data not shown) whereas the measured water potential decreased from -400 kPa to -700 kPa (Fig. 3.7). This was supported by the water retention characteristics, which showed that the sands drained rapidly beyond -400 kPa and that small changes in θ caused large changes in water potential. The θ_{PT} ranged from 5% to 10% but the wilting point (-1500 kPa) of the sands was between 12 and 14% (Fig. 3.6b). The profile, or at least large parts of the profile, were outside the plant available water range (0 to -1500 kPa) for extended periods and water availability was certain to have limited tree water-use of the DF site.

The dry conditions at the DF site were frequently beyond the accurate operating range of the watermark sensors (-125 kPa). However, the data do serve to show the relatively dry conditions in the main rooting area of the profile (0 to 0.125 m). At 0.25 m the soil water potential fluctuated rapidly but the water potential was generally lower (less negative) than at 0.125 m. At 0.5 m and 1.5 m the water potential fluctuated less but there was an increasing trend (more negative) in water potential with depth indicating that the profile became drier with depth beyond 0.25 m.

3.4.3 Tree water-use

At the PSF site, the maximum water-use of the evergreen, overstory tree (*Syzygium cordatum*) ranged from approximately 30 L d^{-1} in winter to 45 L d^{-1} in summer. The total water-use of the measurement period (20 months) was 15800 L and the accumulated water-use line has a constant gradient indicating a relatively constant water-use throughout the year (Fig. 3.8a). Of the two summer seasons observed (October to March 2009-2010 and 2010-2011), the water-use was 16% higher in the first summer (5402 L vs. 4643 L). The first summer was drier with a rainfall of only 424 mm vs. 735 mm in the following year. However, the wetter year was no more cloudy and the difference in total solar irradiance between the two summer seasons was within 4% (3367 MJ vs. 3488 MJ), the average daily VPD was similar (~0.8 kPa) and the total accumulated reference evaporation (ET_r) 583 mm versus 601 mm in 2009-2010 and 2010-2011, respectively. The difference in water-use between the two summer periods therefore remains unexplained based on adequate soil water availability and similar atmospheric demands. The

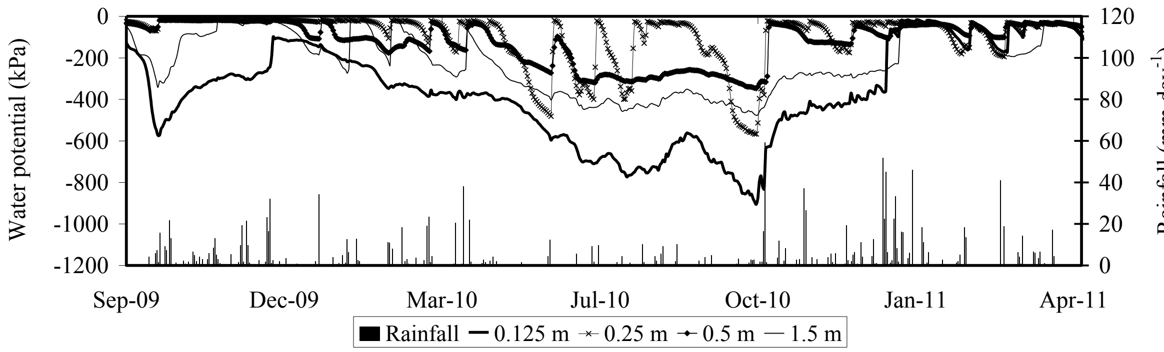

Figure 3.7 Water potential and daily rainfall measured at the Dune Forest site

mid-canopy tree (*Shirakiopsis elliptica*) was a smaller, semi-deciduous tree. The water-use was distinctly seasonal (2 L d^{-1} in winter and 12 L d^{-1} in summer) as shown by the s-shape of the accumulated water-use line which totaled 3500 L over the measurement period (20 months). The shaded mid-canopy tree therefore used about 75% less water than the overstory tree. In contrast to the overstory tree, the mid-canopy tree water-use was 8% higher in the wetter summer of 2010-2011 (1264 L vs. 1361L).

The three evergreen DF trees (Figs 3.8c to 3.8e) exhibited similar seasonal patterns and a regression of sapflow between the mid-canopy and overstory trees (*Eugenia natalitia* versus *Mimusops caffra*) indicated a similar response in sapflow at a daily level (R^2=0.81). The linear relationship between a mid-canopy tree (*Eugenia natalitia*) and the smaller understory tree (*Drypetes natalensis*) was not as good (R^2=0.71) indicating a difference in water-use dynamics due to rooting depth or understory versus overstory light or VPD conditions. The total water-use of the overstory tree *Mimusops caffra* and mid-canopy *Eugenia natalitia* was 10400 L and 6400 L, respectively, while the understory tree water-use was the lowest at 1100 L.

For all three DF trees, summer transpiration was higher than in winter (shown by the s-shaped accumulated water-use in Figs 3.8c to 3.8e, yet within the summer season there was daily variation due to cloud and rain. The daily water-use was highest for the emergent *Mimusops caffra* (5 to 45 L d^{-1}), whereas for the *Eugenia natalitia* and *Drypetes natalensis* daily water-use was lower (2 to 28 L d^{-1} and 1 to 4 L d^{-1}). The summer (October to March) water-use of the emergent *Mimusops caffra* was 3924 L during the drier summer of 2009-2010 and 4057 L in the wetter summer of 2010-2011. The understory *Drypetes natalensis* displayed the same pattern with a lower water-use (362 L) in the drier summer of 2009-2010 and higher water-use (423 L) in the wetter summer of 2010-2011.

The dependence of DF transpiration on soil water availability was clear from the increase in observed transpiration from all three trees (*Mimusops caffra*: 3.8 to 13.7 L d^{-1}, *Eugenia natalitia*: 1.8 to 7.9 L d^{-1} and *Drypetes natalensis*: 0.8 to 2.4 L d^{-1}) between 13 August and 15 September, 2010, following 45 mm of rainfall in the previous few weeks. This corresponded to a positive response in the soil water potential near the surface (0.125 m) from 8 August (Fig. 3.7) from -800 to -550 kPa. Following the increase in transpiration, the upper soil profile water potential increased again rapidly from -550 kPa (at 0.125 m) to drier levels of -900 kPa (Fig.

3.7) with a concomitant decrease in transpiration until the seasonal spring rains arrived in October 2010.

In terms of climatic indicators of sapflow, the linear regressions of sapflow with climatic variables were generally poor. For example, VPD and solar radiation separately accounted for 22% and 47% respectively, of the variation in emergent *Mimusops caffra* sapflow in the DF. At the PSF site, VPD and solar radiation accounted for 42% and 47% respectively, of the variation in the sapflow of the *Syzygium cordatum*.

A split-line regression (also known as continuous two phase regression or breakpoint regression) is used to describe abrupt changes in the relationship between physiological responses and environmental parameters that cannot be described by a single regression equation (Perry, 1982). In Figs 3.9 and 3.10, a split-line regression using Genstat software (VSN International, 2011) was applied to determine whether changes in the ratio (unitless) of tree water-use to FAO-56 reference evaporation (ET_r) were related to θ at a depth of 0.075 ($\theta_{7.5}$); where the highest root concentration existed at both sites. A single significant regression would indicate a constant relationship between tree water-use over ET_r against $\theta_{7.5}$ and would suggest that as ET_r increases (atmospheric demand), tree water-use increases with no limit imposed by $\theta_{7.5}$ or that $\theta_{7.5}$ continuously imposes a constant limit on tree water-use. However, a split line regression would indicate that ET_r over tree water-use is dependent on $\theta_{7.5}$ over a range but reaches a $\theta_{7.5}$ beyond which it is independent - the breakpoint. At the PSF site, there was no indication of a $\theta_{7.5}$ limit imposed on water-use (Figs 3.9a and 3.9b). The $\theta_{7.5}$ was mostly between 36% and 42%, but drier at times, reaching 30%; yet, the ratio of water-use to atmospheric demand remained >5 (Figs 3.9a and 3.9b). However, at the DF site, the split-line regressions (Figs 3.10a to 3.10c) indicated that $\theta_{7.5}$ imposed a severe constraint on tree water-use. On days when the profile water content was below a breakpoint value, there was a concomitant decrease in the ratio of water-use to ET_r indicating a two stage relationship. The understory *Drypetes natalensis* $\theta_{7.5}$ breakpoint was 5.6% while the overstory *Eugenia natalitia* and *Mimusops caffra* were 6.2% and 6.1%, respectively. The soil water was a limit for 53% (*Drypetes natalensis)*, 68% (*Eugenia natalitia)* and 70% (*Mimusops caffra*) of the measurement period.

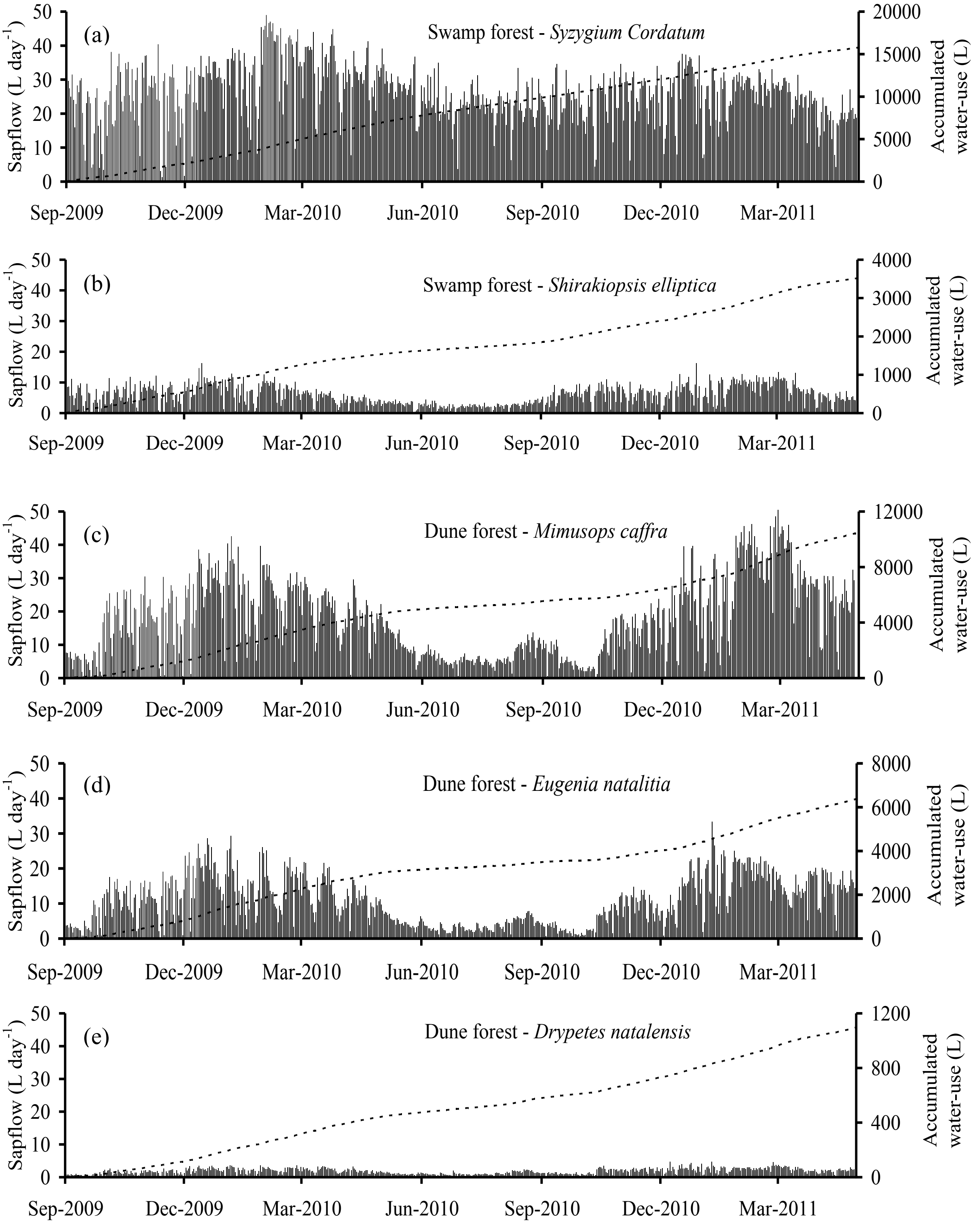

Figure 3.8 Daily water-use (bars) and accumulated water-use (dashed line) over 20 months of the Peat Swamp Forest trees (a) *Syzygium cordatum* (b) *Shirakiopsis elliptica* and Dune Forest trees (c) *Mimusops caffra*, (d) *Eugenia natalitia* and (e) *Drypetes natalensis*

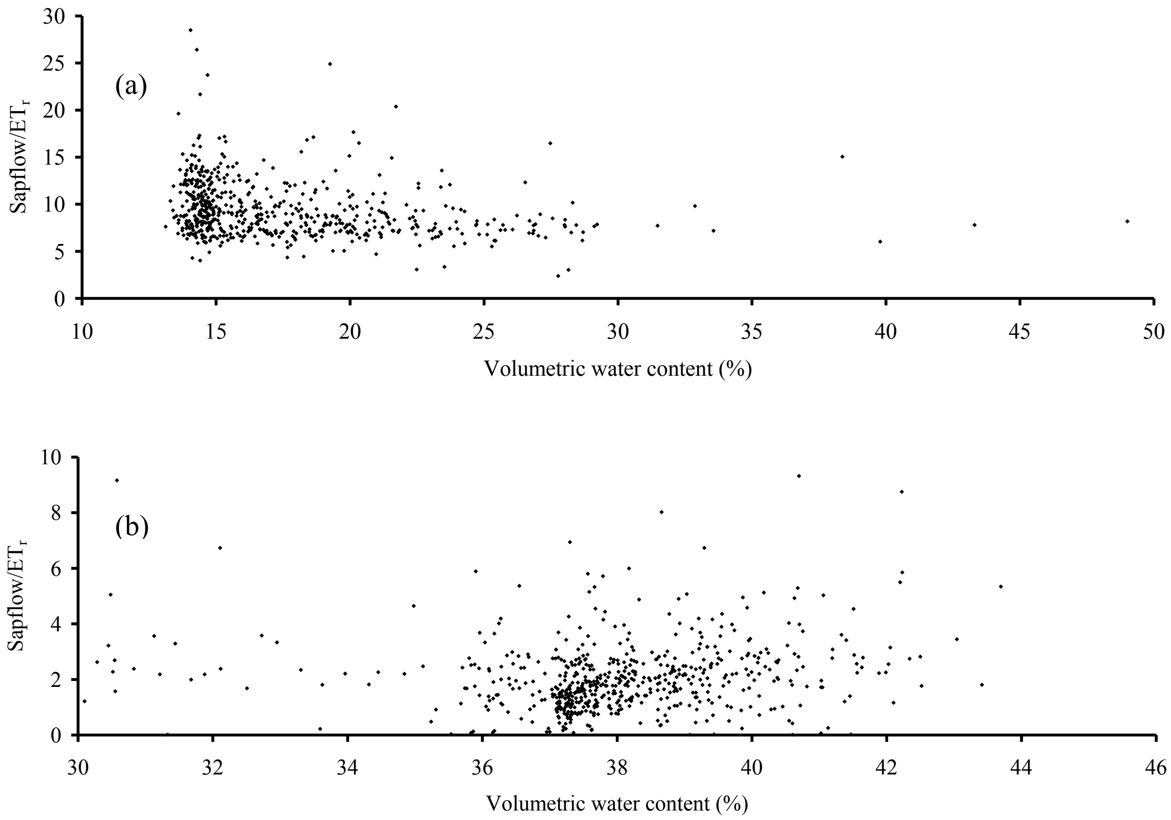

Figure 3.9 The ratio of sapflow to reference evaporation versus the soil water content (0.075 m) at the peat swamp forest site for (a) *Syzygium cordatum* and (b) *Shirakiopsis elliptica*

3.5 Discussion

There are no comparisons of water-use for either forest type in the research literature. In South Africa, the focus of DF research has primarily been rehabilitation following mining, which has been widespread on the east coast of South Africa (van Aarde et al., 1996; Ruiz-Jaen and Mitchell Aide, 2005; Grainger and van Aarde, 2012). Dune forest biodiversity (Wassenaar et al., 2005) as well as water-use and the spread of some dune pioneer species including the shrub *Scaevola plumieri* and exotic grass *Ammophila arenaria* have been studied (Peter, 2000, Peter and Ripley, 2000; Peter et al., 2003; Ripley and Pammenter, 2004).

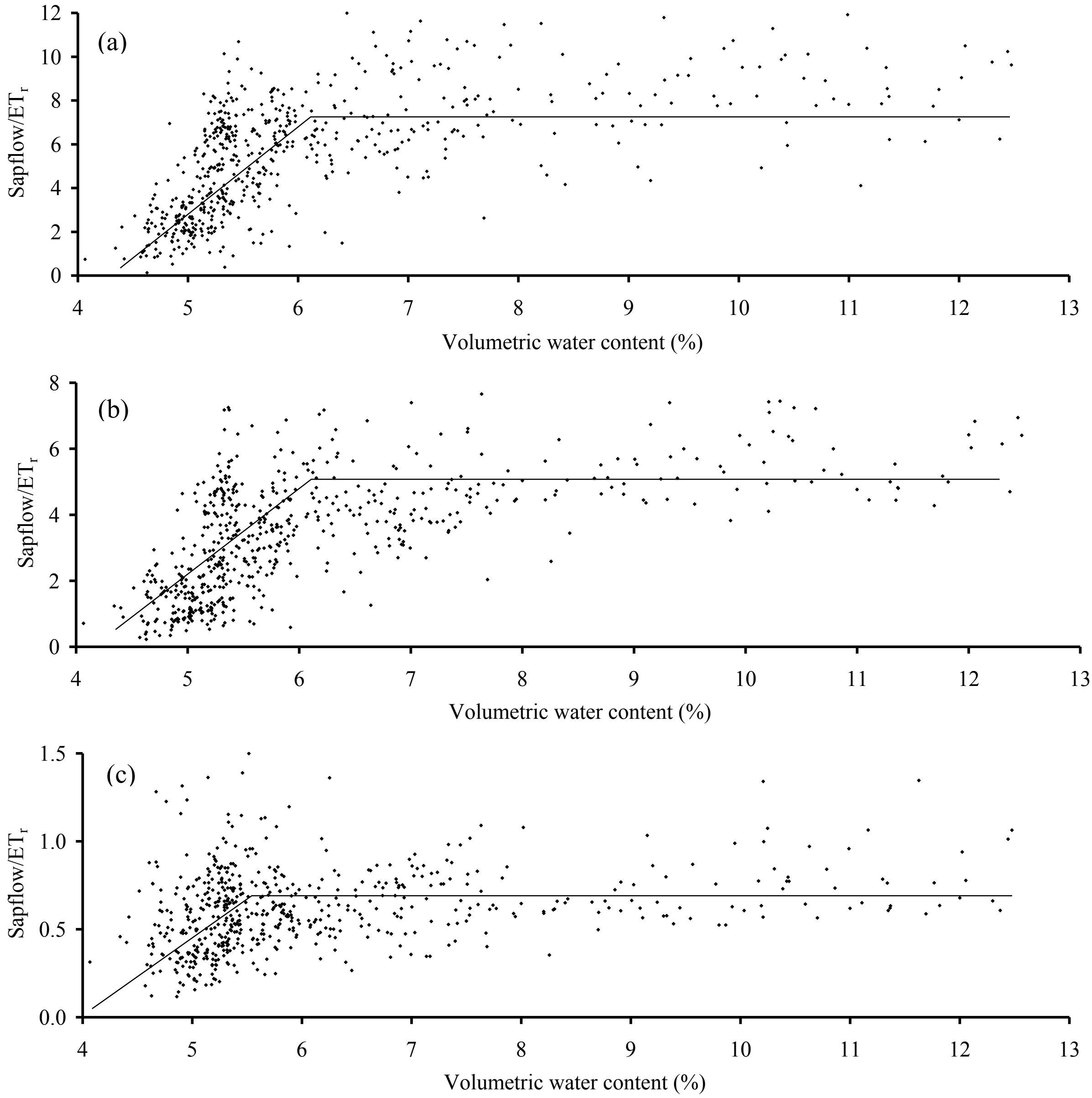

Figure 3.10 The ratio of sapflow to reference evaporation versus soil water content (0.075 m) at the Dune Forest site for (a) *Mimusops caffra*, (b) *Eugenia natalitia* and (c) *Drypetes natalensis* with the solid line representing the split-line regression

Furthermore, PSF research in general is limited internationally. Much of the existing tropical peat swamp forest research stems from South East Asia (Anderson et al., 1983; Rieley and Ahmed-Shah, 1996). Internationally, existing subjects include, amongst others, fires (Page et al., 2002; Grundling and Grobler, 2005), species composition studies (Wessels, 1997; Venter, 2003; Grobler, 2009), carbon flux measurements (Jauhiainen, et al., 2005) and cultivation (Grobler et al., 2004). Oren et al. (1999) provided information on transpiration rates of *Taxodium distichum* trees flooded in an artificial impoundment; however, this swamp Cyprus, found in Carolina in the USA, is deciduous and has needle like leaves that are very different in structure to the PSF trees of Maputaland. Some tropical forest research may be applicable to the PSF's of Maputaland, but in terms of water-use, it would be unreliable to use existing tree water-use data from other countries due to differences in vegetation structure, soil types and weather patterns. These results are therefore unique internationally and will provide the basis for further studies and modeling.

Page et al. (1999) state that tropical peat swamp forest ecosystems have until recently received little attention as they fall between the two disciplines of peatland ecology and forest ecology. However, with the increased awareness of the carbon stored in peatlands and the recognition of their role in the global environmental change process, there has been a renewed interest in peatlands. Yet, despite an understanding of the influence of droughts and water levels on carbon releases from peatlands (Suzuki et al., 1999; Hirano et al., 2007; Wösten at el., 2008), together with impending climate change, there remains little understanding of their vegetative water-use. This research therefore fills an important gap in our understanding of PSFs vegetation. It provides some of the first results of individual tree water-use within a PSF as well as the contrasting water-use from trees in a nearby DF and expands on the differences in the water-use dynamics between the two forest types.

The proximity of the two sites (4 km) and the similar climatic conditions experienced, allowed a comparison of water-use from two types of indigenous forest and showed the importance of landscape position and site-specific conditions such as soil water content profile. From the soil water data, it was clear that the roots of the PSF trees have permanent access to soil water, whereas the DF tree roots only have access to soil water following rainfall that was temporarily stored in the soil profile. Although large rainfall events (>20 mm d^{-1}) recharged the soil profile at depths of up to 1.5 m at the DF site, many rainfall events were <10 mm (over a few h) and only recharged the shallow profile (0 to 0.125 m) where there was a high root density (Table 3.3). Relatively small changes in volumetric water content translated into larger changes in water potential due to the sandy texture of the profile at the DF. For example, from May 2010 to July 2010, a drop in θ of 1% corresponded to a 300 kPa decrease in water potential. However, during relatively small rain events (>4 mm but <10 mm over a few h) the soil water potential increased (less negative) and the tree water-use increased correspondingly, as evidenced between 13 August and 15 September, 2010 (Figs 3.8c to 3.8e). This adaptation of the trees to dune locations allows the trees to survive extended dry periods by opportunistically utilising water coming from the numerous smaller rainfall events that only wet the shallow soil profile.

In the water limited environment of the dune forest, interception was important and it was found that rainfall events <4 mm within a few hours had no impact on the surface θ or water potential if the antecedent conditions were dry. Research by Bulcock and Jewitt (2012) also found that in precipitation events of 4 mm or less, 100% interception commonly occurred in forest interception studies depending on antecedent conditions of the leaf litter and canopy. The variable weather conditions and the type of rainfall experienced have an effect on θ and therefore the water availability and DF water-use.

The complexity of soil water in dune sands was studied by Ritsema and Dekker (1994), who found that the pattern of soil water was irregular in dune sands. Due to a steep relationship between hydraulic conductivity and θ in the dry range, small changes in θ gave rise to large changes in hydraulic conductivity. These differences in hydraulic conductivity together with the water repellency of the surface sands, induced soil water variability and preferential flow paths. Similar processes are likely in the dune sands of Maputaland, which explains some of the irregularities observed in the soil water potential results down the profile, such as the rapid fluctuations at 0.25 m but not above that level in the profile. The relatively large changes in hydraulic conductivity and soil water potential brought about through small changes in θ means that plant water availability changes rapidly. This emphasises the importance of the tree adaption to respond quickly to changes in soil water conditions but also warns of single site measurements to characterise the soil water regime of dunes.

Tree water-use was clearly not limited by soil water availability at the PSF site. The limits to transpiration of the overstory tree were primarily radiation (due to prevailing cloud) and VPD. At the DF however, soil water was found to play a dominant role in limiting water-use (Figs 3.10a-c). Due to the variable climate and well-documented droughts in the area, this limitation was frequently imposed and affected the water-use of all three DF trees. Existing evaporation models such as the Priestley-Taylor and Penman-Monteith that are meteorologically driven with moderating functions built on physiological controls may provide good results for the estimation of PSF water-use, but are not suitable in applications such as the DF. At the DF, supply was critical and detailed meteorological measurement and calculation of atmospheric demand are likely to be largely irrelevant for a large proportion of the time. Calder

(1998) suggested that evaporation could be interpreted in terms of six types of controls and limits on the evaporation process depending on climate, namely: advection, solar radiation, raindrop size (influences interception evaporation), soil water, tree size and physiology. The PSF and DF sites are however, only 4 km apart and rather than separating the controls based on climatic areas in the Eastern Shores, it would be most appropriate to consider landscape position. The work by Calder (1998) was an important conceptual step towards understanding limits and constraints to evaporation but was limited to homogenous vegetation stands and does not explain the complexity and heterogeneity of indigenous vegetation types and different landscape positions.

The seasonal water-use at the DF site was dependent on the rainfall, which in turn created a limit, imposed on water-use by soil water availability. It is logical that the tree water-use at the DF site was therefore higher during the wetter summer of 2010-2011, when more soil water was available. However, at the PSF site, the summer water-use of the overstory tree was higher during the drier summer (2009-2010) by 16%. It was shown that soil water did not limit the tree water-use and it therefore seems a reasonable result if climatic parameters supported a higher transpiration. However, this was not supported by the solar radiation, VPD or atmospheric demand (ET_r) which indicated little difference in the year on year results.

Modelling water-use using a two stage model is a concept understood by scientists in the past. Richie (1972) used a two stage model to estimate soil evaporation, differentiating between an energy limited constant stage and a second stage where the soil evaporation is limited by the hydraulic properties of the soil. Federer (1979) found that simple functions of volumetric water content could be used to determine the reductions in tree water-use due to a soil water limitation. More recently this has been included in the FAO-56 reference evaporation and crop co-efficient model as a soil evaporation reduction coefficient and to the reduction in crop transpiration as a water stress coefficient. The water-use and soil water results for the DF site indicated that this type of two stage model, for growth or water-use, would have been applicable up to 70% of the time (for the *Mimusops caffra*) over the measurement period. However, the FAO-56 reference evaporation model has been developed for uniform canopies shorter than the DF and PSF canopies. Forest canopy water-use has in the past been modelled using the Penman-Monteith formula together with a stomatal resistance model (Grip et al., 1989; Dolman et al., 1991). Results over longer periods (annual) have been reasonable but poor over shorter periods (less than a day). Roberts et al. (1993) used a multi-layer approach to solve the Penman-Monteith formula and measure canopy conductance at five canopy levels in an Amazonian forest. A simplification of the model using average values for the canopy were compared to measured transpiration and resulted in over-estimates of up to 50%.

Peat swamp forests and dune forests are under extreme pressure in South Africa (Grundling, 1998). Mining, agriculture, population expansion and poverty are amongst the major threats and to their existence. Peat swamp forests in particular, are targeted by informal community gardens due to fertile soils and water availability. Grundling and Grobler (2005) estimated that 60% to 80% of PSF's include crop species such as *Musa paradisiaca* (bananas), *Colocasia esculenta* (madumbes, also known as taros) and *Ipomoea batatas* (sweet potatoes). Governments are struggling to prioritise the flow of funding for the protection of these ecosystems (James et al., 2001). However, water neutral and water offset strategies are amongst the ideas and concepts to emerge that will sustainably provide finance for the protection of these critical ecosystems (Hoekstra, 2008). However, it is necessary to understand and quantify the water-use of these indigenous ecosystems so that these offset strategies can be implemented. The water-use of PSF and DF trees has until now been poorly understood and received little attention internationally. These results will therefore provide useful baseline information for further measurement and modelling studies.

3.6 Conclusions and future research

The two sites were in contrasting landscape positions but, due to their proximity, under similar climatic conditions. However, different limiting factors existed at the two sites, controlling water-use at times. The soil water limitation at the DF site was clearly shown to reduce transpiration at the DF and not at the PSF, however, linear regression with climatic variables did not produce a good correlation at either site. Regression modelling of water-use against multiple climatic variables and the soil water limits derived in this research forms the focus of a follow-up research paper. This will provide information on the controlling variables of water-use to determine canopy conductance models for the PSF and DF. At the DF for example, when θ is not a limit then understanding the limits imposed by VPD or tree physiology for the overstory or VPD and solar irradiance for the understory trees are the next step towards providing a suitable model that can be used to estimate forest water-use.

Both sites were dominated by shallow-rooted trees. The watertable was close to the surface during the measurements at the PSF site and only briefly went below 1 m at the end of the winter during an extended drought period. It is therefore not necessary for the trees to have deep roots to access water and a concentration of roots near the surface where nutrients are available is more effective. In contrast, the roots of the DF trees, on the 80 m.a.s.l. high dunes, are not able to access the watertable and are therefore concentrated near the surface to optimise the uptake of through fall (Stone and Kalisz, 1991; Laclau et al., 2001). Rainfall events affected the soil water profile measurements at a depth of up to 1.5 m suggesting that groundwater recharge from the DF takes place but it is speculated that only extreme events (1 in 100 years) such as the Demoina floods of 1984 are able to penetrate the deep sands of the dune.

The diversity of the vegetation and irregular spacing of the trees within the forests adds complexity to the possibility of up scaling the individual tree water-use to forest community water-use. It would be necessary to understand the relationships between tree water-use and tree height, stem diameter or canopy area to investigate the reliability of up scaling single tree water use. However this still ignores soil evaporation and undergrowth water-use and in terms of understanding the wider catchment hydrology it would therefore be beneficial to derive the ET of the PSF and DF using eddy covariance or scintillometry where appropriate. Analysis similar to those presented in this research, but with ET in place of individual tree water-use (Figs 3.9 and 3.10), would provide a useful indication of how effectively ET of the PSF and DF could be estimated from simple meteorological and soil water data. These ET results would provide the ET information typically used at catchment scales in hydrological modelling studies.

Within the DF in particular, the results presented were from a site at the dune crest. Water-use may be different on lower slopes where the roots have access to groundwater. In addition, the orientation of the dunes along the coast results in east and west facing aspects. The DF trees facing the sea on the east are exposed to salt spray which may affect the process of transpiration (Sykes and Wilson, 1988; Robinson et al., 1998). According to Pooley (2003), the high winds and salt spray limit growth (and therefore water-use) in the Maputaland DF's. Further research to investigate the occurrence of DF areas that potentially use groundwater on the lower slopes and the influence of slope position on transpiration would be beneficial particularly in terms of up scaling the water-use of the DF from individual tree water-use results.

At the PSF, the dense *Nephrolepis biserrata* fern that covers the forest floor and the *Stenochlaena tenuifolia* (Blechnaceae) fern which grows up the tree stems had a higher leaf area than the tree canopy above, yet there is no information on their water-use dynamics. The ferns remained actively growing throughout the year and an understanding of their water-use, including interception, would be critical to understand fully the long-term water-use of the PSF as a whole.

The ecological and tourist value of the iSimangaliso Wetland Park have been acknowledged. In addition, the anthropogenic impacts were discussed as well as the susceptibility of the area to prolonged dry and wet periods. However, beyond the borders of the Park, the natural vegetation gives way to large areas of commercial forestry (mainly *Eucalyptus*) and sugarcane plantations. In terms of the current legislation in South Africa, forestry is a streamflow reduction activity, whereas sugarcane is not. Quantification of the water-use of these commercial vegetation types is necessary to model the water-balance of the wider catchment and determine more accurately the legislative allowance of streamflow reduction and the resulting impacts on blue and green water in the catchment.

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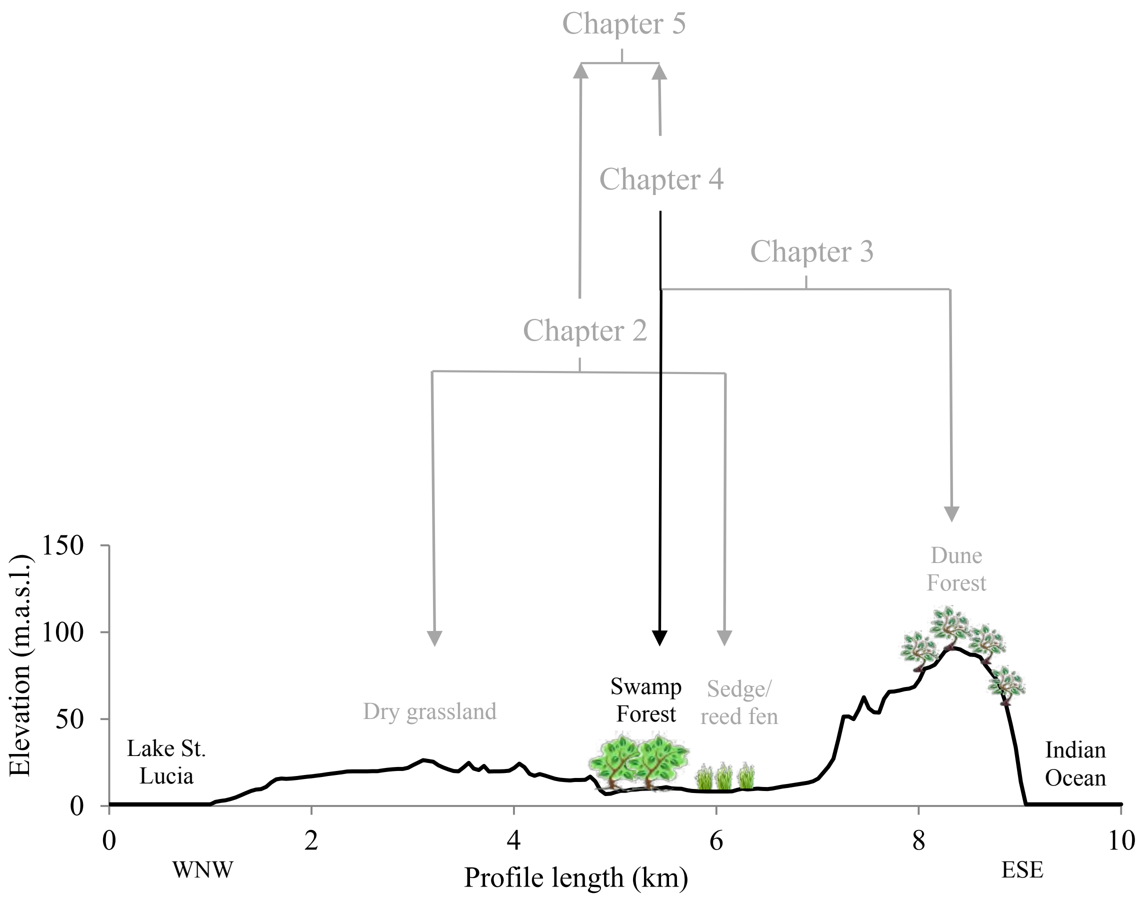
Lead into Chapter 4

Once the water-use dynamics of the forests were captured in Chapter 3, it became imperative for the final water-balance of the Mfabeni Mire, to derive the long-term ET of the swamp forest plant community. However, it was not practical to apply the ideal method (eddy covariance) over a long-term period above the swamp forest, or upscale the sapflow due to the diversity and complexity of the canopy structure. Chapter 4 describes how the long-term ET of the swamp forest was derived using a combination of techniques. Figure 1.1 has been reproduced below but modified to show the plant community investigated in Chapter 4 and the context of the chapter in the thesis.



CHAPTER 4: EXTENDING PERIODIC EDDY COVARIANCE LATENT HEAT FLUXES THROUGH TREE SAPFLOW MEASUREMENTS TO ESTIMATE LONG-TERM TOTAL EVAPORATION IN A PEAT SWAMP FOREST

4.1 Abstract

A combination of measurement and modelling was used to find a pragmatic solution to estimate the annual total evaporation (ET) from the rare and indigenous Nkazana Peat Swamp Forest (PSF) on the east coast of Southern Africa to improve the water-balance estimates within the area. Total evaporation was measured during three window periods (between seven and nine days each) using an eddy covariance (EC) system on a telescopic mast above the forest canopy. Sapflow of an understory and an emergent tree was measured using a low maintenance heat pulse velocity system for an entire hydrological year (Oct 2009 to Sept 2010). An empirical model was derived, describing the relationship between the observed ET of the Nkazana PSF measured during two of the window periods (R^2=0.92 and 0.90) which, overlapped with sapflow measurements, thereby providing hourly estimates of predicted ET of the Nkazana PSF for a year, totalling 1125 mm (while rainfall was 650 mm). In building the empirical model, it was found that including the understory tree sapflow provided no benefit to the model performance. In addition, the observed emergent tree sapflow relationship with observed ET between the two field campaigns was consistent and could be represented by a single empirical model (R^2=0.90; RMSE=0.08 mm).

During the window periods of EC measurement, no single meteorological variable was found to describe the Nkazana PSF ET satisfactorily. However, in terms of evaporation models, the hourly FAO56 Penman-Monteith equation best described the observed ET from EC during the August 2009 (R^2 = 0.75), November 2009 (R^2 = 0.85) and March 2010 (R^2 = 0.76) field campaigns, compared to the Priestley-Taylor model (R^2 = 0.54, 0.74 and 0.62 during the respective field campaigns). From the empirical model of ET and the FAO56 Penman-Monteith equation, a monthly crop factor (K_c) was derived for the Nkazana PSF providing a method of

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estimating long-term swamp forest ET from meteorological data. The monthly crop factor indicated two distinct periods. From February to May, it was between 1.2 and 1.4 compared with June to January, when the crop factor was 0.8 to 1.0. The derived monthly K_c values were verified as accurate (to one significant digit) using historical data measured at the same site, also using EC, from a previous study.

The measurements provided insights into the microclimate within a subtropical peat swamp forest and the contrasting sapflow of emergent and understory trees. They showed that expensive, high maintenance equipment can be used during manageable window periods in conjunction with low maintenance systems, dedicated to individual trees, to derive a model to estimate long-term ET over remote heterogeneous forests. In addition, the contrast in ET and rainfall emphasises the reliance of the Nkazana PSF on groundwater.

Keywords: *Indigenous forest, tree water-use, tree transpiration, evaporation modelling, energy balance closure, crop factor, groundwater dependent*

4.2 Introduction

Severe water scarcity in parts of South Africa has threatened the health of internationally recognised environmental areas such as the iSimangaliso Wetland Park, a UNESCO world heritage site. To optimise the management of the water-balance and understand the functioning of the area, there has been a need to quantify the water-use of the dominant vegetation types of the Park such as the endangered Peat Swamp Forests (Grundling et al., 1998; Chapter 2), a dominant plant type of the Mfabeni Mire. However, little is known about the water-use characteristics of the species diverse Peat Swamp Forests (PSFs) both locally and internationally in terms of model parameterisation. Despite significant improvements to measurement techniques over vegetated surfaces (Savage et al., 1997), these have not been of benefit for PSFs due to their remote and inaccessible nature. In addition, well documented extreme events (such as the Demoina floods in 1987) pose a real threat in the area. Sophisticated instruments are unfortunately vulnerable to damage and malfunction in such environments and PSFs are therefore not good locations for long-term deployment of sensitive equipment, a challenge facing researchers internationally and particularly in developing countries.

There are numerous, complex evaporation sources, which interact and contribute to total evaporation (ET) in the Nkazana PSF. The areas of open water fluctuate, depending on groundwater levels. Open water evaporation is well described from the early work of Penman (1948) to the more recent work of Finch (2001) and Rosenberry et al. (2007) but none accounts for the effects of dense vegetation cover on radiative shading and the prevention of convection over the water surface by a tall and dense canopy. There are surface evaporation studies of peat (Nichols and Brown, 1980; Koerselman and Beltman, 1988; Lafleur and Roulet, 1992; Thompson et al., 1999, Chapter 2), but none in the context of a subtropical swamp forest. In addition the vegetated canopy is complex. There is a dense cover of ferns, of which little is understood in terms of transpiration (Andrade and Nobel, 1997). Above the ferns, the tree canopy consists of two levels described below (understory and emergent trees) and there are tree-climbing vines. Estimating the ET of the Nkazana PSF is clearly multifaceted due to its diversity and our lack of understanding of the water-use of the specific plants, together with the potential variation in the evaporative demand within and above the canopy.

Within South Africa, the only comparable study took place over an evergreen indigenous mixed forest in the Southern Cape near the coast. Dye et al. (2008) measured ET using eddy covariance (EC), scintillometry and Bowen ratio over 18 days in total, during three different field campaigns, representing three different seasons within the year. The periods in-between were modelled using the FAO56 Penman-Monteith reference equation of Allen et al. (1998) which generally underestimated ET under high evaporative conditions and overestimated under low evaporative conditions. This was attributed to the assumption of a constant surface resistance. The Penman-Monteith equation (Monteith, 1965) was found to give the best match of predicted to observed daily ET, but required measurements or a sub-model accounting for variable canopy conductance. The more complex WAVES (CSIRO, Canberra, Australia) process-based model simulated canopy growth and water-use processes in much more detail. However, successful parameterisation of the many model inputs was a significant challenge and despite their best efforts, the WAVES output revealed an overestimation of daily ET under conditions of low evaporative demand which could not be corrected. They concluded that the best technique for interpolating the periods between the three field campaigns to be the Penman-Monteith equation despite the problem of the variable canopy conductance and recommended that further research into understanding the most appropriate techniques for interpolating measured data was necessary.

Internationally, no studies were found with measurements over a comparable subtropical peat swamp forest. However, Vourlitis et al. (2002) provide a valuable study in which they attempted to measure the long-term ET with an EC system over a tropical forest in Brazil. Despite the proximity to the city of Sinop (offering a nearby base from which maintenance could be conducted), power issues hampered the data collection and EC data was only collected 26% of the time. Meteorological data was therefore used to estimate the latent energy flux (LE) using the Priestley-Taylor expression.

Since the beginning of the FLUXNET project, which was established to compile long-term measurements of water vapour, carbon dioxide and energy exchanges from a global network of EC systems, the problem of complete EC data sets and gap filling of records was recognised and is still an ongoing challenge (Baldocchi et al., 1996; Baldocchi et a. 2001). Falge et al. (2000) found the average data coverage for long-term EC systems to be only 65% due to system failure or data rejection with most of these located in developed countries. Clearly, despite the benefit of EC systems, long-term, continuous records of observed ET data over indigenous subtropical and tropical forests are improbable without significant research budgets allowing daily maintenance, gap filling and processing of data including complex spectral corrections, 3D corrections and coordinate rotation amongst others (Massman and Lee, 2002; Finnigan et al. 2003; Hui et al. 2004). Intensive, short-term field campaigns, offering reliable, continuous records, during different seasons seems an appropriate strategy to determine the annual cycle of ET, above all at temporary sites. This is particularly the case in South Africa, where theft of equipment and especially batteries from the foot of visible towers is a severe limitation although this is overcome by employing 24-hour security guarding services to protect the equipment during the short-term measurement periods (Dye et al., 2008). However, this strategy only provides a viable solution if the ET during the in-between periods can be adequately estimated.

Wilson et al. (2001) applied EC and sapflow techniques in a deciduous forest of the South-eastern United States, and found that there was a qualitative similarity between ET_{ec} and tree transpiration. With the recent advances in sapflow measurement techniques and upscaling of individual tree transpiration measurements to canopy ET, it is believed, that sapflow techniques offer a reliable, standalone, long-term solution to estimating ET in uniform tree stands (Hatton and Wu, 1995; Meiresonne et al., 1999; Crosbie et al., 2007). There are however, numerous complexities bringing some doubt as to the accuracy of the absolute sapflow results, such as the anisotropic properties of sapwood (Vandegehuchte et al., 2012), species composition effects (Wullschleger et al., 2001), tree symmetry (Vertessy et al., 1997), radial patterns of sapflow (Cermak and Nadezhdina, 1998) and changes in spatial patterns of transpiration (Traver et al., 2010). In heterogeneous and complex canopies such as the Nkazana PSF described above, sapflow systems alone are impractical for the prediction of stand ET even with the recent advances in process based models of vegetation function such as the Measpa model (Duursma and Medlyn, 2012). However, whether it is possible to use the qualitative relationship of sapflow with ET_{ec}, as found by Wilson et al. (2000), remains unknown.

For these reasons, a strategy to provide a measurement and modelling framework was developed and tested, in which detailed water flux measurements were recorded using EC instruments in an indigenous, heterogeneous forest over three window periods in August 2009, November 2009 and March 2010. This minimised the cost and risk of damage to these expensive systems, and provided continuous and reliable data from well-maintained instruments operated by a team of scientists, but were limited to three window periods. Two of these window periods overlapped in time and space with long-term sapflow measurements, and a nearby weather station provided measurements during the full period. The sapflow and weather station systems had lower maintenance and power requirements, were less delicate, less visible, able to withstand the harsh environment, and operated for longer periods unattended (one to two months) without compromising data quality. The aims were therefore to (1) establish whether the long-term ET of the Nkazana PSF could be determined by this combination of EC window periods and long-term sapflow measurements, (2) to provide a means of modelling the ET of surrounding PSFs from nearby meteorological data and (3) to investigate the controlling climatic variables and their influence on sapflow as well as the energy fluxes and microclimate within the swamp forest.

4.2.1 The Study Area

The study area is located in Maputaland, South Africa, on the Eastern Shores of the iSimangaliso Wetland Park. It has held international status as a UNESCO World Heritage Site since 1999 (Taylor et al., 2006) and falls within the St Lucia Ramsar Site designated in 1986 (Taylor, 1991). It is one of the largest protected aquatic systems in southern Africa and due to its biodiversity and natural beauty, has become an international tourist destination and now a "regional economic hub" (Whitfield and Taylor, 2009).

The Eastern Shores area has a subtropical climate and lies in a summer rainfall area (Schulze et al., 2008). It has been reported that "the rainfall gradient westwards from the coast is strong, with a precipitation at Mission Rocks on the Indian Ocean coastal barrier dune exceeding 1200 mm yr^{-1} and decreasing to around 900 mm $year^{-1}$ at Fanies Island on the western shoreline of the estuary" (Taylor et al., 2006). However, Lynch (2004) provides mean annual precipitation values of 1056 mm yr^{-1}, 844 mm yr^{-1} and 910 mm yr^{-1} from the nearby Fanies Island, Charters Creek and St. Lucia from a 125 year raster database and the Agricultural Research Council measured an average annual rainfall at St. Lucia over a 22 year period of 975 mm yr^{-1} (ARC-ISCW, 2011). Clearly rainfall in the area is variable and figures depend on the period over which the rainfall was measured and the particular location. During this study there was a well reported drought in the region (Grundling et al., 2014).

The Eastern Shores area is flanked by the Indian Ocean to the east and Lake St. Lucia to the west (Fig. 4.1a). It includes coastal dunes (dune forest) to the east, the Embomveni Dunes (grassland) to the west and the Mfabeni Mire as an interdunal drainage line through the middle. The perennial Nkazana stream drains from the Mfabeni Mire providing freshwater to Lake St. Lucia. This stream was recognised by Vrdoljak and Hart (2007) as an ecologically important source of freshwater to Lake St. Lucia during droughts. Chapter 3 states that "Organic matter and sediment have accumulated in the Mfabeni Mire over the past 45 000 years, forming one of South Africa's largest peatlands and one of the oldest active peatlands in the world (Grundling et al., 1998)". The Mfabeni Mire is approximately 8 km long (north-south direction) and 4 km wide in places (east-west direction). It comprises of subtropical freshwater wetland (SFW) vegetation described by Vaeret and Sokolic (2008) and with a variable canopy height averaging approximately 0.8 m (Chapter 2). The Nkazana PSF is the other dominant vegetation type that runs down the western side of the Mfabeni Mire (Fig. 4.1b). The Nkazana PSF falls within the Indian Ocean Coastal Belt Biome, and is described as being a "mixed, seasonal grassland community" (Mucina and Rutherford, 2006). The Nkazana PSF is further classified by von Maltitz et al., (2003) and Mucina and Rutherford (2006) as an Azonal Forest indicating its presence due to, and reliance on, the groundwater surface within the Mfabeni Mire.

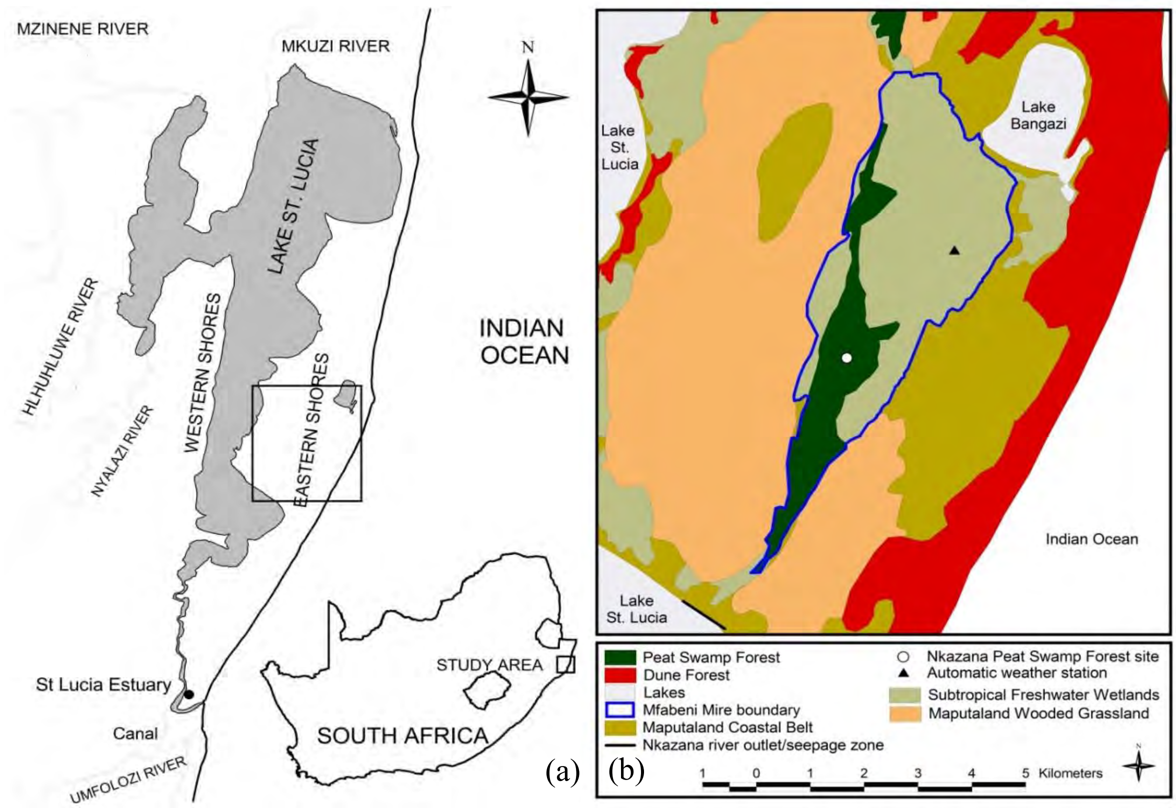

Figure 4.1 (a) Location of the Eastern Shores within South Africa, (b) the Nkazana Peat Swamp Forest site (where the EC and sapflow systems were located) and the automatic weather station within the Mfabeni Mire on the Eastern Shores (data from Mucina and Rutherford, 2006).

4.2.2 Site description

The Swamp Forest site (28º 10.176'S, 32º 30.070'E) posed significant logistical challenges due to the 20 m high tree canopy, thick undergrowth, soft ground, dangerous animals and general inaccessibility by road. The measurements were concentrated at its widest point (approximately 1 km) to maximize the fetch for the flux measurements above the tree canopy. Chapter 3 describes previous botanical research explaining the structure of the Nkazana PSF and the vegetation in the vicinity of the research site:

> "Wessels (1997) classified the swamp forests of the area into three logical subgroupings based on dominant species, stand density and basal areas. The *Syzygium cordatum* subgroup is characterised by an irregular, broken canopy of predominantly *Syzygium cordatum* trees (known locally as the Water Berry) of up to 30 m, emerging above an intermediate canopy of approximately 6-15 m. Dominant tree species found in the Swamp

Forest and in the vicinity of the site included: *Macaranga capensis, Bridelia macrantha, Tarenna pavettoides* and *Stenochlaena tenuifolia*. An impenetrable fern (*Nephrolepis biserrata)* covers the forest floor with a height of approximately 2.5 m and the *Stenochlaena tenuifolia* (Blechnaceae) fern grows up the tree stems to a height of approximately 10 m."

The layer of peat at the Nkazana PSF site was approximately 2 m thick and underlain by sand. The water table depth was < 1.0 m but at the surface in low lying areas of the forest. The leaf area index (LAI-2200, LI-COR Inc., Lincoln, Nebraska, USA) beneath the ferns and trees was approximately 7.2 and below the trees approximately 3.3.

4.3 Materials and methods

4.3.1 Micrometeorological measurements

An automatic weather station provided supporting meteorological data. It was located adjacent to the Nkazana PSF in the Mfabeni Mire over a sedge, reed and grass dominated vegetation, described broadly as SFW (Fig. 4.1b). Observations of rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA), air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200X, LI-COR, Lincoln, Nebraska, USA), net irradiance (NRLite, Kipp and Zonen, Delft, The Netherlands), wind speed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA) were made every 10 s. The appropriate statistical outputs were stored on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA) at 30-minute intervals. Sensors were installed according to recommendations of the World Meteorological Organisation (WMO, 2008) with the raingauge orifice at 1.2 m and the remaining sensors 2 m above the ground. Vapour pressure deficit (VPD) was calculated on the datalogger from air temperature (T_{air}) and relative humidity (RH) measurements according to Savage et al. (1997).

4.3.2 Measurement of energy fluxes and total evaporation

The shortened energy balance equation is commonly used in evaporation studies (Drexler, et al. 2004) to describe the partitioning of energy at the earth's surface and provides an indirect method to determine ET (Eq. 4.1). The "shortened" version ignores those energies associated with photosynthesis, respiration and energy stored in plant canopies. However, these are considered small when compared with the other terms (Thom, 1975). The shortened energy balance equation is written as:

$$R_n = G + H + LE \tag{4.1}$$

where, R_n is the net irradiance, H is the sensible heat flux, G is the ground heat flux and LE is the latent energy flux, which is the energy equivalent of ET by conversion (Savage et al., 2004).

Eddy covariance is based on the estimation of the eddy flux which is expressed as:

$$F = \rho_d \overline{w's'} \tag{4.2}$$

where, ρ_d is the density of dry air, w is vertical wind speed (measured with the sonic anemometer described below) and s is the concentration of the scalar of interest (water vapour in this case). The primes indicate fluctuation from a temporal average (i.e. $w' = w - \overline{w}$; $s' = s - \overline{s}$) and the over-bar represents a time average. The averaging period of the instantaneous fluctuations, of w' and s' should be long enough (30 to 60 minutes) to capture all of the eddy motions that contribute to the flux and fulfil the assumption of stationarity (Meyers and Baldocchi, 2005).

The vertical flux densities of H and LE were estimated by calculating the mean covariance of sensible (Eq. 4.2) and water vapour fluctuations respectively, with fluctuating vertical velocity (Baldocchi et al., 1988).

Soil heat flux was measured using two soil heat flux plates (HFT-3, REBS, Seattle, WA, USA) and a system of parallel thermocouples (Type E). The plates were placed at a depth of 0.08 m below the peat surface. The thermocouples were buried at 0.02 and 0.06 m and were used together with volumetric water content (CS615, Campbell Scientific Inc., Logan, Utah, USA) in the upper 0.06 m to estimate the heat stored above the soil heat flux plates. The measurements were stored every 10 s on a datalogger (CR23X, Campbell Scientific Inc., Logan, Utah, USA) and 30-minute averages were computed. During the measurements at the Nkazana Swamp Forest, the groundwater level was deeper than 0.1 m below the surface and therefore, the total G was determined using the calorimetric methodology described by Tanner (1960).

Over the corresponding time period, R_n was measured above the forest canopy, using a 21.3 m telescopic mast (WT6, Clark Masts Systems Limited, Isle of Wight, England). It was erected within the forest, on a fallen tree stump approximately 2.5 m high (Fig. 4.2a). This formed a firm base for the 90 kg mast which was carried into the forest from the nearest road approximately 1 km away. The computer box for the EC system (InSitu Flux Systems AB, Ockelbo, Sweden) was installed near the base of the mast (Fig. 4.2b) and a generator that automatically charged a bank of four 100 Ah deep-cycle lead-acid batteries (accumulators) was positioned approximately 50 m from the site in the a predominantly downwind direction (the North-West) to minimise any possible influence from the exhaust fumes on the flux measurements. The generator was controlled by a logger (CR10X, Campbell Scientific Inc., Logan, Utah, USA) which was set to activate the charging system (220VAC petrol generator and 40 A 12 V charger) when the accumulators dropped below 12.4 V.

A "SATI-3VX" style, three-dimensional (3-D) sonic anemometer (Applied Technologies, Inc., Longmont, CO, USA) and open-path infrared gas analyser (LI7500, LI-COR, Lincoln, NE, USA) were mounted on the head of the mast (0.089 m diameter) orientated to face the east (predominant wind direction) to avoid air-flow distortion from the mast (Fig. 4.2c). In addition, T_{air} (PT-10, Peak Sensors Ltd., Chesterfield, UK) and R_n (NRLite, Kipp and Zonen, Delft, The Netherlands) were measured at the head of the mast. Data collection and analyses of the system was made in real time by the ECOFLUX software fully described by Grelle & Lindroth (1996) using a Flux Computer (In Situ Flux Systems AB, Ockelbo, Sweden). The system operated with a sampling rate of 10 Hz and the average fluxes were calculated every 30 min. The raw data were also stored for further processing. All the necessary corrections for air-density effects and 3-D coordinate rotation were performed on the Flux Computer to determine *H* (Grelle & Lindroth (1996).

The Bowen ratio (β) has historical significance in evaporation studies and is defined as:

$$\beta = \frac{H}{LE} \qquad (4.3)$$

for a specified time period. It informs on the dominance of *H* or LE and was calculated at a daily time interval in this study providing a useful means of showing changes in the distribution and weighting of the energy balance components within and between field campaigns.

Figure 4.2 (a) Telescopic mast (21.3 m) erected in the swamp forest to raise the eddy covariance instruments above the forest canopy, (b) the computer installed at the swamp forest, housed in a temperature controlled enclosure and (c) the instruments attached to the head of the mast.

4.3.3 Energy balance closure

If each component of the energy balance is measured accurately and independently, then Eq. 4.1 should be satisfied, and closure is considered satisfied. However, energy balance closure could still be achieved if two or more terms have incorrect values and the terms in Eq. 4.1 still sum to zero (Savage et al., 2004). If the components of the shortened energy balance equation are measured independently then, $R_n - G - H - \text{LE} = c$ where c is termed the energy balance closure (W m^{-2}), and closure is satisfied if $c = 0$ W m^{-2}. By rearranging Eq. 4.1, closure is not achieved if the available energy R_n - G does not equal the turbulent fluxes H + LE. Another measure of the lack of closure is the closure ratio or the energy balance closure discrepancy *D* defined by Twine et al. (2000) as:

$$D = \frac{H+LE}{R_n - G} \tag{4.4}$$

in which, a *D* of 1 indicates perfect closure. Several studies using numerous techniques over various surfaces have failed to achieve closure by up to 20 or 30 % (Wilson et al., 2001; Wilson et al., 2002; Bar et al., 2006). The vast majority have found higher energy input by radiation fluxes than loss by turbulent fluxes (*H* and LE) and *G* (Oncley et al., 2007). Therefore, the measured fluxes should be corrected or adjusted or the uncertainties in the measured fluxes accepted (Twine et al., 2000). Several reasons for lack of energy balance closure have been discussed by Twine et al. (2000), Wilson et al. (2002), and Cava et al. (2008) including: (1) sampling errors associated with different measurement source areas for the terms in Eq. 4.1, (2) a systematic bias in instrumentation, (3) neglected energy sinks, (4) the loss of low and/or high frequency contributions to the turbulent flux, (5) neglected advection of scalars, (6) measurement errors related to sensor separation, alignment problems, interference from tower or instrument-mounting structure, and (7) errors in the measurement of R_n and/or *G.* Despite concerns that the direct method of determining total evaporation (ET_{ec}) by measuring water vapour concentrations using an Infrared Gas Analyzer may result in underestimates or overestimates of LE, in this study, it was considered that some of the closure pitfalls of the shortened energy balance method, such as (3) and (7) in particular, could be significant due to the tall canopy at the site (3) and point measurement location (7). Therefore, all ET results reported in this paper were calculated by the direct method. Energy balance closure discrepancy was determined during the day-time period (R_n>0) due to the potentially large nocturnal influences reported by Wilson et al. (2002).

4.3.4 Measurement of tree sapflow

A heat pulse velocity system based on the heat ratio method (Burgess et al., 2001), was used to measure sapflow at various depths across the sapwood of two trees over 20 months from September 2009 to early May 2011 which overlapped with the November 2009 and March 2010 field campaigns. The trees measured were located approximately 40 m from the mast where the EC and energy balance sensors were installed. Representative trees, in terms of species, stem diameter, canopy height and proximity to each other, were selected given the cable length limitations of the HPV system. The *Syzigium cordatum* tree selected was approximately 22.5

m tall and had a breast height stem diameter of 0.430 m. Sapflow was measured at four depths across the sapwood on both the eastern and western sides of the stem to account for differences in the sapwood depth around the tree. Sapflow was also measured in a nearby understory tree (*Shirakiopsis elliptica*) with a smaller stem diameter (0.081 m) at four depths within the sapwood. Air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland) within the canopy at a height of 2 m above the ground was also measured hourly. Further details of the installation, equipment used, wounding corrections applied and calculations to derive the tree sapflow are documented in Chapter 3. In this manuscript, following Dye et al. (2008), sapflow is assumed to equate with tree transpiration and tree water-use.

4.3.5 Predicting annual total evaporation from sapflow

Polynomial regression (second order) analysis in the Genstat software (VSN International, 2011) was used to describe the relationship between observed ET_{ec} and observed sapflow of the emergent and understory trees during the overlapping periods of the November 2009 and March 2010 field campaigns in order to understand the possibility of predicting ET of the Nkazana PSF using the long-term sapflow records. The hourly data was checked for homoscedasticity and square root transformed where necessary. The model derived was applied over a full year of sapflow data (October 2009 to September 2010) to obtain an annual predicted ET.

4.3.6 Evaporation models assessed

Two well recognised evaporation models were tested for applicability of estimating ET from the Nkazana PSF. After assessment of the models at an hourly temporal resolution, over the three field campaigns, the most applicable model was applied to the long-term predicted ET discussed above and verified using historic data collected by the Council for Scientific and Industrial Research (CSIR) during a preliminary study over the Nkazana PSF from 8 to 12 August 2008 and 12 to 20 November 2008 (unpublished). The CSIR measured ET with the identical EC equipment used during the field campaigns in 2009 and 2010 described above and at the same site in the Nkazana PSF making the data ideal for verification of the models.

FAO56 Penman-Monteith: The original Penman evaporation model (Penman, 1948), assumed an absence of any control on evaporation at the earth's surface, in effect, an open water or wet surface situation. This was extended by Monteith (1965) to incorporate surface and aerodynamic resistance functions applicable to vegetated surfaces and was widely used in this form as the Penman-Monteith model. It is however, highly data intensive (Mao et al., 2002; Drexler et al., 2004) and the model was therefore standardised by the Food and Agriculture

Organisation in Irrigation and Drainage Paper No. 56 (Allen et al., 1998) into a form known as the FAO56 Penman-Monteith (FAO-PM) model that could be applied at both hourly and daily time intervals. The model received favourable acceptance internationally in establishing a reference evapotranspiration (ET_r) index (atmospheric evaporative demand) as a function of weather variables measured at most standard weather station systems. The definition of a reference crop over which the weather variables should be measured was a "hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered" (Allen et al., 1998). A nearby crop ET (ET_c) is calculated by adjusting the ET_r by a crop factor (K_c) in the form:

$$ET_c = ET_r \cdot K_c \tag{4.5}$$

where, the crop is not water-stressed. In Allen et al. (1998), values of K_c have been compiled for different vegetation types at different stages in crop development. Since recommendations by the American Society of Civil Engineers (ASCE) Evapotranspiration in Irrigation and Hydrology Committee (Allen, et al., 2000) and the work by Irmak et al. (2005) and Allen et al. (2006) amongst others, the tall crop reference (alfalfa height=0.5 m) and separate daytime (r=50 s m^{-1}) and night-time (r=200 s m^{-1}) resistances for hourly calculations were introduced.

By rearranging Eq. 4.5 to make K_c the subject of the equation, and using the long-term predicted ET as a surrogate for ET_c, K_c was calculated for the Nkazana PSF at an hourly interval (while R_n>0 and ET_{ec}>0.1 mm hr^{-1}) and summed to daily totals as recommended by Irmak et al. (2005). The reference evaporation approach has been successful internationally, partly due to technological advances leading to improvements in temporal and spatial data availability but also because it provides a method for estimating ET_c, which is transferrable and can be applied to different vegetation types and locations across the world.

Priestley-Taylor: Priestley and Taylor (Priestley and Taylor, 1972) simplified the theoretical Penman equation for specific conditions. They reasoned that, as an air mass moves over an expansive, short, well-watered canopy, ET would eventually reach a rate of equilibrium. In this case, where humid air moves over a wet surface, the aerodynamic resistances become negligible, while irradiance dominates, and the rate of ET would be equal to the potential evaporation (ET_p) which is written as:

$$ET_p = \frac{\alpha}{L_v} \cdot \frac{\Delta}{\Delta+\gamma} \tag{4.6}$$

where, α is a constant, L_v is the specific latent heat of vaporisation of water (2.45 MJ kg^{-1}), Δ is the slope of the saturation water vapour pressure versus T_{air}, and γ is the psychometric constant.

The definition of the Priestley-Taylor model makes it suitable for estimation of evaporation from open water areas and wetlands (Price, 1992; Souch et al., 1996; Mao et al., 2002) but it has been applied over numerous other surfaces such as forests (Shuttleworth and Calder, 1979), cropped surfaces (Davies and Allen, 1973, Utset et al. 2004), pastures (Sumner and Jacobs, 2005) and even soil water limited conditions in forest clearcuts (Flint and Childs, 1991) with varied success and deviations from the originally proposed estimate for α of 1.26. In this study it was applied in the form described by Savage et al. (1997) where $(\Delta / (\Delta + \gamma))$ was estimated by:

$$\frac{\Delta}{\Delta+\gamma} = 0.413188419 + 0.0157973 \cdot T_{air} - 0.00011505 \cdot T_{air}^2 \tag{4.7}$$

where, T_{air} is average air temperature over the interval of calculation (hourly in this study). By rearranging Eq. 4.6, and substituting ET_{ec} for ET_p, α was estimated in the same way as K_c above.

4.3.7 Investigating climatic controls and drivers of sapflow

Sapflow was compared by simple linear regression to climatic variables generally considered to control sapflow in trees such as solar irradiance (I_s) and VPD (Albaugh et al., 2013). Sapflow was also compared by multiple regression analysis to the micrometeorological parameters including I_s, T_{air}, RH and soil volumetric water content (θ) to determine individual and combined drivers of sapflow. The sapflow was logged as the variability in sapflow increased as the magnitude of the predictor variable increased. Significance of variables, with up to four-way interactions were considered. In addition, the predictor variables were broken up into sets of data with different ranges using regression tree analysis in which a different model was applied to individual sets of data rather than a global model (such as regression analysis) in which a single model is applied to the entire range of each variable.

4.4 Results

4.4.1 Weather conditions during the study

The daily radiant densities (integrated solar irradiance over a day) were lowest in August 2009 (~15 MJ m^{-2}) and most consistent (Table 4.1), whereas in November 2009 and March 2010 they were higher and more variable (between ~16 and ~25 MJ m^{-2}), particularly in November 2009 (Tables 4.2 and 4.3). The daily maximum temperatures were highest in March 2010 (~29 ˚C) and lowest in August 2009 (22.8 ˚C). Average minimum RH was lowest in August 2009 (~34%) and the average daytime VPD was highest (1.2 kPa). Average daily wind speeds were notably high in November 2009 (> 7 m s^{-1}) and the dominant wind direction for the site was from the north-east and the south. Some rainfall (< 7 mm) occurred during the field campaigns but fortunately fell at night and did not affect the daytime flux measurements.

The microclimate within the Nkazana PSF was noticeably different to the adjacent SFW areas. The VPD within the Nkazana PSF canopy was consistently lower than the SFW where the automatic weather station was located approximately 3 km away, with the larger differences occurring from March to August, which is the winter period (Fig. 4.3). A difference in dawn T_{air} between the Nkazana PSF and the adjacent area was also noted. The difference was lowest in summer and highest in winter with the Nkazana PSF being up to 6 ˚C warmer on some mornings in June 2010.

Table 4.1 Summary of weather conditions during the August 2009 field campaign

Date	Solar radiant density (MJ m^{-2})	Wind speed (m s^{-1})	Wind direction (˚)	VPD (kPa)	Air temperature (˚C)		RH (%)		Rain (mm)
					Max	Min	Max	Min	
13/8/2009	14.2	4.6	199	1.5	21.9	13.0	88.7	33.7	
14/8/2009	15.4	2.4	194	1.2	21.8	9.8	95.5	43.3	
15/8/2009	15.3	1.9	83	1.1	22.4	7.0	98.9	50.7	
16/8/2009	14.9	2.5	74	1.1	23.3	11.2	97.0	46.5	
17/8/2009	15.9	3.2	38	1.0	22.6	10.4	98.1	48.9	0.8
18/8/2009	14.8	4.3	33	1.0	23.0	14.1	95.0	52.5	
19/8/2009	15.5	5.5	28	1.2	24.5	13.2	96.3	45.8	
Average	15.1	3.5		1.2	22.8	11.1	95.6	45.9	

Table 4.2 Summary of weather conditions during the November 2009 field campaign

Date	Solar radiant density (MJ m^{-2})	Wind speed (m s^{-1})	Wind direction (˚)	VPD (kPa)	Air temperature (˚C)		RH (%)		Rain (mm)
					Max	Min	Max	Min	
4/11/2009	22.0	2.1	115	0.9	23.8	13.2	96.4	51.9	
5/11/2009	16.7	4.2	40	0.6	25.2	17.7	93.3	66.7	
6/11/2009	18.1	5.3	37	0.6	25.8	19.9	93.3	73.0	
7/11/2009	19.0	6.9	36	0.6	25.9	21.6	93.2	70.5	
8/11/2009	25.3	7.4	37	0.7	26.4	21.3	90.5	69.0	
9/11/2009	21.1	6.2	34	0.7	25.3	21.0	94.7	69.2	5.3
10/11/2009	16.2	4.4	223	0.6	24.7	19.4	95.6	61.6	0.3
11/11/2009	21.2	2.3	47	0.5	26.1	15.5	97.1	64.6	
Average	22.8	3.1		0.8	28.3	18.4	94.9	58.2	

Table 4.3 Summary of weather conditions during the March 2010 field campaign

Date	Solar radiant density (MJ m^{-2})	Wind speed (m s^{-1})	Wind direction (˚)	VPD (kPa)	Air temperature (˚C)		RH (%)		Rain (mm)
					Max	Min	Max	Min	
16/3/2010	19.6	3.5	66	1.0	27.9	20.0	92.8	65.2	1.5
17/3/2010	14.6	2.3	245	0.8	28.7	18.4	96.0	60.3	4.6
18/3/2010	17.2	2.2	214	0.8	26.4	17.7	94.1	65.5	
19/3/2010	20.2	3.0	58	0.8	28.6	16.1	96.8	62.6	
20/3/2010	20.6	3.8	66	1.0	30.0	22.1	93.2	59.0	
21/3/2010	16.2	1.9	90	1.0	28.6	21.9	92.8	59.9	
22/3/2010	22.5	1.7	97	0.8	28.9	16.4	96.7	59.6	0.3
23/3/2010	19.9	2.3	234	1.0	28.8	16.8	97.3	63.9	
24/3/2010	21.2	2.1	79	1.0	30.2	18.6	96.7	56.6	
Average	19.1	2.5		1.1	28.7	18.7	95.2	61.4	

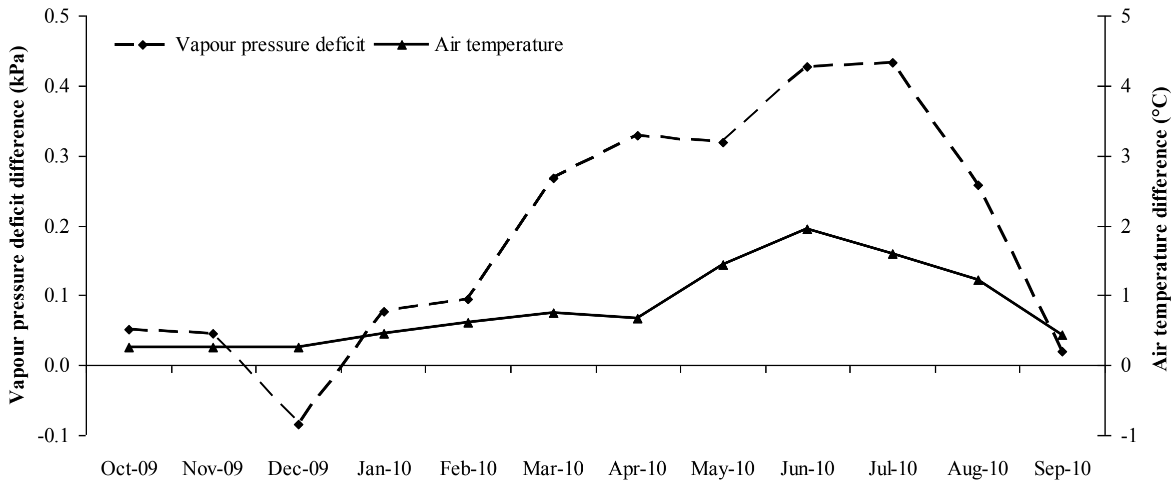

Figure 4.3 The difference in the monthly daytime (9am to 3pm) vapour pressure deficit and difference between the monthly average dawn air temperatures. Differences were measured between the subtropical freshwater wetland area of the Mfabeni Mire (reeds, sedges and grasses) and within the canopy of the Nkazana Peat Swamp Forest site.

4.4.2 Eddy covariance flux measurements

Despite the apparent consistency in the daily radiant density during August 2009 noted above (Table 4.1), the 30-minute net irradiance flux data showed that all field campaigns were affected by cloud during the daytime, as indicated by the standard error bars of the net irradiance (Figs. 4.4a-c). Even the August 2009 data, despite being in the middle of the dry season, was influenced by cloud during six out of the seven days of measurement (not shown). During the August 2009 and March 2010 field campaigns, there was a noticeable dip in the average R_n at approximately 11:00 a.m. LT. with large standard errors (> 90 W m^{-2}) due to cloud cover. In November a dip occurred at approximately 1:00 p.m. LT., also accompanied by large standard errors (> 90 W m^{-2}). The cloud affected pattern of R_n was translated through to H and LE, which were positive during the day, and with largest standard errors coinciding with those of the R_n except for the early morning observed LE in August 2009 which was attributed to the evaporation of dew on some days. The maximum rates of LE were approximately 400 W m^{-2} in August 2009, 600 W m^{-2} in November 2009 and 700 W m^{-2} in March 2010 (not shown). The pattern of G fluctuated diurnally but due to attenuation (sensors were below the soil surface) the pattern was smoother than the other fluxes during the course of the day.

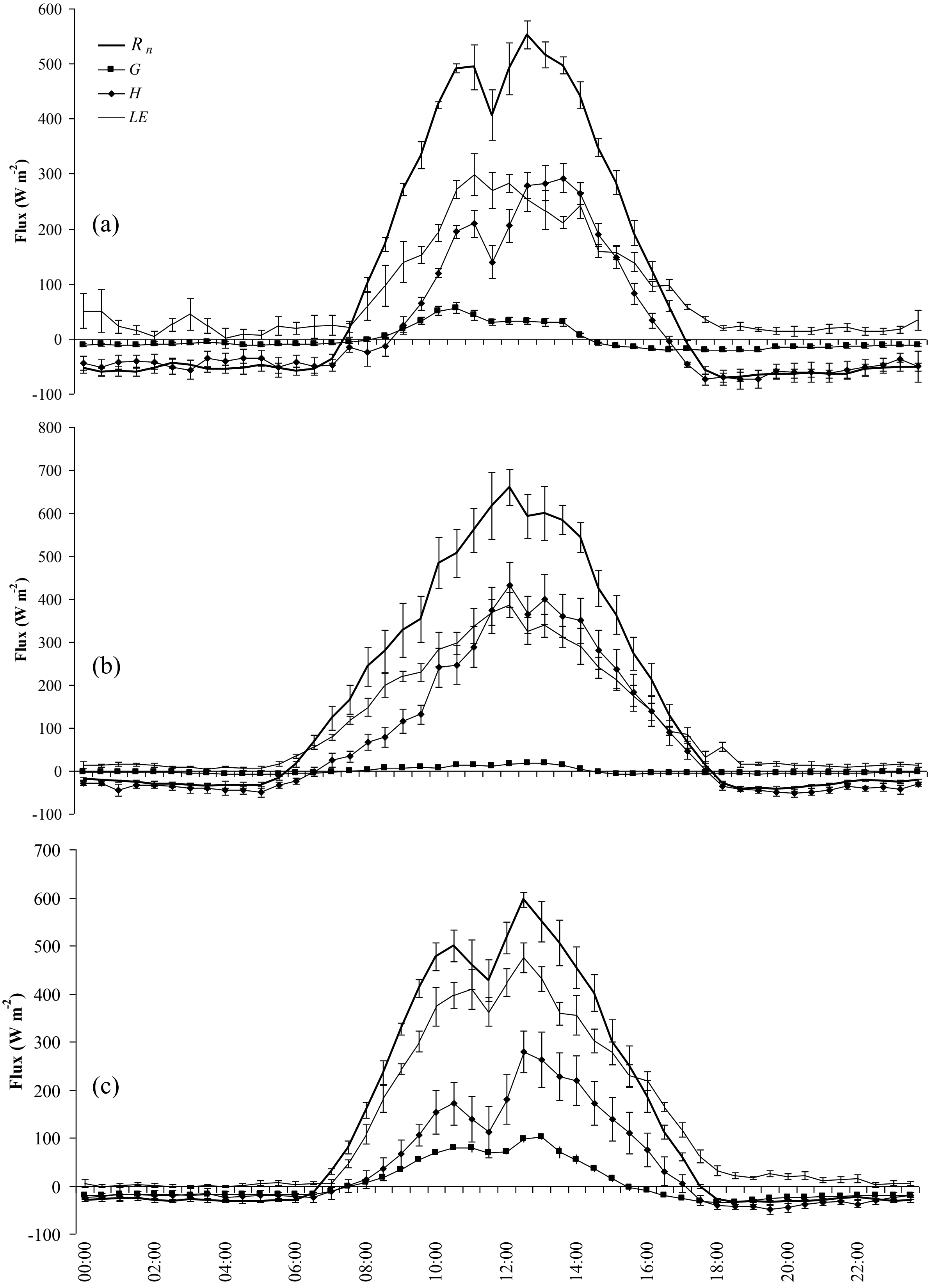

Figure 4.4 The average of the half-hourly energy fluxes, with error bars indicating the standard error, measured at the Nkazana Swamp Forest in (a) August 2009, (b) November 2009 and (c) March 2010

During the August 2009 field campaign the daily net radiant density was between 10.2 and 11.8 MJ m^{-2} which, despite the irregularity observed from the 30-minute data, were reasonably consistent at a daily level (Fig. 4.5a). During the November 2009 (11.4 to 18.3 MJ m^{-2}) and the March 2010 (9.0 to 14.4 MJ m^{-2}) field campaigns, the daily net radiant density was more variable (Figs. 4.5b and 5c). This variability at a daily level was translated through to the H and LE results, which during August 2009 were fairly consistent, but irregular during November 2009 and March 2010. The average daily net radiant density was lowest in August 2009 (11.2 MJ m^{-2}), highest in November 2009 (15.1 MJ m^{-2}) and in-between during March 2010 (12.7 MJ m^{-2}). The average daily soil heat flux did not mirror the pattern of R_n and was highest in March 2010 at approximately 11% of R_n (up to 1.8 MJ m^{-2}), lower in August 2009 at 5% of R_n (0.7 MJ m^{-2}) and lowest in November 2009 at 1% of R_n (up to 0.3 MJ m^{-2}).

The daily total LE was higher than H in August 2009 (Fig. 4.5a), with a daily average β ratio of 0.7 (0.4 to 0.9). In November 2009 (Fig. 4.5b) the daily average β ratio was higher with a daily average of 0.9 (0.5 to 1.3) but in March (Fig. 4.5c) however, LE dominated the energy balance with an average β ratio of 0.4 (0.1 to 0.6).

Closure discrepancy was different for each field campaign. In August 2009 the D was 0.98 indicating exceedingly good closure. However, the second and third field campaigns produced D's of 1.18 and 1.33 in November 2009 and March 2010, respectively, indicating (1) either an overestimation of LE and/or H, and/or an underestimation of the available energy ($R_n - G$) and/or (2) unaccounted energy such as advection or storage in the canopy biomass.

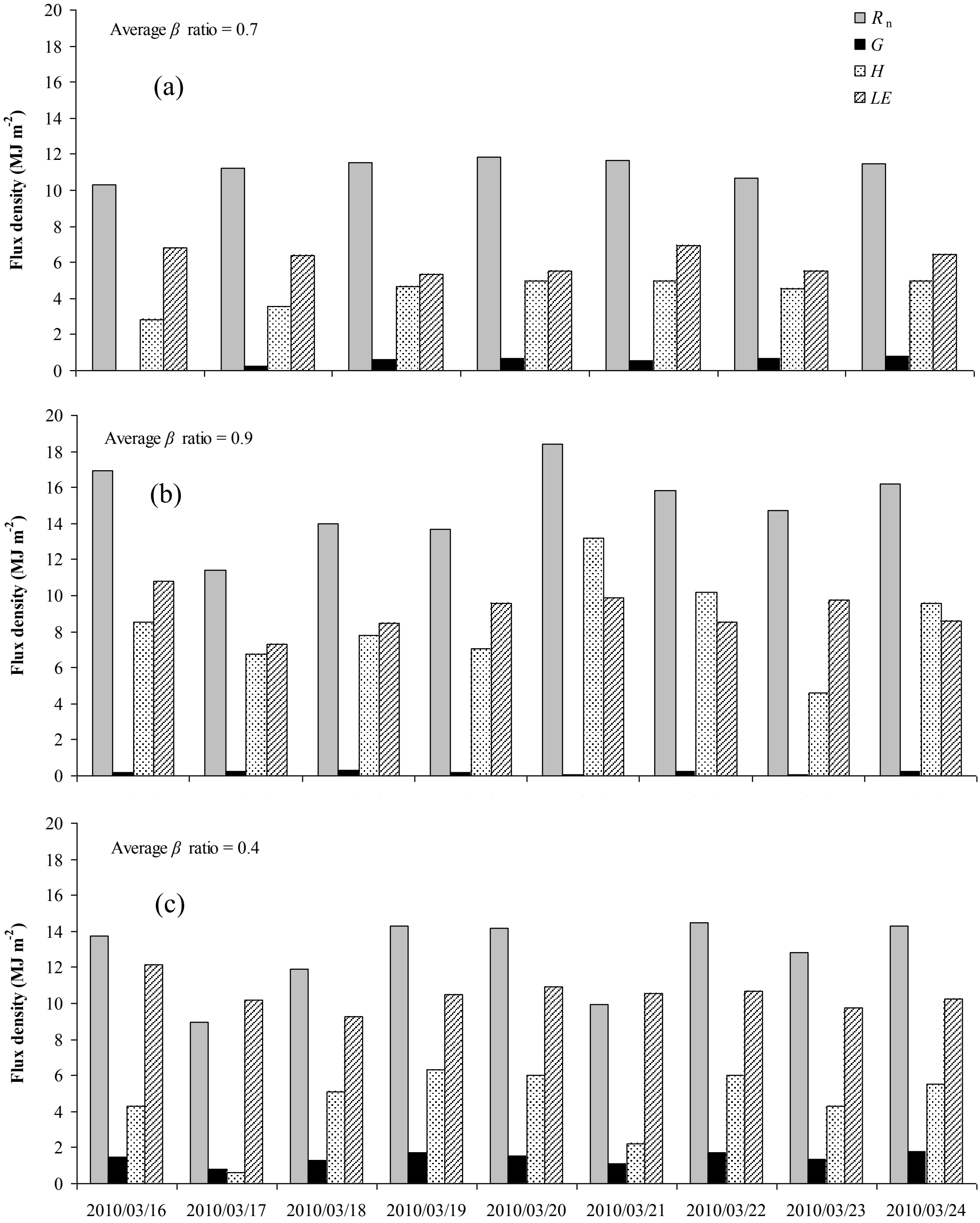

Figure 4.5 Daily total energy densities (while R_n>0) measured at the Nkazana Swamp Forest in (a) August 2009, (b) November 2009 and (c) March 2010

4.4.3 Observed total evaporation

The mean daily ET over the three field campaigns was significantly different (based on their 95% confidence interval). The daily ET (Fig. 4.6) was lowest in the August 2009 (winter) and increased progressively through November 2009 (early summer) to March 2010 (late summer). The standard deviation for all field campaigns was similar (0.3 to 0.4 mm) but the coefficient of variation (not shown) differed with the highest in November 2009 (12.0) and August 2009 (11.0) and lowest in March 2010 (8.8).

4.4.4 Relationship between sapflow and observed total evaporation during two field campaigns

The diurnal course of the sapflow from the emergent and understory trees were surprisingly smooth in comparison to the ET_{ec} results (Figs. 4.7a, 4.7b, 4.8a and 4.8b). The ET_{ec} is an integrated measure of soil evaporation and transpiration from numerous plants at different levels within the canopy over the contributing area described by the footprint whereas the transpiration measurements (assumed to equal sapflow) describe the physiology of a single tree. The R_n, frequently considered a significant driver of tree physiology, fluctuated due to cloud cover (Figs. 4.4a-c). These fluctuations were not translated into fluctuations in tree sapflow but are evident in the ET_{ec} results particularly over the midday period. A similar pattern was observed in the March 2010 ET_{ec} data (Figs. 4.7a, 4.7b, 4.8a and 4.8b).

Despite the greater midday variability of the ET_{ec} data, the polynomial regression (least squares) between hourly ET_{ec} and tree sapflow showed a strong relationship in November 2009 for the emergent tree (RMSE=0.05 mm) as well as the understory tree (RMSE=0.06 mm). The polynomial regression was convex in the case of the emergent tree (Fig. 4.9a) and concave in the case of the understory tree (Fig. 4.9b), indicating that the increase in the rate of sapflow of the emergent tree was exponential for lower values of ET_{ec} (morning and evening) but that this rate of sapflow for higher values of ET_{ec} slowed down as the tree reached its peak transpiration rate. In contrast the understory sapflow rate increased gradually per unit increase in ET_{ec} at lower values but at higher values of ET_{ec} the increase in sapflow was exponential. In March 2010 the results were similar with RMSE's of 0.07 mm and 0.08 mm for the emergent and understory trees, respectively (Figs. 4.10a and 4.10b). Lagging the sapflow by one hour as suggested by Granier et al. (2000) did not improve the regression of sapflow on ET_{ec}.

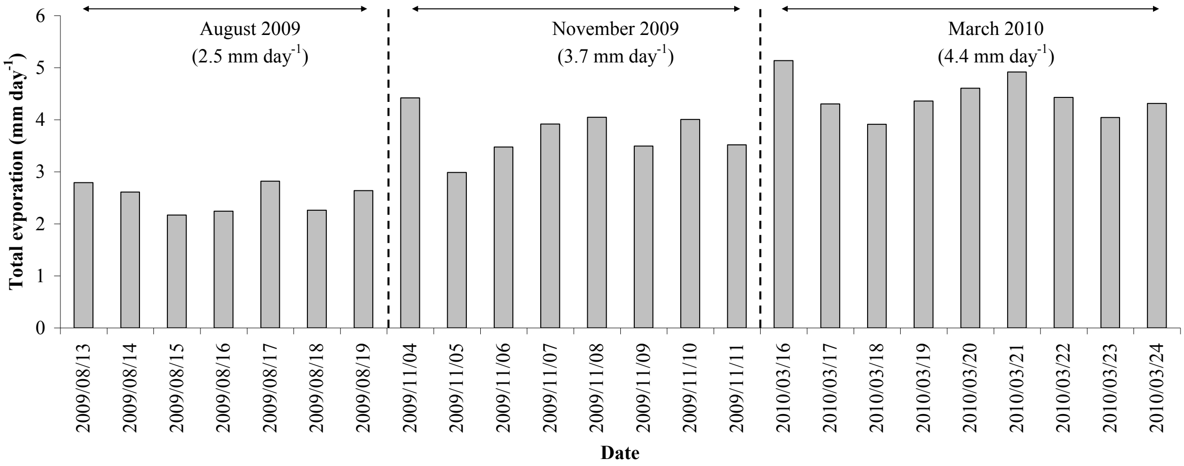

Figure 4.6 Daily total evaporation measured using eddy covariance over the Nkazana Swamp Forest during three representative periods, with the daily average provided in brackets for each period.

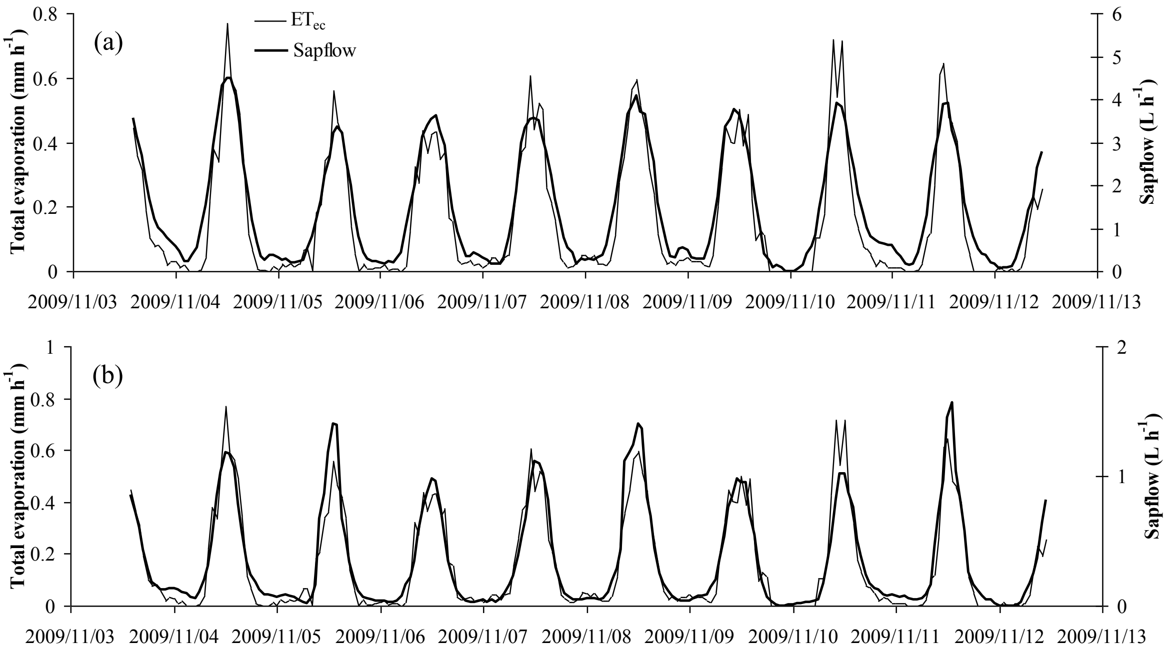

Figure 4.7 The diurnal course of the hourly sapflow of the (a) emergent tree and (b) understory tree in the Nkazana PSF together with the hourly total evaporation during the November 2009 field campaign

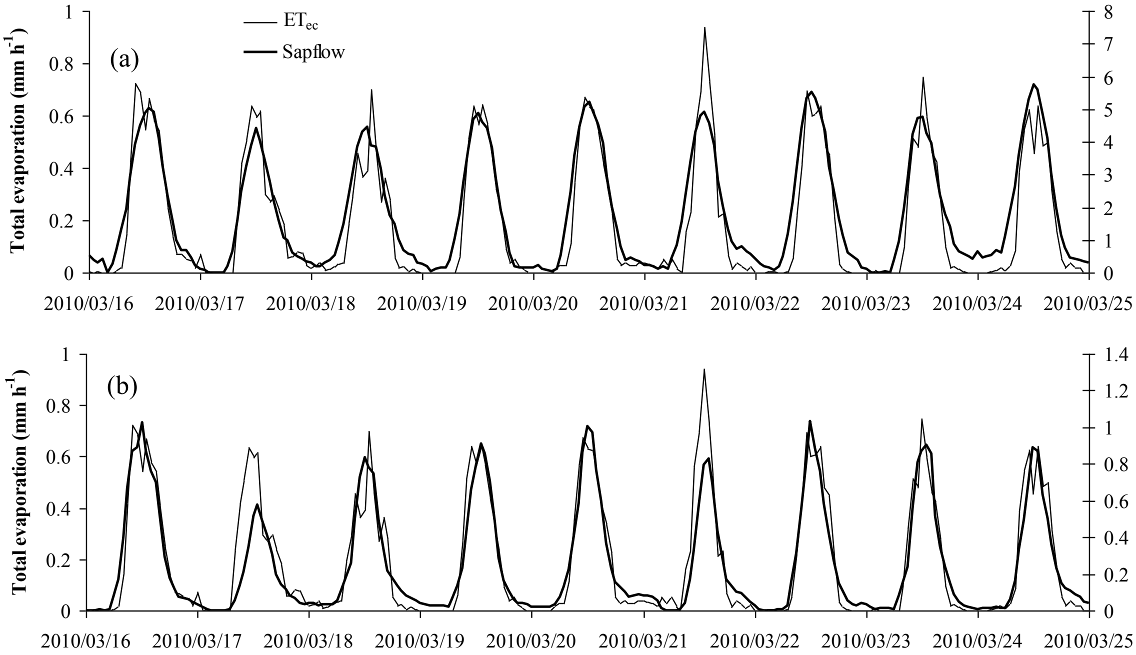

Figure 4.8 The diurnal course of the hourly sapflow of the (a) emergent tree and (b) understory tree in the Nkazana PSF together with the hourly total evaporation during the March 2010 field campaign

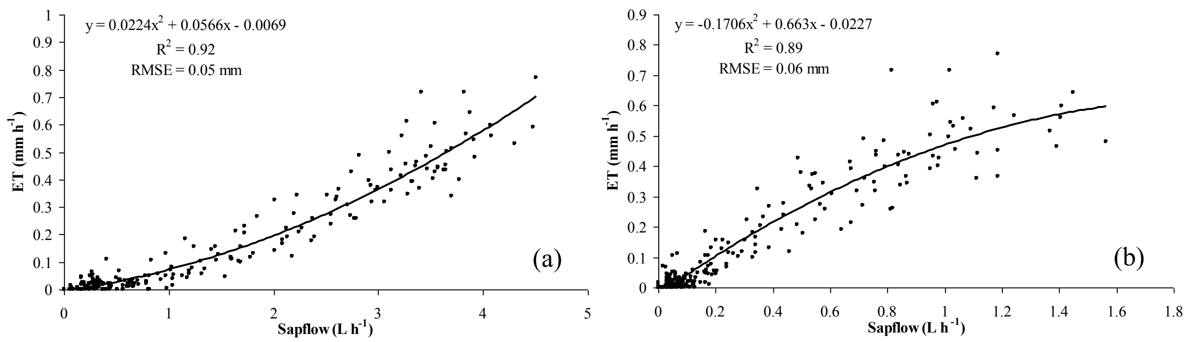

Figure 4.9 Polynomial regressions of the total evaporation (ET) against the hourly sapflow for the (a) emergent tree and (b) understory tree in the Nkazana PSF during the November 2009 field campaign

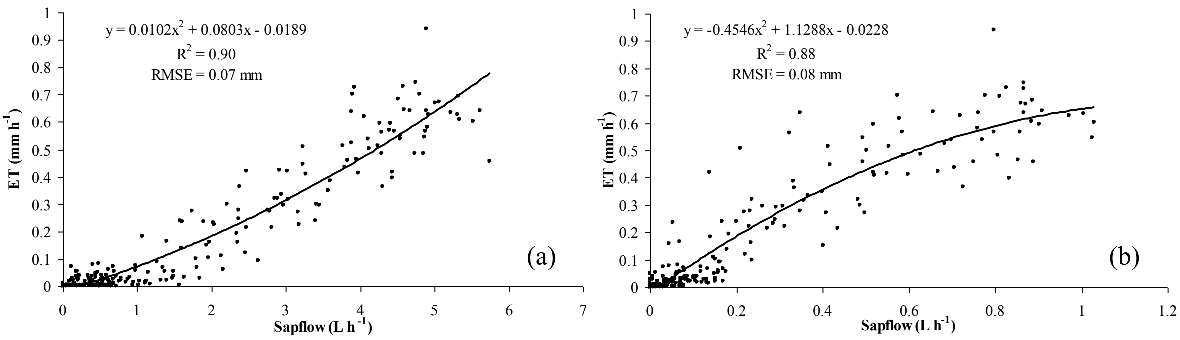

Figure 4.10 Polynomial regressions of the total evaporation (ET) against the hourly sapflow for the (a) emergent tree and (b) understory tree in the Nkazana PSF during the March 2010 field campaign

4.4.5 Comparison of the FAO56 Penman-Monteith versus the Priestley-Taylor model during the three field campaigns

The linear regression (least squares) of the hourly FAO56 Penman-Monteith modelled ET (ET_r), against hourly ET_{ec}, explained 75%, 85% and 76% of the fluctuations in ET_{ec} during the August 2009, November 2009 and March 2010 field campaigns, respectively (Table 4.4). The Priestley-Taylor model did not perform as well, accounting for 54%, 74% and 62% of the variation in ET_{ec} during the August 2009, November 2009 and March 2010 field campaigns, respectively (Table 4.4).

The slope of the linear regression (K_c) varied between field campaigns (Table 4.4) and was highest in March (1.3), and lower in November 2009 (1.1) and August 2009 (0.8). The α, also estimated by the slope of the linear regression, was similar during the August (1.0) and November 2009 (1.0) field campaigns (Table 4.4) while during March 2010, α was slightly higher (1.1). The standard deviations and root means square errors (RMSE) of α were higher than those of the K_c (Table 4.4). Therefore, the FAO56 Penman-Monteith model was adopted as most suitable for use over the Nkazana PSF in this study.

The time interval (hourly and daily) at which the FAO56 Penman-Monteith and Priestley-Taylor models were computed resulted in different K_c and α estimates. Daily computations used average daytime T_{air}, typically derived from an average of maximum and minimum daily T_{air}. In this research the models were run hourly and the average T_{air} derived from 10 s measurements of T_{air} (while R_n>0) accurately representing that hour. However, using hourly data produced outliers in the calculation of K_c and α at the beginning or end of a day where the measured or modelled results are very small numbers, producing, from division, erroneous estimates of K_c and α (Eqs. 5 and 6). These typically occurred near sunset or sunrise and were filtered out of the data as they represented outliers. In addition, due to the vastly different canopy structures and heights within the Mfabeni Mire, of the SFW (~0.8 m) and Nkazana PSF (~20 m), climatic data from above the forest was used as an input to the models to determine whether the standard deviations of K_c and α could be minimised, but no significant improvement was found. This indicated that the nearby weather station data (from within the SFW) was a suitable input for both models supporting the application of these models using the standard FAO56 weather station sensor heights of two meters (Allen et al., 2006).

4.4.6 Predicted long-term total evaporation and monthly crop factors

The long-term ET (October 2009 to September 2010) was predicted by modelling the relationship between the observed ET_{ec} and observed sapflow over the November 2009 and March 2010 field campaigns. In regressions of the emergent tree sapflow with ET_{ec} over the two field campaigns (Figs. 4.9a and 4.10a), it was found that there was little gain in using separate linear models for the two periods (R^2 = 0.90 and 0.89; RMSE = 0.05 mm and 0.06 mm) as a single, combined model, described ET_{ec} equally well (R^2=0.90; RMSE = 0.07 mm). A similar result was found for the understory tree, indicating that for both trees a single relationship between ET_{ec} and sapflow represented both field campaigns.

Table 4.4 Summary of the hourly crop co-efficient K_c and advective term α with standard deviation and root mean square error (RMSE) for each of the three field campaigns

	K_c				α			
	K_c	Coefficient of determination	Standard deviation	RMSE	α	Coefficient of determination	Standard deviation	RMSE
Aug 2009	0.8	0.75	0.22	0.07	1.0	0.54	0.35	0.08
Nov 2009	1.0	0.85	0.17	0.07	1.0	0.74	0.34	0.11
Mar 2010	1.3	0.76	0.39	0.11	1.1	0.62	0.46	0.13

In addition, a multiple regression, including the emergent and understory trees as predictors of ET_{ec} (R^2= 0.91; RMSE=0.08 mm), provided insufficient benefit over the use of the single model based on only the emergent tree (R^2=0.90; RMSE=0.08 mm). The understory tree sapflow was considerably less (by 85%) than that of the emergent tree and the density of the understory trees within the Nkazana PSF is much lower than the emergent trees. These results support the omission of the understory tree from the prediction of ET_{ec}, and the use of the following model to estimate the ET of the Nkazana PSF from hourly sapflow data:

$$ET = (0.16341 \cdot T_r + 0.06)^2 \tag{4.8}$$

where, ET is the estimated total evaporation (mm hr^{-1}) and T_r the emergent tree sapflow (L hr^1).

The estimated total annual ET (October 2009 to September 2010) from the Nkazana PSF was 1125 mm, over-which period the rainfall was 650 mm (well below the long-term average for the area). Finally, K_c was calculated at a daily interval from the modelled ET and ET_r (Eq. 4.5) and averaged for each month of the year (Fig. 4.11). These results equated well with the results of K_c calculated during the field campaigns (Table 4.4) which were 0.8, 1.0 and 1.3 in August, November and March, respectively. During a distinct period from February to May, K_c was between 1.2 and 1.4 while for the rest of the year it was 0.8 to 1.0.

The derived crop factors were verified using independent measurements of ET_{ec} over the Nkazana PSF collected during window periods at the same site from 8 to 12 August 2008 and 12 to 20 November 2008 in an experimental unpublished study conducted by the CSIR. The surface conditions during 2008 within the Nkazana PSF were much wetter as the water table was close to the surface with open water in low lying areas whereas in 2009 and 2010 the dry period had caused the water level to drop resulting in only a few areas of open water within the forest. Despite this difference in groundwater level, the K_c was 0.8 in August of 2008 and 0.9 during November 2008, validating the results derived for K_c from the ET modelled from sapflow of the emergent tree and confirming the K_c for non-water stressed situations was applicable.

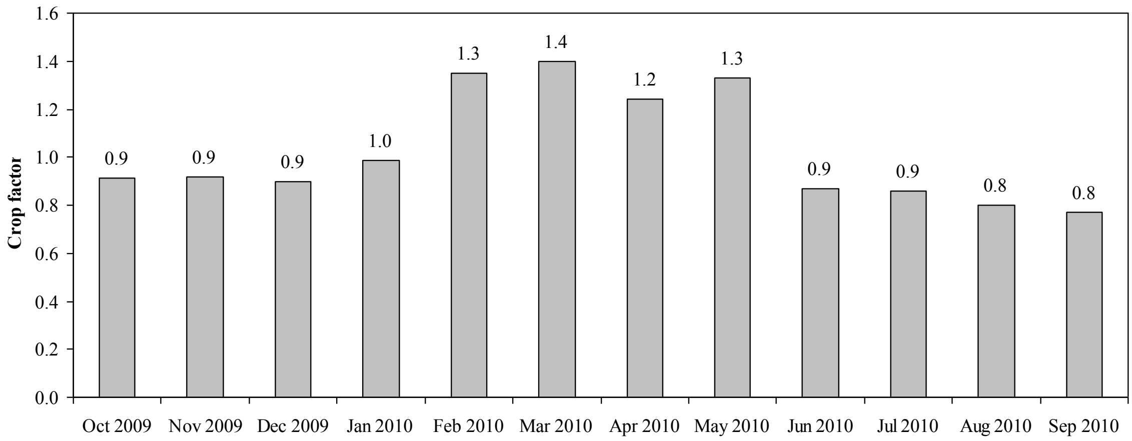

Figure 4.11 Monthly crop factors K_c for the Nkazana Peat Swamp Forest

4.4.7 Response of sapflow to climatic variables

The equation developed between sapflow and total observed ET (Eq. 4.8) allowed us to predict ET over the period during which we had sap flow measurements (Oct 2009 to September 2010). The purpose for this was to better understand the relationship between important climatic variables and ET in order to understand the climate risks over a long-term period. Three statistical approaches were used to determine these relationships with sapflow, which were directly related to ET and the climatic variables. We considered the simple linear regressions of daily sapflow with radiant flux density and VPD and found that these were poor, with coefficients of determination of only 0.51 and 0.52 respectively (not shown). Clearly the relationship between climatic conditions and sapflow is complex. We applied multiple regression analysis and found I_s, RH, T_{air} and θ at 0.075 m to be significant ($p<0.001$) with up to four-way interactions. We finally applied a regression tree analysis of hourly log-transformed sapflow with the meteorological variables I_s, RH, T_{air} and θ (Fig. 4.12). This showed again that the relationships are complex but that T_{air} and θ were not required for the optimal split for the Nkazana PSF emergent tree sapflow. The most important split was between data with I_s of less than 55.7 W m^{-2} and data with I_s greater than 55.7 W m^{-2}. Solar irradiance was clearly a key variable to include and the first split observed essentially separates day and night-time data. Solar irradiance was also highly correlated with T_{air}, which may be the reason T_{air} was not found to be an additionally required variable. The next important splits are for RH above and below 93.2% for the night time data (essentially when it is raining and when it is not) and an additional split for I_s above and below 279.2 W m^{-2} for the day time data; therefore splitting day time data during high and low irradiance periods. At night the logged sapflow was found to be negative, with the greatest negative average logged sapflow when the RH was less than 96.4%. The greatest average positive logged sapflow was found to be when I_s was greater than 279.2 W m^{-2}, and this occurred 28% percent of the time.

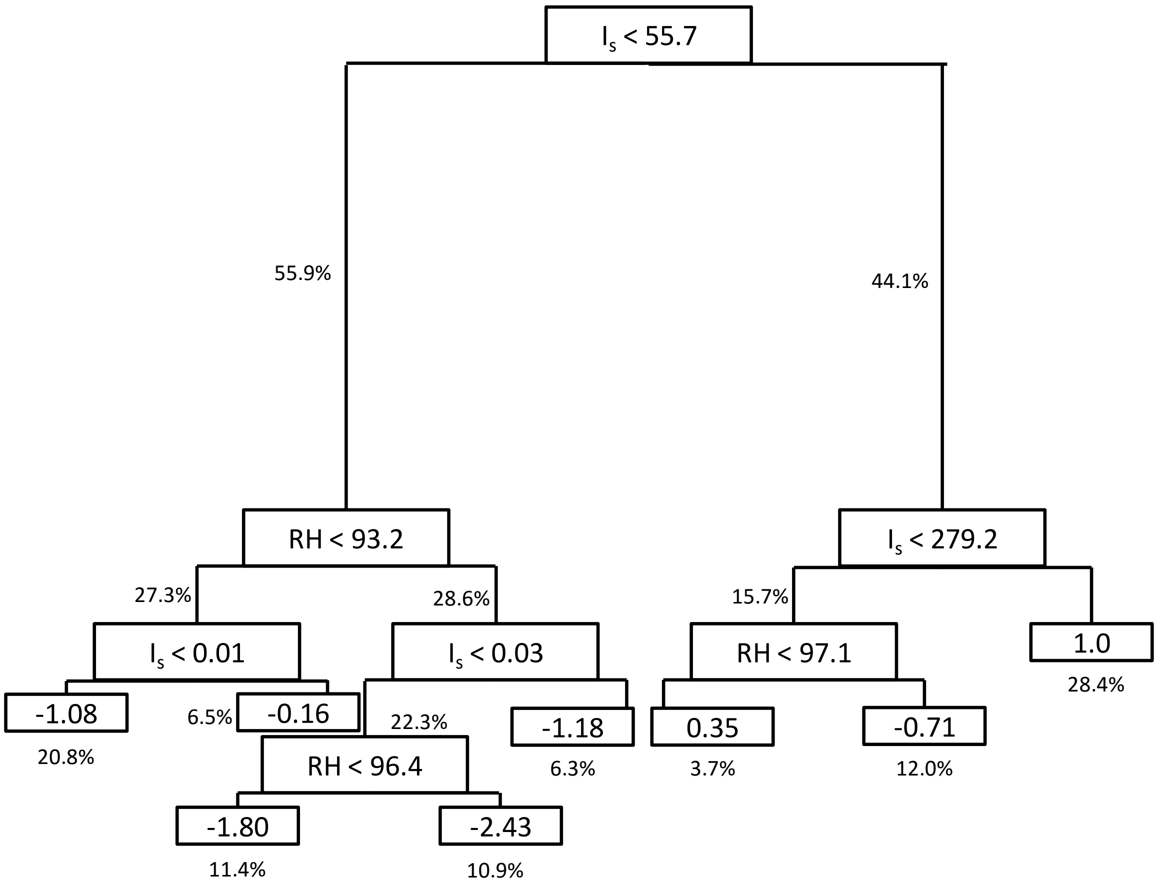

Figure 4.12 A regression tree analysis for sapflow showing the optimal splits of solar irradiance (W m^{-2}) and relative humidity (%). Air temperature and volumetric water content were included, but these variables were not required for the optimal splits. The percentage of the total data at each split is also shown

4.5 Discussion

The EC method is recognised internationally to be a suitable and accurate technique for estimating ET over vegetated surfaces and long-term EC measurements over the Nkazana PSF could provide the data required to understand the annual cycles of ET. However, EC systems have relatively high power requirements and need careful and frequent attendance as well as data checking, correction and analysis for complete records. The remote location of the Nkazana PSF, with no road access and difficult access on foot, high wind speeds and dangerous wild animals such as buffalo, rhinoceros, hippopotamus and crocodiles, prompted a research strategy to characterise the ET of the Nkazana PSF during field campaigns conducted in representative seasons, as it was impractical to maintain a full EC system over an extended period of time (such as a year). There was a risk that a period of unusual weather could have coincided with the window periods (between seven and nine consecutive days at a time), however the weather conditions during the field campaigns showed that a range of climatic conditions were captured that were representative of the seasons (Tables 4.1 to 4.3). With this approach, field campaigns could be extended if unusual weather conditions are encountered over the planned measurement period.

The challenge remained in interpolating and extrapolating the ET_{ec} results from the EC system to annual ET. In long-term evaporation studies where gaps occur or where window periods have been used, and interpolation of the ET record is required, meteorological models are typically used. Total evaporation has been estimated using models that are computationally simple such as the Priestley-Taylor model (Priestley and Taylor, 1972; Shuttleworth and Calder, 1979) to more complex models using multi-layer approaches within the canopy, but still based on the Penman-Monteith approach (Roberts et al., 1993; Harding et al., 1994), with significant deviations between measurements and modelled results. These meteorological models are however, uncoupled from the transpiring vegetation and therefore the pattern of actual tree sapflow was considered in this study as a predictor of ET.

External regulation of sapflow has been described by numerous variables including the readily available soil water of the rooting area (Oren and Pataki, 2001), the micrometeorological conditions of the atmosphere (Lundblad and Lindroth, 2002), leaf area (Granier et al., 2000), canopy conductance (Granier et al., 2000), aerodynamic resistance, shading of lower leaves and wind stress. However, it has been found that trees can have several mechanisms of internal regulation related to species specific morphology and physiology that is partially uncoupled from the external conditions (Zweifel et al., 2002). Nevertheless, in most trees with actively transpiring leaves and some readily available soil water, a diurnal pattern of sapflow results from a combination of internal and external conditions, which determines how a tree contributes to the ET of a forest stand.

With advances in sapflow measurement techniques, long-term forest ET has been estimated by up-scaling from tree transpiration to forest ET using various techniques generally based on sapwood area (Čermák et al., 2004). However, the large majority of these studies, especially where tree transpiration has been up-scaled, have been conducted in uniform forest stands (Oren et al., 1999; Wilson et al., 2001) and much of the work has taken place in temperate boreal stands (Lundblad and Lindroth, 2002; Launiainen et al., 2011) and their applicability to other climatic zones needs consideration. In addition, it has also been recognised that transpiration often varies amongst species (Oren and Pataki, 2001; Ewers et al., 2002, Bowden and Bauerle, 2008) and up-scaling to forest transpiration in species rich indigenous forests is complex.

The results from this study showed that the hourly sapflow of a single emergent tree, selected as a dominant species, correlated well with the hourly ET measured over two window periods. In species rich forests, measuring the sapflow of the different vegetation types (including the ferns, vines, understory and emergent trees) would be challenging, and up scaling questionable, due to the variety of plant structures within the canopy and our lack of information on the plant physiologies. Therefore the empirical relationship between the single tree and ET provided an ideal opportunity to model the annual ET. This relationship indicated that the emergent canopy trees are the main contributors to ET. The other contributors to ET, including open water, peat, ferns, vines and understory trees were either (1) insignificant contributors due to the low irradiance and VPD below the emergent tree canopy (supported by the low measured sapflow rate of the understory tree), or (2) follow similar diurnal trends in evaporation and sapflow as the emergent tree (also supported by the diurnal trend in the sapflow rate of the understory tree) and are therefore captured in the empirical model of the emergent tree.

Variation of the energy balance closure discrepancy (D) occurred between field campaigns, despite replication of the same instrumentation at the same site and with the same data processing procedures. Only the placement of the soil heat flux sensors changed slightly within the vicinity of the site between field campaigns. However, the soil heat fluxes (as a percent of net irradiance) fluctuated from 1% to 11%, likely due to the specific placement of the sensors within the Nkazana PSF in a predominantly shaded area in contrast to a sunlit location due to gaps in the canopy. During August 2009 when $D = 1$ (i.e. perfect closure of the energy balance), the soil heat flux was approximately 5% of R_n and was likely to be the most representative result for G for a forested area agreeing with Dye et al. (2008). In March, G was 11% of R_n and may have contributed to the poorest result of $D = 1.33$. Wilson et al. (2002) found that energy balance closure, especially over forests, is seldom achieved. However, in most cases the magnitude of the long-term turbulent fluxes is lower than the available energy (Twine et al., 2000; Oliphant et al., 2004), which was not the case in the Nkazana PSF study where D increased with increasing ET from August 2009 through November 2009 to March 2010.

An important observation made over the three field campaigns, was that the average ET measured during March 2010 (4.4 mm day^{-1}) did not correspond to the period of highest R_n (November 2009), which is commonly accepted to be one of the main driving variables in the process of ET (Albaugh et al., 2013). This indicated a lag in the ET of the Nkazana PSF in relation to the maximum R_n, possibly explaining the poor relationships observed between tree sapflow and climatic variables (such as R_n). This lag was also observed in the high K_c values from February to May, where the ET of the PSF was higher relative to ET_r. Typically, K_c is higher while vegetation is more actively transpiring and is associated with higher I_s and water availability, which in the Nkazana PSF would coincide with the summer period (October to March). However, the period of higher K_c values in the Nkazana PSF occurred quite late (February to May) in the summer season (Fig. 4.11). Chapter 3 showed the Nkazana PSF sapflow to be relatively consistent between seasons but that ET_r rapidly decreased from February to May (4.2 mm day^{-1} to 2.4 mm day^{-1}). The high K_c is therefore likely a result of decreasing ET_r while transpiration rates in the Nkazana PSF were maintained into the late autumn period. A number of reasons may be attributed to this including the microclimate of the Nkazana PSF. For example, the lower energy loss at night from the ground and within the canopy due to the combined effect of high water vapour levels (a greenhouse gas) and reduced infrared emission as a result of canopy absorbance, reflectance and re-emission downwards, compared to areas outside the PSF with shorter canopies, resulted in higher minimum daily temperatures (Fig. 4.3). The area adjacent to the Nkazana PSF where the automatic weather station was located (with a shorter canopy of approximately 1 m in height) experienced lower daily minimum temperatures (Fig. 4.3). The importance of this result is that T_{air} affects biochemical processes such as photosynthesis and senescence. This T_{air} difference, although greatest in winter, starts to build in January and could play a role in influencing the ET in relation to the summer season as well as the period of higher K_c values in the latter half of summer.

Two important points regarding the weather station data and model calculations were noted. Firstly, where possible, hourly model time intervals should be used which, concurs with Irmak et al. (2005). However, this frequently resulted in outliers in K_c and α at the beginning or end of a day where the measured or modelled results were small numbers, producing, through division, erroneous estimates. It was therefore favourable to sum the hourly ET_r and ET data for each day (while R_n>0) and calculate the daily K_c (which was then averaged for each month). Secondly, when calculating the K_c and α coefficient's, there was no benefit in using the climatic data from above the tree canopy rather than the climatic data from the adjacent SFW of the Mfabeni Mire which, sufficiently represented the microclimate for the model calculations. This showed that data from nearby weather stations can be used with the K_c to estimate the ET although this may only hold in humid environments where there is little difference in the VPD of the boundary layer conditions over the Nkazana PSF and the surrounding wetland areas which are likely to all be at, or near, equilibrium evaporation.

The shape of the regressions of hourly ET_{ec} versus hourly sapflow (Figs. 4.9 and 4.10) showed that sapflow of the emergent tree responded rapidly for low conditions of ET_{ec}. These conditions occur most frequently in the early morning and late afternoon when the angle of the I_s is low but still incident upon the emergent tree leaves. At higher rates of ET_{ec} the sapflow peaked as the physiology of the tree limited the sapflow rates. In contrast, the understory tree sapflow rate increased slowly relative to ET_{ec}, while ET_{ec} was low, and exponentially for higher values of ET_{ec}. This is likely due to shading of the understory trees for low sun angles (early morning and late afternoon) with I_s limiting transpiration (together with the low VPD discussed above) with maximum rates occurring when shading by the emergent trees was at a minimum (noon) and ET_{ec} was at a maximum. These different responses of the trees indicated that a model to derive ET from sapflow would require the inclusion of both trees. However, the sapflow and density of the understory trees was much lower than the emergent trees and therefore its inclusion in the empirical model not found to significantly improve the relationship between entire canopy ET_{ec} and sapflow. This conclusion applies specifically to the Nkazana PSF. Some models such as the WAVES model permits two canopy simulations due to the importance of the understory canopy in some forest sites (Dye et al., 2008).

Within South Africa, the study by Dye et al. (2008) measured daily ET's of between 2 mm and 6 mm on clear days over three field campaigns during February, June and October 2004 which are comparable with the results from the Nkazana PSF of between 2.2 mm (August 2009) and 5.1 mm (March 2010). Internationally, no results of ET or modelling guidelines for peat swamp forests were found, signifying the unique contribution of this study.

The comparison of meteorological variables with sapflow revealed that it is unlikely that a single climatic variable is able to determine sapflow, and in turn ET. The relationships were revealed to be non-linear and that to model sapflow accurately, data need to be sub-set into different periods; at least into day and night.

4.6 Conclusions and opportunities for further research

This study portrayed the difficulties of using the most advanced systems available to measure ET, such as EC, in remote and difficult to access areas. It showed that intensive window period measurements using high maintenance EC systems provide reliable and continuous measurements of ET but require a method to determine the ET during the in-between periods to be able to estimate long-term ET. This was overcome by measuring the long-term sapflow of an emergent canopy tree and deriving a qualitative model for ET based on sapflow measurements. Further research on the benefit of measuring multiple emergent trees and the possible variability of transpiration within different species and the extent to which this could improve the long-term estimate of forest ET together with window periods of EC data would be beneficial.

Energy balance closure discrepancy (*D*) remains an unresolved matter which affects flux measurements such as ET and CO_2. Corrections suggested in research studies can be applied but without conclusively identifying the source of the error in the observations. In contrast to most studies reported, the closure discrepancy of the energy balance over the Nkazana PSF was greater than 1 for two of the field campaigns. Although attributed in part to unrepresentative *G* measurements, *D* increased as ET increased.

The empirical model used to derive the annual ET from sapflow, and then monthly crop factors was verified with data from two independent field campaigns in 2008, when conditions were much wetter and there were larger areas of open water within the forest. The crop factors derived during these two field campaigns in 2008 (August and November) verified those derived from the empirical model calculations. The much wetter conditions in 2008 however did not alter the K_c indicating that the relationship between ET and ET_r remained constant and that the K_c derived can be applied over a range of climatic conditions. In addition, it indicates that the humid, low VPD environment within the forest canopy minimises the contribution of open water evaporation within the forest to ET. However, the general dearth of information on the ET of subtropical indigenous forests internationally allows little comparison of the results obtained from the Nkazana PSF and similar forest types and the extent to which these crop factors can be extrapolated geographically and to similar forests would benefit from further comparisons.

The Mfabeni Mire is actively managed by the iSimangaliso Wetland Park. These results provide the basis for improved estimates of the ET component of the Nkazana PSF water-balance and the environmental water requirements. Water is critical to the functioning of this ecosystem for biotic and abiotic life, the sequestration or release of carbon from the Mire and the spread of fires. The annual ET estimated in this study (1125 mm) was significantly higher than the measured rainfall (650 mm) and even higher than the reported estimates of mean annual precipitation (~950 mm). The difference between ET and rainfall highlights the importance of the groundwater contributions and the critical role it plays in assuring the survival of this groundwater dependant ecosystem. The groundwater available to the Mfabeni Mire is in part determined by the management of the upstream catchments and the groundwater levels of the greater Zululand Coastal Aquifer, emphasising the need for an integrated catchment management approach to the area.

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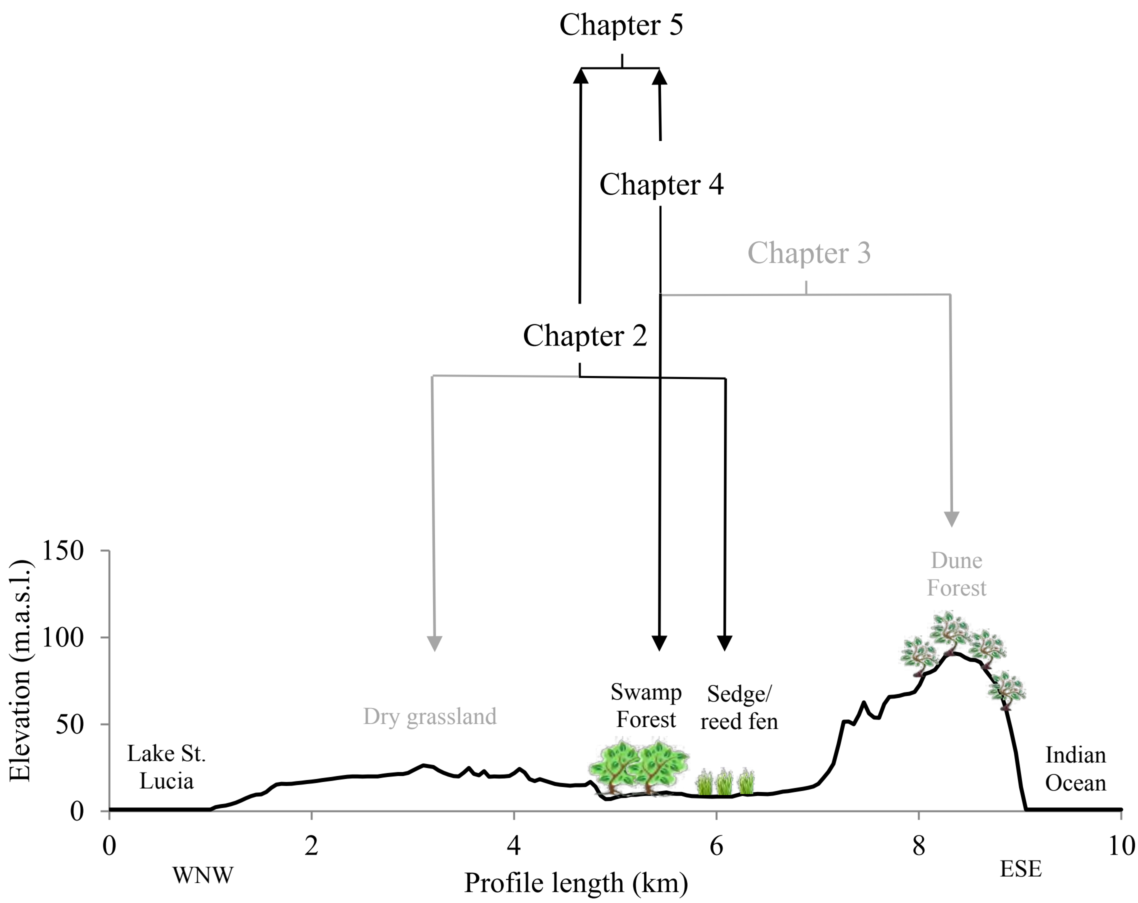
Lead into Chapter 5

The measurements and modelling frameworks used to derive long-term estimates of ET from both plant communities of the Mfabeni Mire (swamp forest and sedge/reed fen), provided the opportunity to calculate the annual water-balance of the Mire, where all components were measured and accounted for. This not only demonstrates the value of the new knowledge we have established on the water-use of indigenous plant communities of the Eastern Shores, but also provides insight and reflection on the function and value of wetlands in an area prone to seasonal rainfall (wet summers and dry winters) and extended drought conditions. Figure 1.1 has been reproduced below but modified to show how Chapter 5 integrates the results from the previous Chapters 2 and 4.



CHAPTER 5: QUANTIFYING THE WATER-BALANCE OF THE MFABENI MIRE PEATLAND IN THE ISIMANGALISO WETLAND PARK TO UNDERSTAND ITS IMPORTANCE, FUNCTIONING AND VULNERABILITY

5.1 Abstract

Peatlands occurring in regions with high rates of total evaporation (ET), matching or exceeding 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 was to quantify the annual water-balance of the Mfabeni Mire, a significant peatland in southern Africa, and thereby define its contribution to downstream and adjacent ecosystems and identify risks to future shifts in the water-balance and also the consequences of any such shifts.

Rainfall (1031 mm) and ET (1053 mm) dominated the water-balance measured from May 2008 to April 2009. These were followed by groundwater inflows (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. The limits to ET were low vapour pressure deficit and cloud cover.

Although the water-balance of Mfabeni Mire was dominated and equally split 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 on climatic variability such as prolonged drier cycles. This creates a more stable environment for adjacent ecosystems by contributing to a steady groundwater condition. 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. Management of the area should include careful consideration of any proposed changes in land-use or the encouragement of one plant community at the expense of another as this will alter the equilibrium of the current water-balance.

Keywords: *wetland, groundwater, hydrology, peat*

5.2 Introduction

Peatlands are an integral part of the larger hydrological cycle and its different components, including precipitation (*P*), total evaporation (ET), 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 interaction and magnitude of processes giving rise to their occurrence in drier climates of the world such as the sub-tropics of southern Africa are poorly understood (Lappalainen 1996; Joosten and Clark 2000; Grundling and Grobler, 2005), thus requiring further consideration to optimise their management within the hydrological environment. In such regions, ET can equal or exceed precipitation during seasonal dry periods or longer term dry-cycles (Tyson, 1981; Mucina and Rutherford, 2006; Riddell et al., 2013), and the mechanisms ensuring waterlogged and anaerobic conditions - and therefore peat accumulation - are more sensitive to the complexities of internal water storage, redistribution by surface and groundwater flows, and variability in *P*.

Wetlands most commonly studied in southern Africa have been seasonally saturated, reflecting intra-annual precipitation patterns (Tooth and McCarthy, 2007; Grundling et al., 2013). Their hydrogeomorphic setting 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 and Riddell et al. (2013) found that ET from a headwater wetland was higher than the surrounding catchment (in summer and winter) and did not augment baseflows. 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 differences in the local landscape and lithology, which control water stores and flows (Grundling, 2014). This is particularly important for the development of peat-forming wetlands, which require sustained wet conditions, occurring where the climate is less seasonal (shorter dry periods), or where sustained groundwater discharge occurs (Grundling et al., 2013). 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 occurred.

In a recent ten year drought (2001-2011), the Mfabeni Mire was found to provide diffuse freshwater seepage along the banks of the Eastern Shores of Lake St. Lucia and critical refugia to organisms threatened by the hypersaline conditions measured in the Lake (Taylor et al., 2006). Clearly the Mfabeni Mire plays a vital role in the linked ecosystem of the Lake. Quantifying the water-balance of the Mfabeni Mire is critical to advancing our understanding of the hydrological function of the Mire. This is especially important where rainfall is variable and extended drought conditions occur, 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 1462 ha sedge/reed fen and swamp forest peatland. This will define its contribution to downstream and adjacent ecosystems (ecosystem services) and provide an understanding of the magnitude of the annual components of the water-balance together with an indication of system vulnerability in terms of hydrological function. This will guide authorities and policy makers who 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 succession.

5.3 Study area and hydrological setting

The Mfabeni Mire is located close to sea-level in a low-lying depression (Fig. 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). Taylor et al. (2006) reported a strong rainfall gradient, the main source of precipitation in the catchment, which decreases from the coastal dunes towards Lake St Lucia. 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 (Grundling et al., 2013). It is bound in the north and south by beach ridges that separate it from Lake Bangazi and Lake St. Lucia, respectively (Grundling et al., 2013). 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 (Grundling, 2014). 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 losses, gives way to the younger, more permeable cover sands of the eastern dune cordon (Grundling, 2014).

Groundwater flows from the regional groundwater mound below the western dune complex (the primary recharge area) into the peatland and it discharges at the seepage area defined by the swamp forest (Grundling, 2014). 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 (Grundling, 2014). It is postulated 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 (Grundling, 2014). 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 (Grundling, 2014). Surface water in the southern section is captured by the Nkazana stream within the swamp forest, and drains southwards to Lake St. Lucia. Total evaporation plays a significant role in the hydrology of Mfabeni Mire and has been shown to exceed rainfall during drier cycles (Chapter 2).

5.4 Methods

5.4.1 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 ET (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:

$$P + GW_{in} + S_{in} - ET - S_{out} - GW_{out} - \Delta V - \eta = 0 \qquad (5.1)$$

where, P is precipitation (rainfall in this study), GW_{in} is groundwater seepage influxes, S_{in} is the diffuse surface inflow and/or open channel inflow, ET is total evaporation, GW_{out} are the groundwater seepage outflows, S_{out} are diffuse surface outflow and/or open channel outflow, ΔV is the change in stored water and ŋ is the error term.

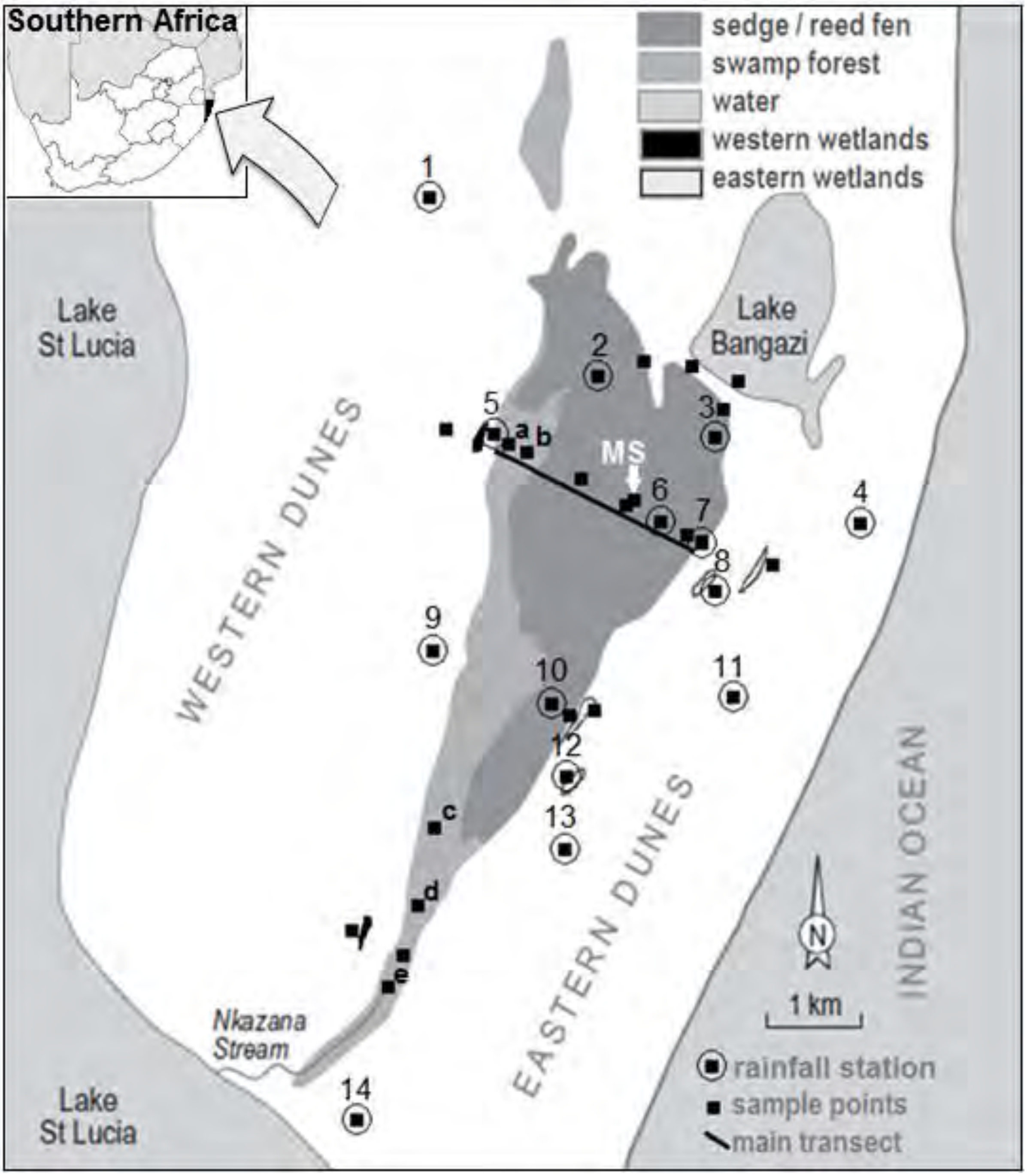


Figure 5.1 The study area. Rainfall stations and the main transect are indicated. Note the position of the meteorological station (MS)

In water-scarce regions or in sub-tropical areas where droughts persist, ET frequently dominates the water-balance (Clulow et al., 2012). It is therefore important to understand and quantify the Mfabeni Mire ET and the contribution of the different wetland vegetation types to the ET component of the water-balance. Where high ET rates persist during drought conditions and water table levels of the peatlands drop, changes in peat volume, through peat surface oscillation (PSO), could be important in calculating water storage changes (Price and Schlotzhauer, 1999), but significant PSO was not noted during the study period (Grundling, 2014).

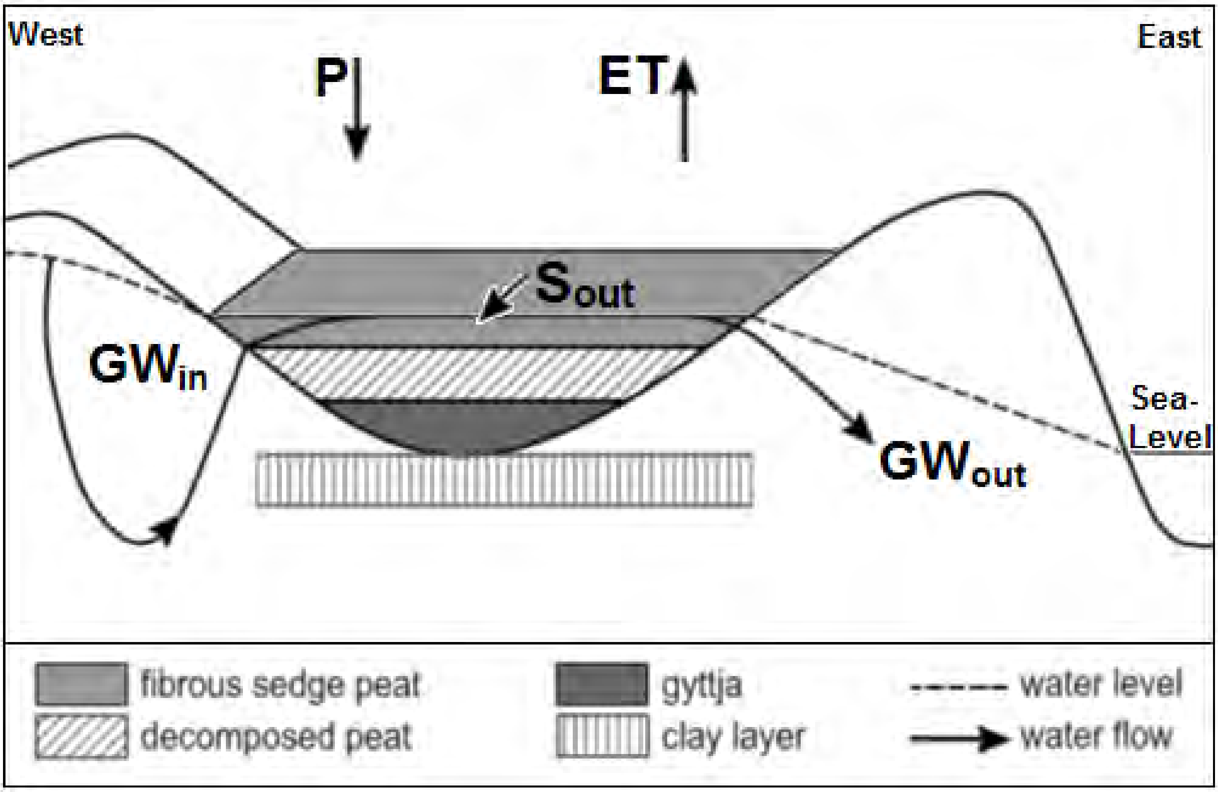


Figure 5.2 The schematic diagram of the basic assumptions of Mfabeni Mire's water-balance. Note that no stream inflow occurs as the site is located in the headwaters of the Nkazana stream

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 (Fig. 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 (Grundling, 2014). No surface inflows occurred over the duration of this study. Stream outflow occurred 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 occurred only along small portions of the outflow boundary. Stream outflow to Lake Bangazi occurred only intermittently and was assumed to be negligible.

5.4.2 Measurement and modelling of the water-balance

5.4.2.1 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. Rainfall data from the 13 manual gauges averaged 13% less than that collected in the 2 tipping bucket gauges from May 2008 to April 2009. It was assumed that evaporation loss of water in the manual gauges (monitored weekly) caused them to be lower; thus they were corrected accordingly. Rainfall 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.

5.4.2.2 Total evaporation

Total evaporation 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 Allen 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 an LAI that fluctuates between 0.85 in winter and 1.2 in summer. In Chapter 2, the ET over the sedge/reed fen was measured over the period of a year using a combination of the surface renewal and eddy covariance methods. It was found that the Priestley-Taylor model (Priestley and Taylor, 1972) explained 96% of the variation in ET over the sedge/reed fen vegetation type and an α of 1.0 was derived for the Priestley-Taylor model, which was applicable 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 415 ha swamp forest ET was measured and modelled as detailed in Chapter 4 from October 2009 to September 2010 using a combination of eddy covariance (window periods) and sapflow (long-term) equipment. It was 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. Total evaporation was therefore calculated using the equation:

$$ET = ET_r \cdot K_c \tag{5.2}$$

where, 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 (Eq. 5.2). Despite applying the ET to an annual water-balance, monthly and daily values are presented due to the value they add to understanding the water-balance study.

5.4.2.3 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 and 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 (Model 615, Solinst™, Canada, Georgetown, CA) with a 0.02 m 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 six piezometers along the main transect (Model 3001 Levelogger Gold series, 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 Grundling (2014). In the western portion of Mfabeni Mire, groundwater flows (GW_{in}) into the peat body from two sand layers (Fig. 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 (Fig. 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*:*

$$Q = -K\left(\frac{dh}{dl}\right)A \qquad (5.3)$$

where, Q is discharge ($m^3\ s^{-1}$)*;* *K* is hydraulic conductivity ($m\ s^{-1}$); dh/dl is the hydraulic gradient and *A* is the 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.

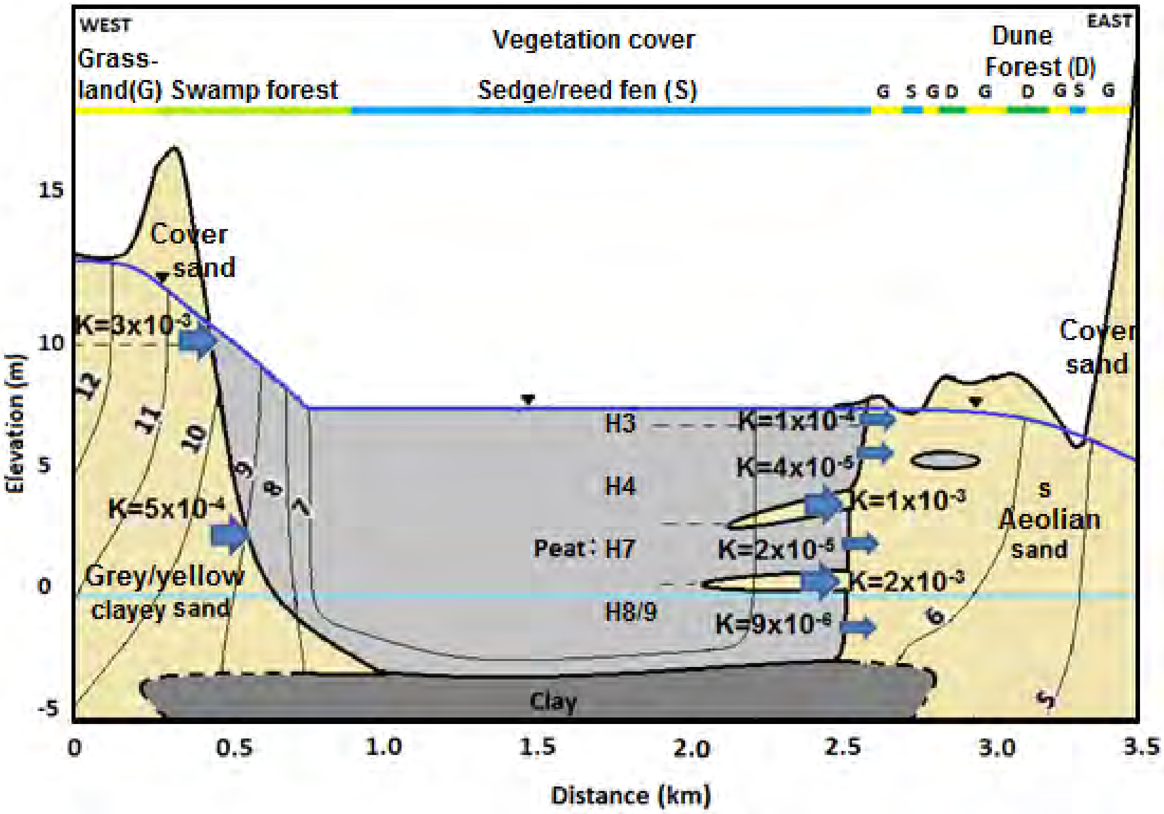


Figure 5.3 Schematic diagram of the simplified groundwater flow through Mfabeni peatland with hydraulic conductivity in m s^{-1}. Large blue arrows indicate flow through sand and the smaller arrows the flow through peat

<u>5.4.2.4 Stream outflow</u>

A compound V-notch weir beneath the Nkazana bridge (sample point 'e' in Fig. 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 (Grundling, 2014) from May 2008 to mid-February 2009. The discharge from mid-February to April 2009 was inferred from an adjacent measuring weir in the Mphate catchment operated by the Department of Water Affairs as described in Grundling (2014).

<u>5.4.2.5 Change in storage</u>

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).

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

Lithological Unit	*K* (m s^{-1})	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:	3.80E-07	7480	2.5
Sand	1.19E-05	2380	0.6
Peat	2.01E-07	6040	2.4
Sand	2.29E-05	2380	0.6
Peat	1.09E-07	3230	3.4

**H refers 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).*

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:

$$S_y = \frac{V_{wd}}{V_T} \quad (5.4)$$

where, V_{wd} is the 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:

$$\Delta V = S_y \cdot \Delta h \quad (5.5)$$

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

5.5 Results

5.5.1 Rainfall

Rainfall at Mfabeni Mire meteorological station exhibited the seasonality and variability described by previous studies of the area (Taylor et al., 2006). The highest daily rainfall (not shown) was 93 mm on 27 January 2009, while on five different occasions the daily rainfall was approximately 50 mm.

The monthly rainfall (Fig. 5.4) was highest in January 2009 (250 mm) and lowest in July 2008 (4 mm). Although described as a summer rainfall region (October to March), 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.

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 (up to 10%) over a period of a year from May 2008 to April 2009 (Fig 5.5). The rainfall was higher in the northern parts (1050 to 1100 mm) of the Mire compared to the southern region (1000 to 1050 mm). The area-weighted rainfall determined for the water-balance of Mfabeni Mire was 1031 mm.

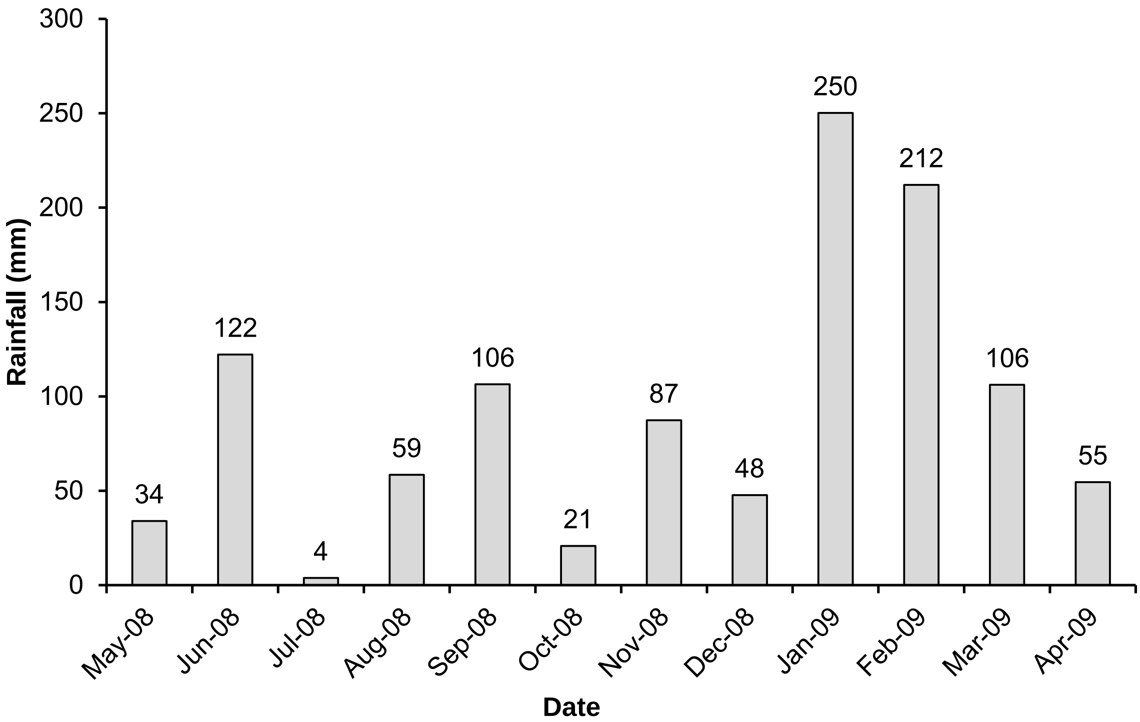


Figure 5.4 Monthly rainfall measured at the meteorological station in Mfabeni Mire using an automatic raingauge from May 2008 to April 2009

5.5.2 Total evaporation

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 (Figs. 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 with outliers in daily ET.

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 or below the higher rates of neighbouring days.

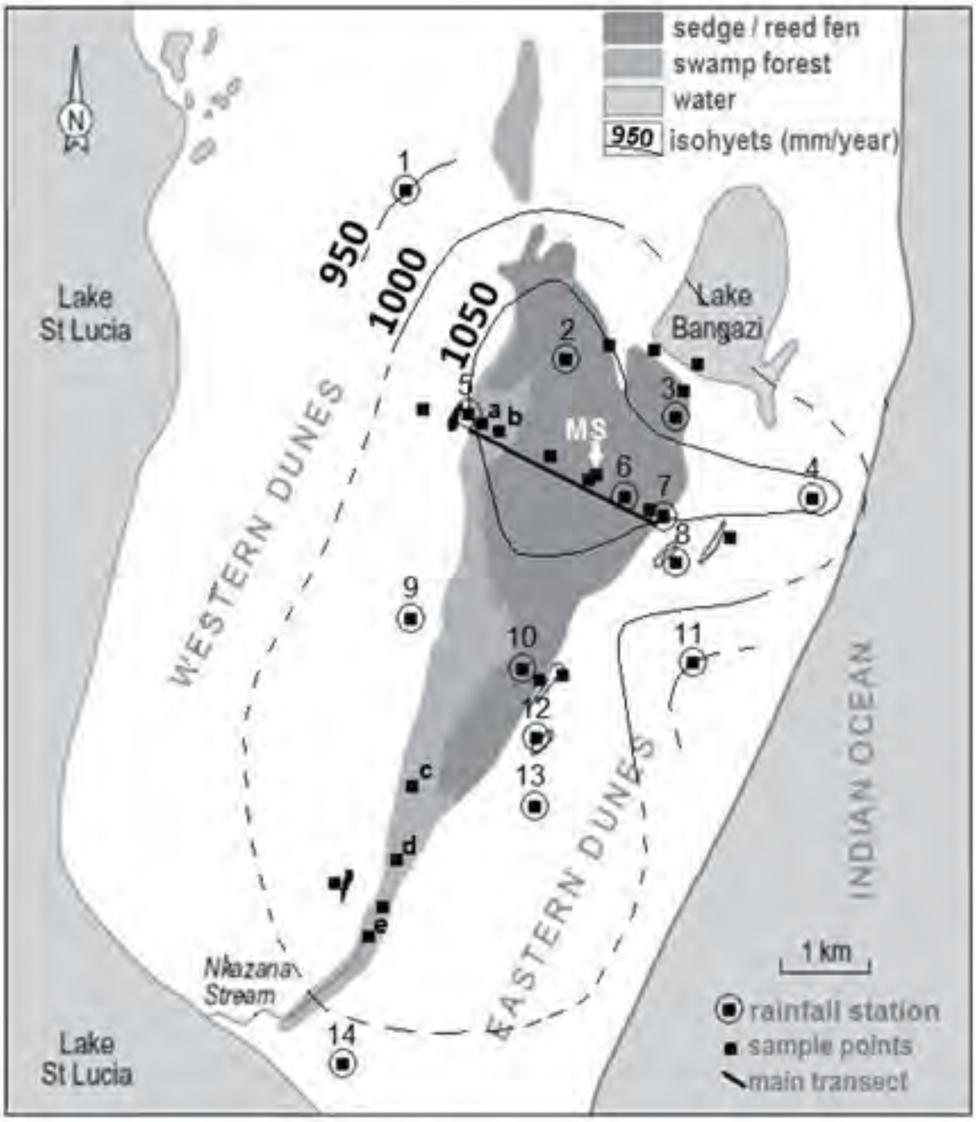


Figure 5.5 The spatial distribution of rainfall at Eastern Shores from May 2008 to April 2009. Dashed isohyets represent areas of greater uncertainty in the interpolation

The Mfabeni Mire ET accumulated to monthly values, exhibited a typical seasonal pattern (Fig. 5.7). The summer monthly ET (October to March) ranged between a minimum of 94 mm in November 2008 and a maximum of 126 mm in January 2009. The winter monthly ET (April to September) ranged between a minimum of 46 mm in June 2008 to a maximum of 85 mm in September 2008. Clearly there was a discernible difference in the winter and summer ET.

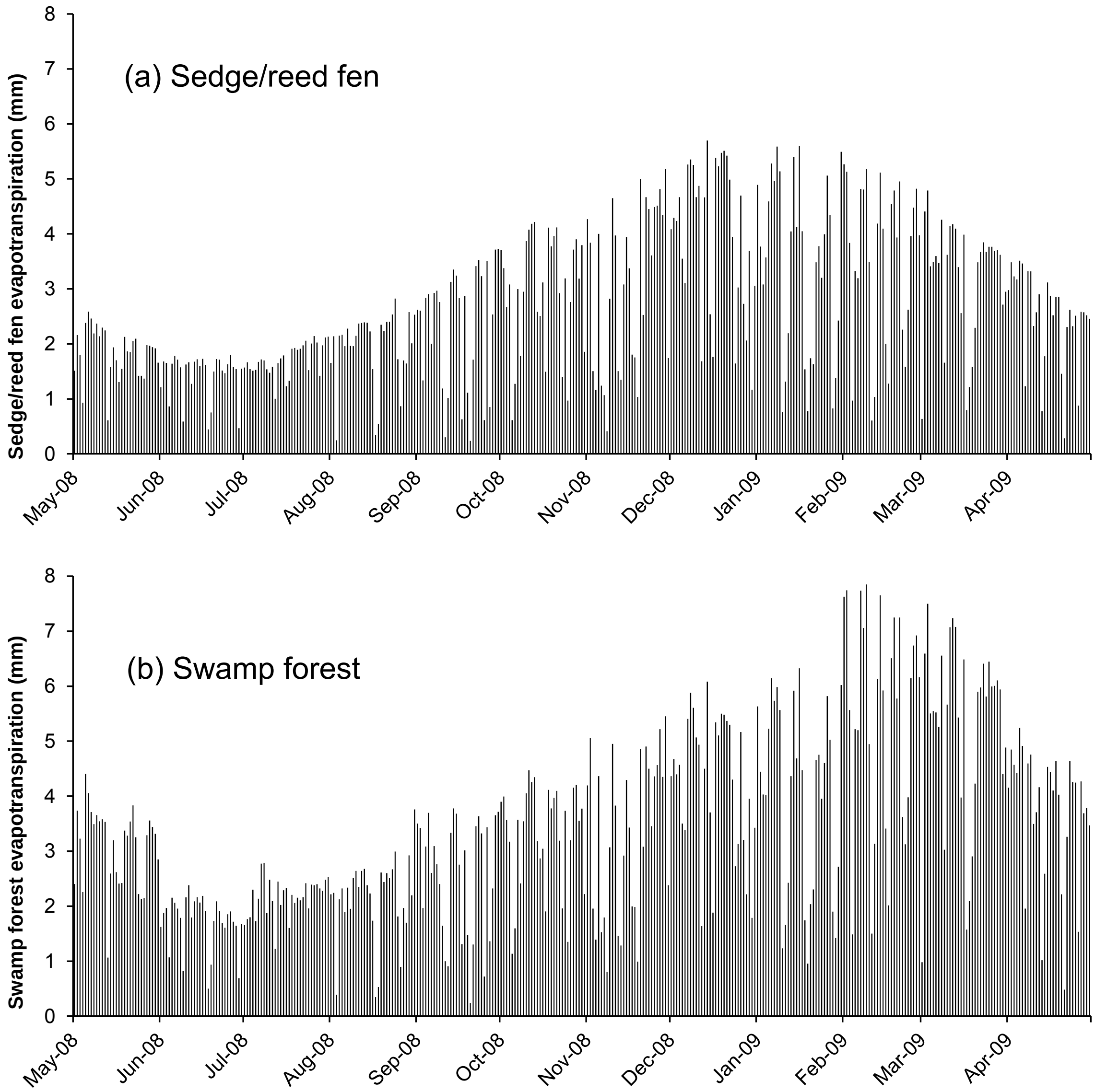


Figure 5.6 Daily total evaporation modelled for the (a) sedge/reed fen and (b) swamp forest plant communities

The swamp forest (28% of the Mire surface area) contributed 34% (354 mm) to the Mire ET whilst the sedge/reed fen (72% of the Mire surface area) contributed only 66% (699 mm). This disproportionately high contribution of the swamp forest to ET versus its areal weighting, is driven by the higher annual ET from the swamp forest. For an equivalent area of sedge/reed fen, the swamp forest annual ET is 28% higher than from the sedge/reed fen.

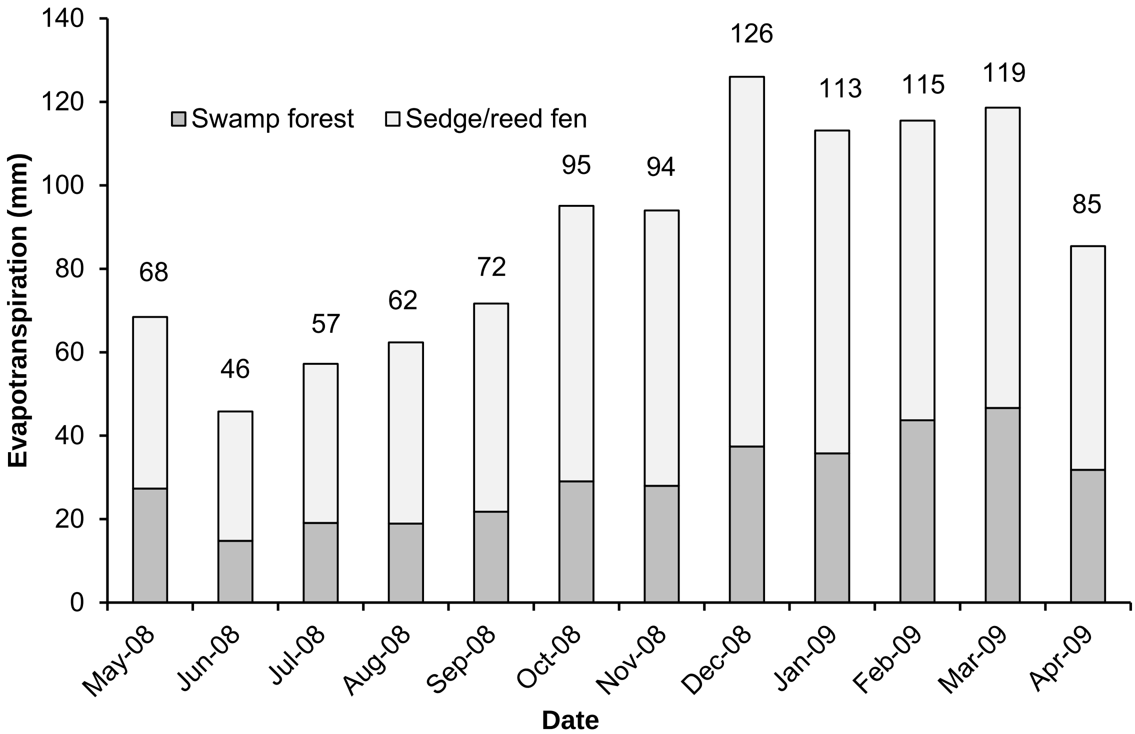


Figure 5.7 Total evaporation modelled for Mfabeni Mire from May 2008 to April 2009 by area weighting the contribution to total evaporation from the swamp forest and sedge/reed fen plant communities

5.5.3 Groundwater inflows and outflows

Groundwater flows through the peat body of Mfabeni Mire from west to east. Based on the simplified geology described in Grundling et al. (2013) and hydrological characteristics described by Grundling (2014), the groundwater flows into and out of Mfabeni Mire along its western and eastern boundaries, respectively. Groundwater flows, as determined at the geological boundaries along the main transect, were assumed to represent the groundwater flow all along the respective boundary due to the consistent geological profile found to run parallel to the coastline in Taylor et al. (2006). An annual GW_{in} of 2.01 x 10^5 m^3 yr^{-1} (14 mm yr^{-1}) was calculated at the western boundary of the peatland (Table 5.2) with a GW_{out} of 4.13 x 10^3 m^3 yr^{-1} (0.3 mm $year^{-1}$) at the eastern boundary of Mfabeni Mire (Table 5.3).

Table 5.2 Inputs to the Darcy equation (Eq. 5.3) and the final annual groundwater inflow at the western boundary of Mfabeni Mire.

Flow Unit	*K*(m s^{-1})	*d*h/*d*l (i)	Length (m)	Thick-ness (m)	*A* (m^2)	*Q*=-*K*i*A* (m^3 yr^{-1})
Sand	3.08E-05	4.17E-03	8.50E+03	2.5	2.13E+04	86 000
Sand & 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 1462 ha)						**14**

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

Flow Unit	*K*(m s^{-1})	*d*h/*d*l (i)	Length (m)	Thick-ness (m)	*A* (m^2)	*Q*=-*K*i*A* (m^3 yr^{-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 outflow (mm) (based on the Mire area of 1462 ha)						**0.3**

5.5.5 Changes in storage

The water level differences in the sedge/reed fen plant community 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 5.4). The water level differences over the same period in the swamp forest ranged from 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 (Eq. 5.5) to estimate net ΔV, which amounted to -3 mm (-50 860 m^3) in the Mfabeni Mire (Table 5.6).

Table 5.4 Water table fluctuation (m) 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 (m) 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 (m^3)	Storage change (mm)
Sedge/reed fen	22	1047	-23 034	-0.002
Swamp forest	19	415	-27 831	-0.007
ΔV		1462	-50 865	-0.003

5.5.4 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 (Fig. 5.8) but are in agreement with the rainfall measured during these months (Fig. 5.4). The annual stream flow was 9 mm yr^{-1} (131 916 m^3 yr^{-1} distributed over the 1462 ha of the Mire).

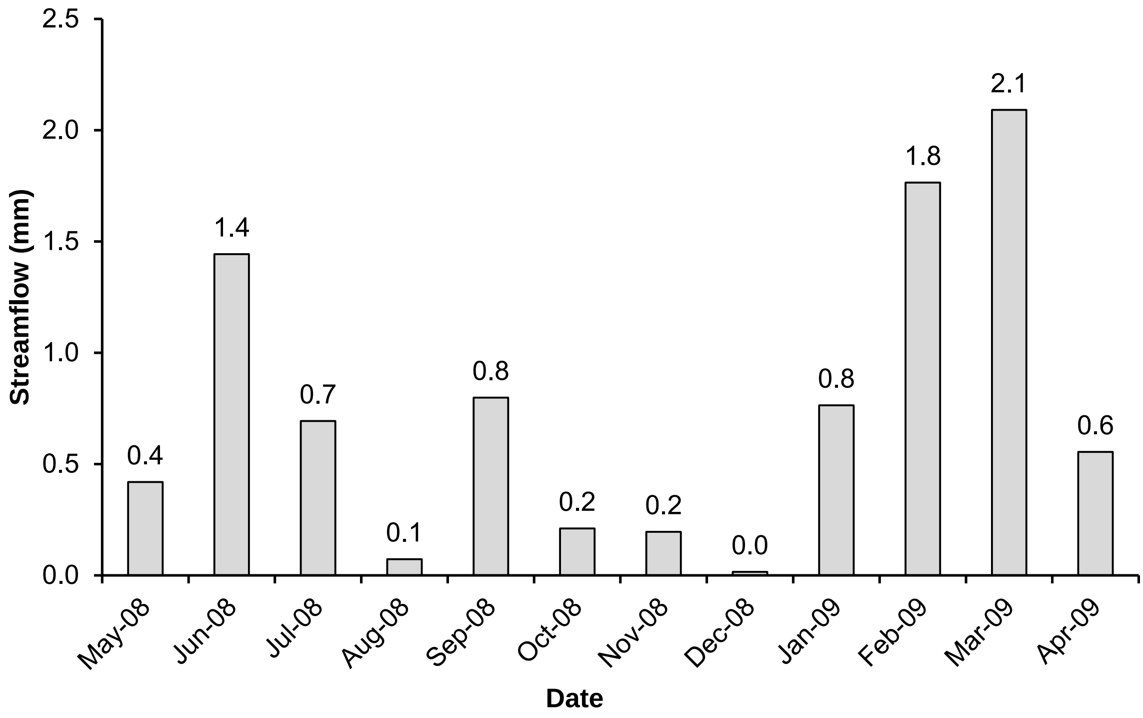


Figure 5.8 The monthly total streamflow for the Nkazana stream from May 2008 to April 2009

5.5.6 Water-balance

The annual water-balance was determined (Eq. 1), where all components were measured or modelled and the equation rearranged to determine the error term (ŋ). Total evaporation (1053 mm) and rainfall (1031 mm) dominated the water-balance (Fig. 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, the error, ŋ, was -15 mm. This deficit is only 1.9% of the ET and considered good closure of the water-balance.

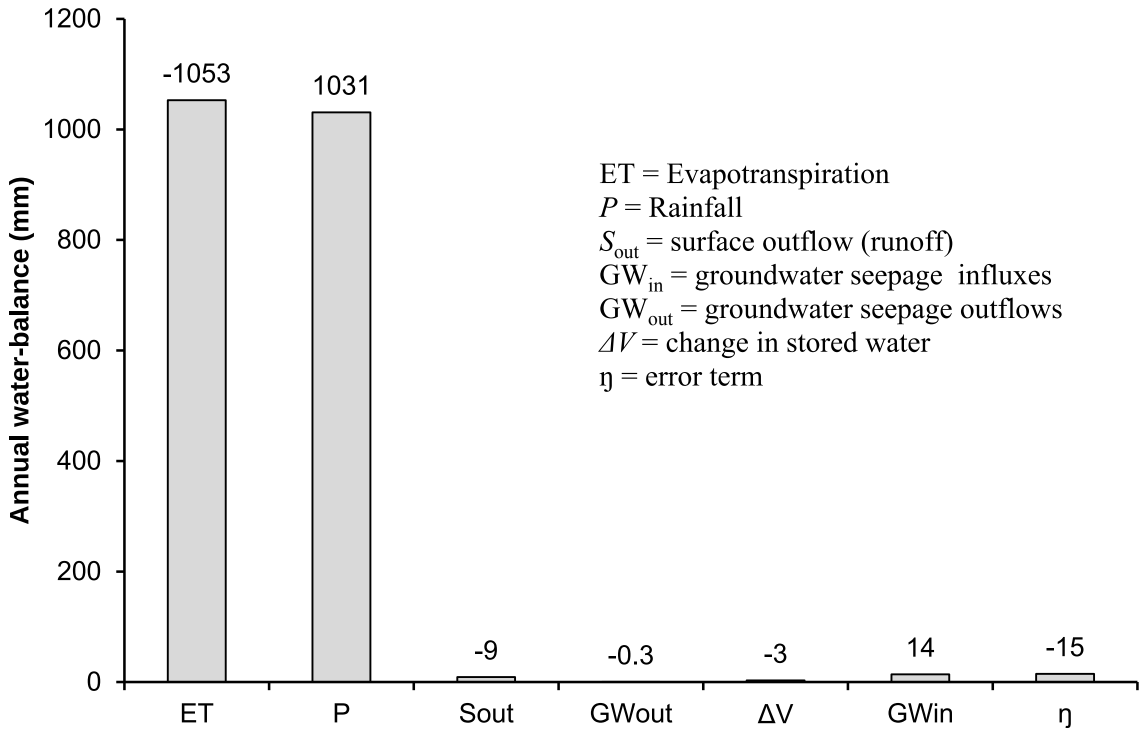


Figure 5.9 Water-balance of the Mfabeni Mire

5.6 Discussion

The annual rainfall for the Mfabeni Mire was determined from May 2008 to April 2009 and was 14% below the long-term annual average of 1 364 mm yr^{-1} (1961 to 1989) at the coast (Wejden, 2003). The rainfall measured in the study year followed a seasonal trend of wetter summer months in contrast to drier winter months. However, the dry period persisted into the summer months of October, November and December 2008 supporting the high variability of the rainfall found in the area (Taylor et al., 2006). Taylor et al. (2006) previously indicated that a strong rainfall gradient persisted from east to west across the Eastern Shores. The fifteen rain stations in the current study covered a relatively small area of 6 km in an east-west direction and 10 km in a north-south direction and only over a year and could therefore not be used to support this previous finding. There was a difference of up to 10% in the annual rainfall from different rainfall stations with the higher rainfall shown to occur toward the northern central area of the Mire. The western dunes, with grassland and relatively extensive bare soil areas (which are the recharge areas for Mfabeni Mire groundwater), received approximately 50 mm yr^{-1} more rainfall than the eastern dune area which is covered in dune forest vegetation that is opportunistic in its water-use, quickly utilising available water (Chapter 3) and contributes no GW_{in} to the Mfabeni Mire .

Total evaporation 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 swamp forest evaporation rates were higher than the sedge/reed fen. Therefore, a change in the balance between the area of swamp forest in relation to sedge/reed fen within Mfabeni Mire would alter the fine balance between ET and *P*, impacting on the resulting stream and groundwater flows. In addition, the suppression of the ET at the Mfabeni Mire due to cloud cover and low vapour pressure deficit are important controls that help maintain an equilibrium in the dominant components in the water-balance of ET and *P*. Any shift in these controls (for example through climate change) on ET could disturb the existing water-balance of the Mfabeni Mire.

The seasonal patterns of the daily swamp forest and sedge/reed fen ET 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 (Tables 5.4 and 5.5). The sedge/reed fen pattern of maximum daily ET was a smooth sinusoidal curve whereas the maximum swamp forest ET fluctuated. This could be as a result of the high and variable wind speeds recorded in the area (Chapter 2) 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 in early summer was delayed but then increased rapidly in February 2009. This delayed increase in ET of the swamp forest was also described in Chapter 4 and ascribed to the increase in the monthly average vapour pressure deficit from approximately 0.7 kPa in January to 1.0 kPa in February. 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 was 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 (Chapter 3). The high wind speeds shown to be dominant in the area are important to the estimation of ET. They are likely to have contributed 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, and hence greater ET.

The hydrological study in Grundling (2014) showed that the water table descends abruptly on the eastern edge of Mfabeni, which is likely as a result of the absence of the highly humified peat and an impeding basal clay layer beyond this point (Grundling et al., 2013) and also the relatively permeable sediments through which flow occurs. Consequently the 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). Groundwater inflows therefore occur mainly from the western dunes unless flood events such as the Demoina of 1984 occur. Most of the time, the contribution of groundwater inflows from the western dunes is a relatively small proportion of the water budget (< 2% of rainfall), although likely to be an important component that helps sustain waterlogging and anaerobic conditions in drier periods, that has aided in peatland development and currently assists in maintaining its integrity (c.f. Lapen et al., 2005). The groundwater outflow from the Mfabeni Mire (-0.3 mm) is insignificant compared to the other water-balance components. It is therefore doubtful if groundwater outflows from the Mfabeni Mire contribute significantly to adjacent ecosystems such as Lake Bangazi and the smaller eastern wetlands.

Surface inflow does not occur into the 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 *P*, underlining the importance of ET 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 by persistently low flows during the dry season. However, this relatively low surface outflow is locally significant during drier periods, providing freshwater refugia at its outflow to Lake St Lucia (Taylor et al., 2006).

Van Seters and Price (2001) concluded that in an 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 to be 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 h^{-1} (Riddel, 2011). Winter (1981) found that 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 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 the 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 the application of these models. Quantifying the absolute accuracy of the ET measurements 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 to assess others methods, and is generally considered to be accurate to within 10 to 20% (Simmons et al., 2007; Castellví 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 (Chapter 3). While many water-balance studies derive ET as a residual in the water-balance, the ET used in this study has been resolutely derived as accurately and precisely as possible due to the acknowledged importance of ET in this environment.

The groundwater inflow and outflow calculations used in the water-balance are a function of the hydraulic characteristics (K) of the substrates adjacent to and within the peatland and their overall 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 20 mm to 50 mm. 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 will result in very small differences in the absolute value of the groundwater flux. Water storage changes are also a function of the hydraulic character (S_y) 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 are likely to cancel each other, and the total change is relatively small.

In determining 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 $m^3 h^{-1}$ were measured for 35% of the time with several high flow measurements exceeding 250 $m^3 h^{-1}$. Due to data loss from mid-February to 1 May, 2009 discharge was inferred for the Nkazana stream. The Mpate stream weir located 15 km to the southwest exhibited similar discharge patterns to the Nkazana weir (coefficient of determination = 0.77). The period of inferred discharge covers 20% of the monitoring period. The average flow in Nkazana stream of 15 $m^3 h^{-1}$ from May 2008 to May 2009 compares well with previous estimates of 10 $m^3 h^{-1}$ (no period provided) (Taylor, 2006) but is less than the 50 $m^3 h^{-1}$ 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 whether this occurs. However, 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.

In considering the major threats to the equilibrium of the Mfabeni Mire water-balance, clearly those factors influencing ET and P are of highest priority. A change in ET would most likely occur through a change in land-use or climate. The land-use of 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) were a significant step in protecting the groundwater resource crucial to ecosystem support by reducing the ET. 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 ET that is higher than the dry grasslands, reduce available groundwater. In Chapter 2 is was shown that the accumulated ET of the dry grasslands of the western dunes was 478 mm over a year where as the accumulated ET over the same time period over the sedge/reed fen plant community was 900 mm and the swamp forest 1125 mm. The low ET rates of the dry grasslands of the western dunes and the GW_{in} which they supply should be considered critical to the functioning of the Mfabeni Mire. In addition, expansion of the swamp forest plant community with its high rates of ET into the Mfabeni Mire would increase the overall ET from the Mire and should be monitored and fully understood in terms of vegetation succession.

Climate change could impact both ET and rainfall. Taylor et al. (2006) state that the impact of climate change in this century is likely to be minor compared to the anthropogenic influences of the last century. However, the controls of cloud cover and low vapour pressure could potentially be nullified by climate change, leading to a deficit in the water-balance of the Mfabeni Mire with lowering of the watertable, drying and burning of the peat. Climate change predictions are complex, but it has been accepted by most that climate change will bring an increase in the frequency of extreme events (Mason et al., 1999). Already prone to extended periods of drought, more frequent and intense droughts are likely to increase episodic hypersaline events, desiccation of the Lake, with less recovery time between events, and a gradual degradation and irreversible loss in biodiversity (Chrystal, 2013). The stabilising affect of the Mfabeni Mire becomes most critical during these periods.

There are few water-balance studies in South Africa where all terms of the water-balance equation were measured. Everson et al. (1998) studied a montane grassland catchment in the Drakensberg mountains of South Africa and found that *P* was equally split between streamflow and ET and over the long-term ET was approximately 54% of *P*. Clulow et al. (2014) quantified the water-balance of an inland afforested catchment where all terms were measured and found ET to exceed *P* over a period of 8 years. Both of these studies were undertaken in a different climatic and geological setting to the Mfabeni Mire. This wetland water-balance therefore provides an important contribution to our understanding of coastal peatlands and their water-balance.

Bullock and Acreman (2003) reviewed 169 studies spanning 70 years of research to determine the role of wetlands in the hydrological cycle. They concluded that wetlands are very important in hydrology and that their appropriate management is critical in an integrated water resources approach. Most importantly however, they discourage, 'generalised and simplified statements on wetland function' but rather encouraged further investigation into their diverse hydrological function. In the present study on the Mfabeni Mire water-balance, the role of the wetland had already been identified as critical, but how that role was achieved required unpacking. The mechanisms to accomplish that role are now better understood through this study. In addition, the risks to the finely balanced system are better understood as are the importance of our management of the area in this study.

5.7 Conclusions

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 the wetland contributes and interacts with the surrounding areas.

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). The 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, is 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.

Of particular importance in such a finely balanced system and one that has already been altered in the recent history of the Eastern Shores is the land-use management of the area. The western dunes for example are the source of the critical groundwater supply, which is essential in maintaining a saturated wetland throughout the year, and enables the formation of peat. Encroachment, by a plant community into the western dunes area, with a higher water-use and/or rainfall interception than the current grasslands, could reduce this critical GW_{in} causing a deficit in the water-balance of the Mire jeopardising this all important hydrological role of the wetland. Similarly, expansion of the swamp forest, which has a higher ET than the sedge/reed fen, into the Mfabeni Mire would destabilise the existing water-balance and result in a deficit. Encouraging one plant community at the expense of another within the Eastern Shores should be carefully considered in terms of the water-balance of the Mfabeni Mire.

The variability of the annual rainfall in the area has been emphasised on numerous occasions in this study and is one of the reasons the stability the Mfabeni Mire is critical to the surrounding ecosystem. However, it must therefore also be acknowledged that this water-balance study covered only a single year and that a longer study period incorporating the variability of the dry and wet cycles would be beneficial.

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 (Chapter 2). 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.

5.8 Acknowledgements

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CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Introduction

Freshwater seepage from the Eastern Shores area into Lake St. Lucia has been identified to provide freshwater refugia during droughts when salinity levels become dangerously high for many organisms (Taylor et al., 2006; Vrdoljak and Hart, 2007). However, water-balance studies of the Eastern Shores area were previously impossible due to the lack of knowledge of the water-use characteristics of the plant communities. The research presented in this thesis examined progressively the water-use characteristics of the different dominant plant communities of the Eastern Shores area. It provides the first measurements of total evaporation (ET) from four different plant communities and compares the differences in the water-use dynamics of the forests (swamp forest and dune forest) and sedge/reed fen with the dry grasslands. Various measurement techniques were employed to achieve this, providing new insight into their application, calibration and combination.

Continued measurement and monitoring of ET over all plant communities is not feasible on a long-term basis and therefore meteorological models were evaluated to estimate ET based on standard weather station data. This provides hydrologists and ecologists with the tools required to estimate ET in a simple manner.

Finally the water-balance of the Mfabeni Mire was quantified with all components being measured. This not only demonstrated the benefits of the modelling recommendations provided for the swamp forest and sedge/reed fen plant communities but also the dominant components of the water-balance, the vulnerability of the peatland and the vital role in maintaining downstream and adjacent ecosystems.

The thesis throughout clearly shows the invaluable contribution that can be gained from field-based measurements. They require a great deal of time and involve expensive equipment, which is exposed to the risk of damage and theft. In addition, funds for travel and accommodation over an extended period can amount to a significant cost where work is conducted in remote locations. However, the results in this thesis have justified the resources allocated. Prior to this study, there was a dearth of information on ET for the dominant plant communities of the Eastern Shores area, which is now provided in this thesis, not simply through modelled estimates but based on actual measurement of the appropriate factors in the environment concerned and using the most up-to-date techniques available. The quantity and quality of data captured for this thesis sets it apart as it provides a resource of baseline measurements that will be used for future hydrological studies in the area.

Looking to the future, it is clear from recent literature that there are two external forces acting on the Eastern Shores, the Lake St. Lucia estuary and indeed the larger iSimangaliso Wetland Park ecosystem. The first is climate change, which has been accepted as a reality that will manifest in various ways, but of particular concern to the area in question are changes in the dominant components of the water-balance, namely ET and P, both of which were quantified in this thesis. Changes in ET and P will affect the water-balance and in turn groundwater levels, upon which the system is highly dependent (Været et al., 2009). Not discussed in detail in this thesis, but requiring consideration, are the associated changes in sea-level with climate change as discussed by Taylor et al. (2006), which will affect the estuary water-levels with significant changes to the structure and functioning of the Lake. The anthropogenic impact is the second external force acting on the system. This includes the land-use management of the Eastern Shores and surrounding areas of commercial forestry, sugarcane and human settlements that influence the freshwater inflows into the Lake. However, the single most significant anthropogenic impact was likely the removal of the Mfolozi River from the mouth of the Lake in 1952, which is currently being re-instated. Future actions in terms of ecosystem management depend on informed decisions. This information comes from research such as that found in this thesis, which has answered the specific questions around the indigenous plant water-use of the Eastern Shores. It is envisaged that this will enable the iSimangaliso Wetland Park Authority to develop resilient and adaptive management strategies to minimise the risks relating to water resource problems in the area.

6.2 Revisiting the aims and objectives

The overall aim of the research described in this thesis was to provide new knowledge and advance our understanding of the plant water-use dynamics and ET over the indigenous plant communities of the St. Lucia Eastern Shores area and also to empower decision-makers in terms of the future hydrological function of the Mfabeni Mire, Eastern Shores area and ultimately the greater Maputaland Coastal Plain.

The objectives of the research were to:

a) Quantify the ET losses from the swamp forest and sedge/reed fen plant communities of the Mfabeni Mire.
b) Differentiate the ET losses of the Mfabeni Mire from those of their contributing catchment.
c) Improve our understanding of the dominant processes controlling ET in the Mfabeni Mire.
d) Assess and validate the most suitable measurement techniques and meteorological models to estimate ET for the plant communities of the Mfabeni Mire
e) Determine the seasonal trends in ET losses from the Mfabeni Mire and their proportional loss from the wetland water-balance.

Specific contributions to new knowledge and how these contributions met the objectives of the research are summarised as follows:

- Quantification of ET in either window and/or long-term periods using modern meteorological equipment, providing the first estimates of ET in South Africa for swamp forest, dune forest, sedge/reed fen and dry grassland plant communities of the Eastern Shores area (Objectives a, b and e).
- Identification of the most suitable meteorological models to determine water fluxes from wetlands of the Eastern Shores area (Objective d).
- Derivation of an FAO-56 Penman-Monteith crop factor for the swamp forest and Priestley-Taylor aerodynamic α term for the sedge/reed fen plant communities (Objective d).
- An assessment of the suitability of the surface renewal methodology to determine the long-term sensible heat fluxes over wetlands such as the Mfabeni Mire (Objective d).
- Derivation of a suitable α factor for the surface renewal methodology in a wetland environment (Objective d).
- The suitability of applying different methods of ET estimation in wetlands with significantly different canopy structures (Objective d).
- An understanding of the contrasting limiting factors controlling the water-use dynamics of the swamp and dune forests (Objective c).
- An innovative approach to determine long-term ET of the swamp forest by combining high maintenance window period eddy covariance measurements with overlapping, low maintenance, long-term sapflow measurements (Objective d).

- Quantification of the water-balance of the Mfabeni Mire showing rainfall and ET to be the dominant hydrological processes but not necessarily the most important in terms of wetland ecosystem function (Objective e). The wetland ecosystem function, in terms of its hydrological contribution, still remains the outflow of fresh water from the Nkazana river and seepage zone into Lake St. Lucia during dry periods when salinity levels are high in the Lake.
- The importance of land-use management particularly that of the grasslands of the western dunes (due to its role in groundwater recharge to the Mfabeni Mire) and the swamp forest plant community (due to its high rates of ET) (Objective e).

6.3 Challenges faced in the course of this research

The greatest challenge in measuring the water-use of the dominant vegetation types of the Eastern Shores area, besides site selection, choice of appropriate measurement techniques and execution of these techniques in a remote area with the continuous threat of damage to the equipment by wild animals, was the achievement of long-term ET in contrast to the short window period measurements.

Short-term measurements were logistically challenging, especially in the swamp forest, and required a research team to implement, rigorously maintain and monitor the equipment. The potential threats to achieving complete and precise datasets were mainly from: power supply failure, computer errors, insect damage to and spider webs on the sensors, hippopotamus damage to the base of the mast and damage to sensor cables by rodents. However, extensive datasets over these short-term measurement window periods were successfully collected from the different sites due to careful planning, implementation and the diligence of the research team. Over window periods of two weeks, the data were processed timeously, any errors identified and rectified immediately. A final advantage of the window period measurements was that the exposure of researchers to the danger of the surrounding wildlife was limited to short time periods.

To achieve long-term datasets of water-use required innovation. Some techniques were tested and evaluated over periods of between 12 and 20 months with monthly maintenance only, but applied in conjunction with the intensive window period measurements. The surface renewal and sapflow techniques were two techniques identified for long-term deployment. The sites were protected by fencing wire (electrified in some cases) and power was supplied using solar panels. Electrical components were well sealed to prevent infestation and damage by ants and corrosion by the high humidity levels. Most importantly however, measurements were duplicated should there be sensor damage. This worked particularly well for both the surface renewal and sapflow methods which had sensors damaged during the course of the research. The fine-wire thermocouples of the surface renewal system were damaged by contact with fast growing vegetation, birds, rain and possibly waterbuck in the sedge/reed fen whereas the thermocouples of the sapflow systems were eaten off by insects or rodents at bark level but were unfortunately never identified. The duplicate measurements were simply additions to the spare channels on the existing loggers and therefore carried very little cost implication but provided essential backup measurements. Techniques such as eddy covariance, especially in the swamp forest could not practically have been implemented over the long-term within available financial budgets as they require almost daily maintenance. However, the window periods of eddy covariance provided an opportunity to calibrate and verify the surface renewal technique over the dry grassland and sedge/reed fen and found to be suitable for long-term estimate of *H*. Sapflow measurements were initially only expected to provide an indication of seasonal sapflow dynamics in the swamp and dune forests without attempting to apply traditional up-scaling techniques due to the diversity in the canopy structure of the indigenous forests. However, the discovery of the relationship between ET measured using eddy covariance over the swamp forest and sapflow from a single emergent tree, provided a sought-after solution to estimating long-term ET from a low maintenance technique in the swamp forest. The limitations to deployment of equipment and financial budgets therefore stimulated innovation in terms of measurement technique combinations and modelling, and forms a valuable contribution to the research outcomes of this thesis.

Fire is a seasonal occurrence in the area in some of the plant communities that can have devastating consequences for field equipment and was a major challenge at some sites. Fire does not penetrate into the swamp forest or dune forest and hence the long-term sapflow sites were safe from this threat. However, it was a seasonal (winter) threat to the surface renewal systems at the dry grassland and sedge/reed fen sites as well as the meteorological station at the sedge/reed fen site. Ideally the vegetation should have been kept short around the sites during winter to minimise the fuel load and heat of the fire but this would have altered the canopy characteristics of the site and ET results. It was therefore necessary that the area around each site be carefully protected from alteration to remain in pristine condition, representative of the surrounding plant community. During controlled burns, firebreaks were carefully burned around the sites to prevent damage to the equipment. However, an uncontrolled wildfire swept through the sedge/reed fen in September 2009 destroying most of the sensors. Fortunately the enclosures protected the loggers and modem but most of the sensors and batteries were destroyed.

An advantage of working in such a remote, uninhabited and protected area was that the risk of equipment theft and particularly batteries and solar panels was reduced and over the measurement period no losses were incurred due to theft. However, in a UNESCO World Heritage Site such as the iSimangaliso Wetland Park all equipment installations, observations and surveys were conducted with utmost care to minimise environmental impact. In addition, equipment could not be setup where it would be visible to visitors of the Park from the roads, which complicated site selection.

Quantifying the water-balance of the Mfabeni Mire involved a number of challenges. These included accounting for the spatial variability particularly in *P* which was previously reported. Manual raingauges were used, together with automatic tipping-bucket raingauges, and differences found between those co-located, and resulting in the need to apply an adjustment to the manually collected data, most likely due to evaporation occurring between weekly site visits. Regarding the water-balance, the error term was small relative to the dominant components of *P* and ET but quantification of the absolute error of each component was not possible although the relative magnitude of the components was informative.

6.4 Future research opportunities

The work presented in this thesis and the knowledge acquired of the research area has highlighted the following for further consideration:

- The iSimangaliso Wetland Park has UNESCO World Heritage Site status and is therefore of international ecological importance. However, it falls within an area prone to severe droughts and floods historically, and is part of a wider catchment that has undergone, and continues to experience, significant anthropogenic changes (Chrystal, 2013). Into the future, the earth’s population continues to increase and climate change scenarios include, *inter alia*, increases in surface air temperatures, rising sea levels and changes in precipitation patterns (IPCC, 2007), all of which, could alter the hydrological and therefore ecological function of the Eastern Shores area. The Eastern Shores area is regarded as a groundwater dependent ecosystem and is therefore vulnerable to sea-level and groundwater level changes (Taylor et al., 2006). Continued hydrological monitoring, appropriate policy and an integrated catchment management strategy, that includes plant communities within the Park as well as commercial forestry (mainly *Eucalyptus*) and sugarcane plantations outside the iSimangaliso Wetland Park boundaries are vital management strategies into the future. This integrated approach will be critical to preserve and manage the water resources of the area in the most appropriate manner.

- The well-known Priestley-Taylor and FAO56 Penman-Monteith models were found to be appropriate for use over the sedge/reed fen and swamp forest plant communities, respectively. However, the extent to which they can be applied beyond these two plant communities and to other South African wetlands under equilibrium conditions requires further investigation. In addition, a more complex model that takes antecedent rainfall into account by including the soil water content is required for estimating ET from the dry grassland and dune forest areas.
- In Chapter 4, transpiration from a single tree in the swamp forest was found to have a significant relationship with ET and was used to derive a long-term record of ET for the swamp forest. The measurement of sapflow across a number of swamp forest trees is necessary to determine whether the relationship between overstory sapflow and ET is reliable across different species.
- Fire plays a role in wetland function across southern Africa, yet the impact of fire on wetland hydrology and particularly its influence on ET is not well understood. During the course of the data collection for this thesis, there were two fires in the Mfabeni Mire, in September 2009 and September 2010. Fire is likely to result in changes to wetland ET brought about through changes to canopy structure, leaf area, removal of dead plant material followed by regrowth. Fire also influences albedo of the wetland surface and therefore results in changes to the energy balance. It is recommended that future research address the impact of fire on wetland hydrology.
- Computer modelling and remote sensing technologies using satellite earth observation data are available to estimate ET over large areas, but with ground-based measurements still required for validation. The measurements of ET over a range of plant communities presented in this thesis provides the ideal opportunity to validate existing remote sensing tools such as the Surface Energy Balance System (Su, 2001) and the Surface Energy Balance Algorithm for Land (Bastiaanssen et al., 1998). It was, however, noted from

the meteorological data, recorded during the the work on this thesis, that clouds frequently occur in the area and should be taken into account when considering remote sensing over Maputaland.

- Peatlands are the top long-term store of carbon in the terrestrial biosphere, and next to oceanic deposits, the earth's second most important store (Gorham, 1991). The development of peat soils is strongly tied to hydrological processes that affect the delicate balance between its production and decay. The carbon balance in peatlands is dictated by water table levels (Johson et al., 1996; Weltzen et al., 2000), soil temperature (Goulden et al., 1998), vegetation activity (Shaver and Jonasson, 1999), microbial activity (Zimov et al, 1993) and atmospheric carbon levels (Van Veen,1991; Ellis et al., 2009). Peatlands in many regions are still actively sequestering carbon, although evidence to date regarding the situation in the Mfabeni Mire peatland is inconclusive. Numerous peatlands that, until recently, were sequestering carbon have become carbon sources following human interventions or climatic shifts (Oechel et al., 1993, 1995; Oechel and Vourlitis, 1994). In particular, anthropogenic disturbances (especially drainage and fires) have led to massive carbon losses from peatland stores, rendering cultivation unsustainable and generating a significant contribution to global anthropogenic carbon dioxide emissions (Langmann and Heil, 2004). It is highly relevant in terms of our management of the the Mfabeni Mire that we consider the carbon fluxes and work towards understanding the processes of carbon sequestration and release from the Mire and their link to water table levels and climate change predictions.
- The mosaic of different vegetation types, together with seasonal inundation of water into some areas of the Mfabeni Mire complicates the long-term estimation of soil heat flux (G). The need for further studies to capture the temporal and spatial variability in soil heat flux is important, particularly as many ET models are driven by available energy (R_n-G).
- The coastal peat swamp forests outside the borders of the iSimangaliso Wetland Park and extending up into Mozambique are under severe threat. In the past, large areas of swamp forest were cleared for sugarcane farming, forestry, slash and burn agriculture, eradication of the tsetse fly and the removal of mosquito habitats. While the swamp forest is now better protected through legislation, in practice a significant and growing portion is being drained and cultivated (Grobler at al., 2004). The installation of drainage ditches lowers the water table to facilitate cultivation, but shortens the drainage

path and may accentuate downstream flooding. This has not been examined, and only recently have baseline measurements from a natural system been reported (Grundling et al., 2013). A lower water table accelerates soil respiration (Waddington and Price, 2000) which, coupled with clearance of natural vegetation and seasonal harvest of crops, eliminates carbon sequestration by photosynthesis, and thus endangers the sustainability of the peat soil resource. In addition to jeopardizing sustainable cultivation, it alters the soil structure and hence its hydrological functions including infiltration, water retention and evaporation. At present we can only speculate about these processes in disturbed systems. The results of ET from pristine areas, as presented in this thesis, are expected to serve as an invaluable benchmark or baseline for future studies of degraded areas beyond the boundaries of the iSimangaliso Wetland Park.

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