MODELLING TRENDS IN EVAPOTRANSPIRATION USING THE MODIS LAI FOR SELECTED EASTERN CAPE CATCHMENTS

BY

A. FINCA

Submitted in fulfillment of the requirements for the degree of Masters in Science at the Nelson Mandela Metropolitan University

December 2011

Supervisor: Prof V. Kakembo
Co - Supervisor: Dr A.R. Palmer

DECLARATION

I, *Andiswa Finca (209202653)*, hereby declare that the *treatise/ dissertation/ thesis* for *Masters of Science* is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

Andiswa Finca

ACKNOWLEDGEMENTS

Every journey has its own ups and down and this was no different, and it wouldn't have been possible without the guidance, encouragements and prayers of a number of important people. Firstly I would like to thank God for being my constant help and my strength through my academic journey and for the people He has brought my way. My sincere gratitude goes to Dr. Palmer, who was not only my supervisor but also my mentor and sometimes even a parent to me. Doc thank you for your guidance, assistance, encouragement and patience, you have given me the push I needed to complete this study. I would also like to thank my second supervisor Prof. Kakembo for affording me the opportunity to do my M.Sc with your department and for constantly assuring me that I am on the right track.

Thanks are also due to the Agricultural Research Council (ARC); Red Meat Research and Development-SA; National Research Fund; and NMMU's Research Capacity Development for funding my studies.

I would also like to thank my colleagues, Mrs. Verwey and Mr. Hintsa and an ex-colleague Nokubonga Mgqatsa for their assistance with field work. Then I would like to thank my family and friends for being there for me and for believing in me.

ABSTRACT

Grassland is the dominant vegetation cover of many of the 19 Water Catchment Areas within South Africa. The inappropriate management of some of these grassland catchments by the communities that depend on them for their livelihoods, often results in overgrazed lands with low biomass or invasive alien species. The short grass maintained by grazing policies of many communities results in high storm flows that have an adverse effect on the quantity and quality of runoff and recharge. Catchment-scale water balances depend on accurate estimates of run-off, recharge and evapotranspiration (ET). This study focuses on the ET component of the catchment scale water balance and explores the effect of two different grazing strategies on ET. To achieve this, two contrasting but adjacent quaternary catchments namely: P10A (a high biomass site) and Q91C (a low biomass site) were selected within the Bushman's River Primary catchment as primary study sites. Within each catchment, a relatively homogenous pixel of 1 km was selected, representing contrasting example of high and low intensity grazing. From an eleven year MODIS leaf area index (LAI) data stack (March 2000 – 2010), 8-day LAI values was extracted for each pixel in each catchment. Using the Penman-Monteith equation, potential evapotranspiration (ET_0) was calculated using data from a nearly automatic weather station. Actual evapotranspiration was estimated by adjusting ET_0 using the values extracted from the MODIS LAI product. The MODIS LAI ET (ET_{MODIS}) obtained for the eleven year period for both 1 km pixels decreased consistently, reflecting a general trend in declining LAI throughout the Eastern Cape. The highest ET_{MODIS} obtained from P10A was 610.3 mm (2001) and the lowest was 333.1 mm (2009). Then from Q91C the highest ET obtained was 534.7 mm (2006) and the lowest was 266.2 mm (2009). The ET_{MODIS} results were validated for each catchment using the Open Top Chamber (OTC) which sums the water lost from vegetation and soil within the chamber. This validation was conducted during the growing season of 2010–11. Wind speed; relative humidity and temperature were measured both at the inlet and the outlet of the chamber on five clear sunny days for each 1 km pixel. ET_a for the same period was compared to the OTC ET (ET_{OTC}) using the regression analysis and a good relationship was observed with the r^2 of 0.7065. The relationship observed confirmed that ET_{OTC} closely approximates ET_{MODIS} and that the OTC can be used as a tool to validate MODIS LAI ET on clear, low winds and sunny days.

In order to demonstrate proof-of-concept for the use of this modeling of ET_{MODIS} within a Payment for Ecosystem Services framework, the approach was applied to two other quaternary catchments under communal tenure. Within each catchment, three land use

scenarios were created for each catchment to reflect potential changes in the standing above-ground biomass. For Scenario 1, the *status quo* was maintained; for Scenario 2, MODIS pixels representing 28 km in each catchment were selected and the LAI of these pixels was doubled; and for scenario 3, LAI was halved. ET_{MODIS} was calculated for each scenario by adjusting the ET_0 data from a nearby automatic weather station with the MODIS LAI product. The results showed that the estimated annual ET_{MODIS} obtained from the high biomass catchment was 111 mm greater than that obtained from the low biomass catchment. When comparing between the scenarios, the annual ET_{MODIS} obtained from scenario 2 was the highest of the 3 scenarios for both sites. These results confirm that increased leaf area results in higher annual ET_{MODIS}. This has a positive long term impact on stream flow, as high grass biomass allows the rainfall to infiltrate the soil and be gradually released to the dams with reduced magnitude of storm flows. This approach has the potential to quantify the benefits to down-stream water users of improving above-ground biomass in catchments.

Table of Contents

CHAPTER 1

INTRODUCTION

1.1. WATER AVAILABILITY IN SOUTH AFRICA

Water is one of the most important sources of life. It is a basic need for all humans, plants and animals and is vital for sustainable social and economic development (Muller 2009). However over the past 100 years population growth coupled with human activities such as intensive agriculture, urbanization and industrialization have increased demand for water, and increased the impact that humans have on water quality. South Africa receives a mean annual rainfall of ~450 mm, which is much less than the world's average of 860 mm, and is categorized as a water stressed country (Ashton 2002; DWAF 2002; Otieno and Ochieng 2004; Scholes 2001). Moreover the impact of climate changes could lead to an overall rainfall reduction of about 20%, decreasing the mean annual runoff and recharge from several rivers in the country (Mugabi 2010; Turpie, Winkler *et al.* 2002). The current mean annual runoff is about 49 200 x 10^6 m^3 including the inflow from Lesotho and Swaziland and the usable yield is about 13 911 x 10^6 m^3 (DWAF 2002).

FAO estimates water available to be 1 154 m^3 per capita y^{-1} and according to International Water Management Institute (IWMI) by 2025 this could be reduced to less than 1000 m^3 per capita y^{-1} (Otieno and Ochieng 2004; Seckler, Amarasinghe *et al.* 1996). Malin Falkenmark, a Swedish hydrologist who developed the concept of 'water scarcity index' on the basis of minimum water required per capita, describes countries that have <1700 m^3 per capita y^{-1} as being water stressed. At <1000 m^3 the country begins to experience chronic water shortage that could harm economic development and lead to degradation of the environment (Falkenmark 1994; Falkenmark and Widstrand 1992). This is a situation faced by South Africa and at the current population rates water requirement is exceeding water availability. The current population is 49 991 300 (StatistcsSA 2010) and the daily minimum water requirement per person was estimated to be 100 l for drinking, bathing and cooking and five to 20 times of this amount is required for agricultural, afforestation, energy and mining and industrial sectors (Falkenmark and Widstrand 1992). At the moment South Africa is ranking water as the most urgent development constraint that needs to be addressed and it is closely linked to poverty, hunger and disease (Ashton and Haasbroek 2002; Ashton and Seetal 2002; Falkenmark 1994)

Water supply in South Africa relies greatly on rivers, dams and under ground water (Turpie, Winkler *et al.* 2002). There are 320 major dams in South Africa with the total capacity of 32 400 x 10^6 m^3 (DEAT 2007). The details of the five major dams including the vegetation types surrounding them named according to an up to date and complete overview of the vegetation of South Africa edited by Mucina and Rutherford (2006) are listed in Table1.

Table 1: Details of the five major dams of South Africa

Dams	**Capacity**	**Located Between**	**Rivers**	**Co-ordinates**	**VEGETATION TYPES**
Gariep dam	5341 x 10^6 m^3	South of EC North of FS 30 km from Colesburg	Orange River	30.40°S, 25.30°E	Xhariep Karroid Grassland; Eastern Upper Karoo; Besemkaree Koppies Shrubland (Mucina and Rutherford 2006)
Vanderkloof dam	3200 x 10^6 m^3	NC, NW of Orania	Vaal River	29.59°S, 24.44°E	Xhariep Karroid Grassland (Mucina and Rutherford 2006)
Vaal dam	2536 x 10^6 m^3	Gauteng and FS	Vaal River	26.53°S, 28.7°E	Frankford Highveld Grassland (Mucina and Rutherford 2006)
Bloemhof dam	1269 x 10^6 m^3	NW and Gauteng	Vaal River	27.40°S, 25.37°E	Soweto Highveld Grassland; Besemkaree Koppies Shrubland; Eastern Upper Karoo (Mucina and Rutherford 2006)
Grootdraai dam	364 x 10^6 m^3	Mpumalanga	Orange River	26.55°S, 29.17°E	Kimberly Thornveld; Highveld Alluvial Vegetation; Vaal-Vet Sandy Grassland; Saldanha Limestone Strandveld; Swartland Granite Renosterveld (Mucina and Rutherford 2006)

Abbreviations: Eastern Cape (EC); Free State (FS); Northern Cape (NC); North West (NW)

Due to water loss caused by high evaporation from dams, only about 62% of the average annual runoff can be used cost-effectively (DWAF 2004). However high evaporation rates from the dams is not the only factor affecting water availability. Factors such as changes in land use activities, climate change, and policy and regulation also affect the availability of water:

- Changes in **land use activities - these** are mostly driven by humans and are one of the major factors that affect water availability. Four main ways that the changing patterns of land use have affected water flow and availability as recorded by Department of Environmental Affairs and Tourism – DEAT (2007) are (i) urbanization which is responsible for the reduced volumes of runoff that can recharge groundwater, because of the solidification of most surfaces, (ii) hydrological patterns that are greatly affected by the construction of dams, weirs and bridges and mining within the watercourse, (iii) the misuse of land (e.g. overgrazing and inappropriate burning regimes) which leads to soil erosion that can result in siltation of dams and rivers, and (iv) invasion of alien vegetation that uses more water than the indigenous vegetation and reduces stream flow by up to 10% (DEAT 2007). According to DWAF (2004) the agricultural sector uses about 60% of the total water requirement and other sectoral allocations are afforestation (4%), urban and rural population (25% and 4% respectively) mining and bulk industrial (6%) and power generation (2%) (DWAF 2004).
- **Climate Changes** - Water availability is greatly affected by low rainfall and high evaporation rates which are due to the changes in climatic patterns, resulting in low run-off (DEAT 2007). Temperature changes may lead to a 10 – 40% increase in average river flows in some regions and a 10 – 30% decrease in others, which could greatly affect the supply of water. A sector such as agriculture, which is the major source of livelihoods for many households in the Eastern Cape, will suffer the most (Sadoff and Muller 2009) as a result of increases in temperature. The Second World Climate Conference recognized "…*that among the most important impacts of climate change were its effects on the hydrologic cycle and on water management systems and, through these, on socio-economic systems.*" (SWCC 1990)
- **Policy and regulations** - National management of water resources is influenced by the National Water Policy 1997; the National Water Act No. 36 of 1998 (NWA), and the Water Services Act No. 108 of 1997, amongst others. Decisions taken in respect

to water management and distribution by relevant authorities of government are determined by these policies. Land use practice policies also have an indirect impact on water quality and availability (DEAT 2000; DEAT 2007).

1.1.2 Water Supply in South Africa

Only 8.6% of SA's annual rainfall is converted to annual runoff, most of which is received by the Eastern region with the Western region being the drier part of the country. This conversion of annual rainfall to annual runoff is the lowest in the world; the rest is lost through evaporation and to groundwater (Walmsley, Walmsley *et al.* 1999). The hard rock base in most parts of this country makes it difficult to have major groundwater aquifers (DWAF 2002). Thus water is provided through the conservation of catchment areas (watersheds), riparian zones and wetlands (Turpie, Marais *et al.* 2008). South Africa has 19 Water Catchment Areas that supply water to the dams (Blignaut and De Wit 2004) and these are predominantly grasslands. Grassland catchments have an ability to act as a sponge that catches the summer rainfall and then gradually release the infiltrated water in the catchment during the dry season (Turpie, Marais *et al.* 2008). However in the Eastern Cape Province these grasslands catchments are often inappropriately managed by the communities that live in them (Hoffman and Ashwell 2001). Many of these communities that occupy catchments in the province have high livestock numbers and there is inconsistent application of a rotational grazing system, and this leads to overgrazing, soil erosion and invasion of alien plants (Fraser 1989; Fraser 2004). These three factors have an adverse effect on water supply. Firstly, the low biomass condition associated with intensive continuous grazing results in high storm flows and rapid erosion, with the resultant siltation of the dams (Mander, Blignaut *et al.* 2007). Secondly, the short green grass that is maintained by the continuous grazing policies of many communities affects the rate and quantity of evapotranspiration (ET). This study set out to examine the effect of two grazing strategies on ET and to quantify the effect on run-off. At present, livestock owners are still reluctant to reduce the number of their livestock and the answer has not been found in legislative instruments (e.g. to enforce stock reduction through the Conservation of Agricultural Resources Act 23 of 1984).

1.2. EFFECTS OF HIGH LIVESTOCK NUMBERS ON WATER QUANTITY

Dense rural settlements, cultivation, overgrazing and excessive burning have led to severe erosion, particularly in the former homeland areas. Overgrazing and soil erosion has resulted in reduced ground water supplies and the silting of dams and rivers (Ongwenyi, Kithiia *et al.* 1993). High livestock numbers in particular have had a great impact on the degradation of natural rangeland. Communal farmers are often reluctant to part with their animals for cultural and traditional obligations, resulting in the continuous heavy use of natural resources. Reasons for keeping livestock include traditional uses, as a source of wealth, provision of milk, draught power, manure and meat (Cousins 1997). Livestock ownership also gives the owner prestige and status in the community (Ainslie 2002). Since most communal grazing is open access, individual livestock owners can continuously increase their herd size without any consideration of the damage to the grazing land because they do not bear the full cost (Vink 1986). Each livestock owner would consider only their own private costs and benefits (Fraser 1989). This in turn affects the land surface condition and ultimately quality and quantity of runoff because overgrazed lands have less grass cover.

Some of the consequences of overgrazing as recorded in African Adrenalin (2007) are:

1. "O*vergrazed agricultural land is permitted to heat up under the sun and as a consequence, water evaporates quickly without being afforded an opportunity to permeate the soil for slow release on a sustainable basis.*
2. *Overgrazed lands also permit any breeze to speed up evaporation and similarly reduce permeation of water into the soil.*
3. *Thirdly, overgrazing removes grass cover on the ground, which permits water to flow in volume over the ground after heavy rains, causing wash away of the topsoil.* " (African Adrenalin 2007)

Also overgrazed lands are more prone to invasion by IAPS and indigenous woody shrubs which in most cases utilize more water and have higher transpiration rates than the native species. Moran *et al* (2009) have shown that soil evaporation contribution to ET was doubled where *Eragrostis lehmanniana*, a southern African grass, had invaded in the United States (Moran, Scott *et al.* 2009) .

One of the ways that could be used to meet the challenge of overgrazed lands is for water users to pay livestock owners directly where they can show that reduction of their livestock numbers coupled with good management practices has lead to an improvement of the grass cover within the catchments. This could be achieved by developing a Payment for Ecosystem

Service (PES) model which is being adopted as a way to solve problems with environmental conservation in many parts of the world (Proctor, Köllner *et al.* 2008). The economic impact of environmental degradation can only be recognized when the ecosystem services have a price. For instance, the availability of objective price can lead to reduction of degradation through the use of economically efficient market based mechanisms (Millenium Ecosystem Assessment 2005). Richmond *et al* (2007) attempted to answer two questions relating to ecosystems: firstly they wanted to find out if ecosystems contribute economic gross domestic production and secondly if it does contribute can the contributions be used to calculate the shadow price for environmental services? To answer these questions they estimated a Cobb Douglas production function using the net primary production, capital and labour. Then the positive output elasticity was used to calculate the marginal product of the net primary production which is the shadow price for the ecosystem service (Richmond, Kaufmann *et al.* 2007). More details on payments for ecosystem service are discussed below.

1.3. PAYMENTS FOR ECOSYSTEM SERVICES (PES)

Degradation of natural resources has had a negative impact on development (Boyd and Banzhaf 2007). One system that has been suggested to counteract this impact is “Payments for Ecosystem Services” (PES). Daily (1997) describes ecosystem services as “the benefits of nature to households, communities, and economies” and promotes the idea that ecosystems are socially valuable (Daily 1997). Payment for ecosystem services is a mechanism to translate external, non-market values of the environment into real financial incentives that encourage land users to provide certain services (Engel, Pagiola *et al.* 2008). Pagiola and Platais (2007) provide the logical framework for the benefits that can be derived from PES (Figure 1).

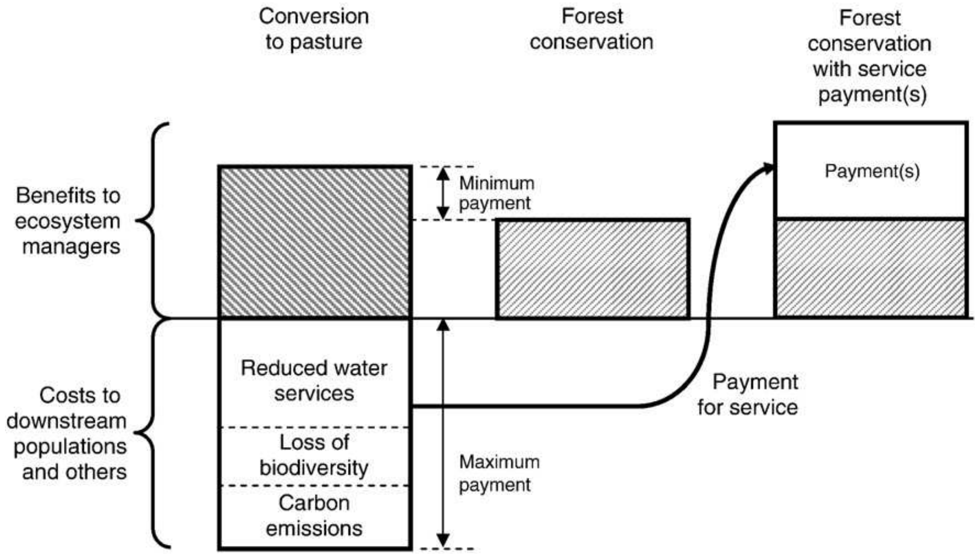


Figure 1: The logic of PES. Source (Pagiola and Platais 2007)

PES came about in South Africa through establishment of the WfW programme in 1995 (Turpie, Marais *et al.* 2008) and has focused on payments for services such as carbon sequestration, improved water supply, biodiversity and soil conservation (Blignaut, Marais *et al.* 2007). In a PES program, a payment for a certain ecosystem service is offered by an ecosystem service buyer to an ecosystem service seller that has a service that will benefit the buyer (Engel, Pagiola *et al.* 2008). Most ecosystem service sellers are landowners, of either the state; private; or communal land (Turpie, Marais *et al.* 2008). Private and communal landowners are mainly farmers that use some of these ecosystem services for either commercial or survival purposes. They also use the affected areas as rangelands, and therefore reduction of alien invasive species and increase in grass biomass will also benefit them and increases their production (Turpie and Heydenrych 2000) and (Turpie, Heydenrych *et al.* 2003). In cases where the ecosystem services paid for involve changing land use activities, the costs are higher as opposed to when they are made for retaining them (Engel, Pagiola *et al.* 2008). In the Eastern Cape there is need for land use activities to change within the grassland catchments that are also used as rangelands. Currently these grassland catchments have less grass cover due to inappropriate land practices such as overgrazing. This leads to rapid runoff that silts the dam and also removes the top soil.

Application of effective management regimes is required in order to improve the grass cover within the grassland catchments as this can ensure that there is gradual supply of water to the catchments. Also this will increase the amount of water available to meet the country's water demand. In the previous years water demands were met through a complex system of engineering supply side solutions which included major inter-basin transfer and water pumping schemes (Smakhtin, Ashton *et al.* 2001). However these have become costly and the water available for that has reduced because 12 of South Africa's 19 water catchment areas receive insufficient rainfall (Blignaut and De Wit 2004). This has increased the need to explore other options for increasing and conserving water supplies (Ashton and Seetal 2002). Therefore through the application of a payment for ecosystem services (PES) approach livestock owners can be encourage to improve the vegetative cover in the catchments they manage and receive direct compensation from the water user (e.g. dam owners, local authorities, irrigation agriculture) (Engel, Pagiola *et al.* 2008).

This approach requires a thorough understanding of the quantity of water that can be guaranteed if the livestock numbers are reduced and the vegetative cover changes. Hydrologists have traditionally tried to predict water supply by using models which rely on data from gauging weirs and a network of rain gauges (ACRU (Schulze 1990); SPATSIM (Hughes 2002) SWAP (Kroes and Van Dam 2003). However, these models need to be parameterized for each catchment and this is problematic in un-gauged catchments, which is the predominant situation in southern Africa. The Working for Water Programme in South Africa has demonstrated the importance of understanding the role of plant water use within a catchment (Blignaut, Marais *et al.* 2007). New techniques have been developed for improving the understanding of the role of evapotranspiration in water balances within catchments, and these can be used to drive management interventions in gauged as well as un-gauged catchments. Several examples of improving estimates of catchment-scale ET have been developed and are strongly driven by input from satellite-borne sensors and programmes (SPOT, MODIS). One of these, the MODerate Resolution Imaging Spectroradiometer (MODIS), produces the leaf area index (LAI) which provides an opportunity (Wang, Woodcock *et al.* 2004) to model actual ET (ET_a) when combined with ground-based meteorological data.

1.5. LEAF AREA INDEX (LAI)

LAI is the total one-sided area of leaf tissue per unit ground surface (Watson 1947). LAI is frequently used to estimate ET and it the component of crop growth analysis that is responsible for the ability of the crop to capture light energy. LAI also plays a key role in canopy microclimate, water interception, radiation extinction, and water and carbon gas exchange between global ecosystems and the atmosphere (Fan, Gao *et al.* 2009). LAI estimates can be obtained by using either the direct or indirect methods.

One of the most direct methods involved physical removal of the leaves from the plants (He, Guo *et al.* 2007) and then the total leaf area of the plant per unit ground surface can be measured using instrumentation (de Jesus, do Vale *et al.* 2001). This approach is however destructive and is time consuming. Also its accuracy is limited to small areas (Breda 2003). Indirect methods that are based on light transmission through plant canopies, making use of the radiative transfer theory (Ross 1981) have been developed. These include commercial canopy analysers such as the AccuPAR Ceptometer (Decagon Devices, Pullman, WA) and Li-Cor LAI 2000 (Li-Cor, Lincoln, NE, USA) and the analysis of photographs taken upward with fish eye lenses (Schleppi, Conedera *et al.* 2007) which include Hemispherical Photography, Digital Cover photography. These methods are usually based on the gap fraction theory at different zenith angles (Nilson 1971). The zenith angle (θ) has an influence on both the distance travelled by the light through the canopy and the angle at which the leaves are seen at the measuring point; hence it is used twice in calculations (Schleppi, Conedera *et al.* 2007). In this study ET was modeled by adjusting ET_0 using the LAI value obtained from MODIS LAI.

1.4. EVAPOTRANSPIRATION (ET)

ET is a process whereby water flows from the soil, through plants to the atmosphere. It is the essential process that enables plants to capture CO_2 from the atmosphere (Teixeira 2010). Because the process is driven largely by incoming solar energy, ET contributes significantly to water loss in arid and semi-arid regions (Warren, Hakonson *et al.* 1996). The available energy and rainfall amounts drive the rates of the annual mean ET, runoff and groundwater recharge for a specific area. Runoff is usually higher than ET when the available energy and potential evaporation rates are low. When available energy and potential evaporation rates are high (e.g. in arid and semi-arid regions), ET may exceed runoff, except in exceptionally wet years. Observations show that annual ET is almost the same as the annual rainfall in regions where the available energy is much greater than the amount required to evaporate annual rainfall. While in regions where available energy is smaller than the amount required to evaporate the annual rainfall, annual ET is closer to potential evaporation (Arora 2002).

An accurate estimate of temporal and spatial distribution of ET is an important component of the water budget in and around a region (Dai, Yosuke *et al.* 2004). Accurate calculations of ET can be obtained using methods such as the Bowen ratio (BR), eddy covariance (EC) techniques and scintillometry (Teixeira 2010). The widely accepted standard method that can be used for estimating potential or reference ET (ET_0) is the Penman-Monteith equation which was derived from the Penman equation (Allen, Pereira *et al.* 1998; Monteith 1965; Penman 1948). ET_0 is the evaporation (E) or transpiration (T) that could occur if the surface is well watered (Allen, Pereira *et al.* 1998). When coupled together, methods for estimating ET_0 and ET provide an understanding of what the regional water budget will be after loss of water through the ET process (Briney 2010).This study set out to explore the effects of the different grazing management systems on ET and ultimately on run-off within the grassland catchments of the Eastern Cape and it was envisaged that the outcomes will pave a way for the establishment of a PES model.

1.6. AIMS OF THE STUDY

1) **To examine the possibility of using a PES system in rural rangelands as a possible solution to degradation and water issues (quantity and quality).** Over the previous years new rangelands management approaches have been introduced to reduce rangeland degradation, however these have not been as successful as envisaged. It is believed tjat land users usually over exploit the rangeland because it is free and they are not paid to conserve it or simply for survival. Therefore the application of the PES can offer a solution to this issue by ensuring that the livestock owners receive direct compensation for reducing their livestock numbers and improving the condition of their rangelands. However this approach will require a thorough understanding of how to quantify the improvements made by the livestock owners and how much water they can guarantee in order to receive the compensation.

2) **To identify suitable models for predicting ET using MODIS LAI and other possible products (SPOT), MODIS ET, from the literature.** ET describes the soil-water-plant interactions and is one of the key components in the catchment-scale water balance and accurately modelling ET can help in the determination of the water budget in and around the

region. Over the years many different techniques for estimating ET based on ground meteorological parameters have been developed and these include the Penman Monteith (P-M), Bowen Ratio (BR), and Eddy Covariance (EC), Large Aperture Scintillometer (LAS). However these techniques are expensive and can only estimate ET on homogenous surfaces at micro-scale (Tsouni, Kontoes *et al.* 2008). Recently, remote sensing techniques have been developed, and though these cannot measure ET directly they provides synoptic surface information, that makes it possible to estimate surface ET at large scale (Carlson, Capehart *et al.* 1995; Kustas and Norman 1996). The MODIS data can be used with other ET models to predict actual ET and the reason it is a preferred technique in this study other than the fact that it is free, is because it has high temporal resolution, moderate spatial resolution and high radiometric sensitivity (Zhang and Wegehenkel 2006).

3) **To explore and compare ET between two land use sites with contrasting biomass states.**
In order to understand the effects that the changes in land-use activity have on the ET rates and ultimately on runoff, it was necessary to explore and compare ET estimates from two different biomass states (high and low biomass). It is argued that high biomass cover is better for water conservation because water from the summer rainfalls is allowed to infiltrate the soil (Turpie, Marais *et al.* 2008). Whereas low biomass cover which is usually associated with intensive continuous grazing may result in high storm flows leading to soil erosion and dam siltation (Hoffman and Ashwell 2001). Dam siltation has a negative effect on both the quality and the quantity of water. The land-use scenarios show how an increase or decrease in leaf area affects the rates of ET.

4) **To apply the selected model for predicting ET to these sites.** Applying the model to the selected sites would allow for accurate estimation of ET.

5) **To validate the predictions of the model using the open top chamber (OTC).** Due to some uncertainties in remote sensing ET data, it is always necessary to develop validation techniques that will give ground truthed measurements of ET. The open top chamber is one such instrument and the advantage of using it as opposed to other ground based techniques is the fact that it is easy to construct, portable, replicable and inexpensive (Marion, Henry *et al.* 1997).

CHAPTER 2

REVIEW OF TECHNIQUES USED TO MEASURE AND ESTIMATE EVAPOTRANSPIRATION

This chapter reviews some of the methods that are used for estimating ET and provides an explanation of their characteristics, applications, limitations and successes. It has been necessary to prepare this review because various instruments and approaches used to measure ET have been sourced to provide validation data for this project. Although it strives for a comprehensive treatment of the methods, it does not claim any degree of completeness and aims to provide the reader with general background material for the other components of this study. Estimation of ET began a little more than two centuries ago when Dalton in 1802 proposed a mass transport equation for estimating ET (Kairu 1991; Savage, Everson *et al.* 2004). Since then different methods for estimating ET have been developed. Factors such as the weather parameters, soil water availability and type of plants affect ET and also influence the quality of ET obtained from different techniques (Allen, Pereira *et al.* 1998). For the purpose of providing background, some comments on the role of various factors in the control of ET are presented. The processes controlling the passage of water from the soil to the atmosphere are complex and their comprehensive review is not the aim of this study.

Weather Parameters: The main weather parameters are temperature, relative humidity (RH), wind speed (U) and solar radiation.

i) **Temperature -** Generally, when the air temperature is warm, T rates increase and this causes the stomata (the openings where water is released) of the plants to open releasing more water to the atmosphere. However if the air temperature becomes too hot the stomata will close. Cooler air temperature also causes the stomata to close, releasing less water and decreasing the T rates (Briney 2010; USGS 2010).

ii) **Relative humidity (RH) -** At high RH, T is expected to decrease. This is because as the RH increases, the air becomes saturated and this makes it difficult for water to evaporate. Consequently when RH is low T rates increase.

iii) **Wind and air movement -** When the wind speed is increased, the, rate of T by plants also increases and this is because when the air is moving, it is less saturated. As the wind moves, the saturated air around the plants is replaced by the drier air.

Soil-moisture availability - Lack of soil moisture causes the plants to transpire less water and they may even lose some leaves.

Type of plant: T by different plants can occur at different rates and things that count for this may be differences in resistance to T, crop height, crop roughness, reflection, ground cover and crop rooting characteristics. For example succulents and cacti transpire less water than other plants so that they can conserve some (USGS 2010). Management and environmental conditions: ET rates may decrease under these conditions – soil salinity, poor land fertility, and inadequate application of fertilizers, hard soil horizons, lack of control of diseases and pests and poor soil management. All of the above factors must be considered when one is assessing or developing procedures to measure ET.

Methods that estimate ET have been grouped in three and they are: water balance methods, micrometeorological (energy balance) methods and plant physiology methods. The most commonly used water balance method is the weighing lysimeter. Methods such as Penman-Monteith equation, Bowen ratio method and Eddy covariance method are widely applied micrometeorological methods. Chamber method, tracer technique and cut-tree method belong to the plant physiology method group (Xiong, Qiu *et al.* 2008). Recently, remote sensing measurements have been developed, though these cannot measure ET directly they extend the above methods which can only estimate ET from homogenous surfaces at micro scale to larger areas (Tsouni, Kontoes *et al.* 2008).

2.1. WATER BALANCE METHODS

Water balance methods determine ET by measuring different aspect of the soil water balance. These measure the incoming and outgoing water flux into the crop root zone and give ET estimates over a week or ten days (Allen, Pereira *et al.* 1998). The most commonly used water balance method is the lysimeter (weighing lysimeter and microlysimeter).

Weighing lysimeters are large containers filled with soil, water, other chemicals and entire plants. The weighing lysimeter provides direct measures of ET fluxes from the vegetation surface and it is regarded as the standard method for measuring latent heat flux (Aboukhaled, Alfaro *et al.* 1982). Weight measurements are made at regular time intervals. The evaporation rates are obtained by dividing the weight difference per unit time difference by the density of water and by the cross-sectional area of the lysimeter. The rate of water lost from the containers can be measured either for very short or long time intervals. The results obtained from the lysimeter can be used as a standard to validate other methods; however these results cannot be used to confirm ET estimates from other methods at regional scale because they only provide point data. Also the weight lysimeter methods are expensive to construct, they are destructive to the soil and not easy to maintain (Kairu 1991; Savage, Everson *et al.* 2004).

2.1.2. Microlysimeter

A microlysimetric is relatively inexpensive to construct, and mostly used to measure soil evaporation rates over a short time interval. This is due to the fact that they have a much small surface area than the weighing lysimeter and often cannot contain the whole plant (Savage, Odhiambo *et al.* 2010).

2.2. MICROMETEOROLOGICAL METHODS

Obtaining accuracy when estimating ET in the field is difficult and the instruments that are constructed for that are either expensive, labour intensive, disruptive to the natural environment or only limited to specific conditions. This has lead to the development of micrometeorological methods which compute ET estimates from weather data and these methods include: Penman Monteith (P-M), optical scintillation methods, eddy covariance (EC), Bowen ratio (BR) energy balance, surface renewal, and flux variance. The advantage of the meteorological methods is that there are no disturbances to the microenvironment and they incorporate fluxes over a big area thereby reducing sampling errors (Mengistu and Savage 2010).

2.2.1. Penman Monteith Method

The P-M method (Monteith 1965) has been adopted by the United Food and Agriculture Organization (FAO) as the standard method for estimating ET_0. ET_0 is what would be evaporated from the surface if it is well watered and it was introduced to study the evaporative demand of the atmosphere without considering the crop type, development and management regimes. ET_0 is not affected by the soil factors because it a climatic parameter that is estimated from the weather data. The crop ET (ET_c) under standard conditions is determined by the crop coefficients (K_c) that relates it to ET_0 while ET_c under non-standard conditions is adjusted by a water stress coefficient (K_s) and/or by adjusting the K_c (Allen, Pereira *et al.* 1998).

The FAO P-M, referred to as FAO-56, has been selected for use in this study because of its close estimation of grass ET_0 at the site being estimated, and it integrates both physiological and aerodynamic parameters (Allen, Pereira *et al.* 1998). The FAO-56 standards for application of the P-M model require daily maximum (T_{max}) and minimum temperature (T_{min}), solar radiation (R_s), maximum (RH_{max}) and minimum (RH_{min}) relative humidity or dew point temperature, and wind speed (U). However in cases where only daily temperature data is available, generalized temperature-based procedures to estimate the other meteorological data required, can be provided by FAO-56 through ClimGen (Castellvi and Stockle 2002; Stockle and Nelson 1999). ClimGen is a weather generation program that can give estimates of several climate parameters based on local input data. ClimGen can give daily estimates of R_s and vapour pressure deficit (VPD) from T_{max} and T_{min} data, and produce statistically correct U values though it is not linked to other weather parameters. Therefore, P-M ET_0 can be calculated using only the temperature records (Stockle, Kjelgaard *et al.* 2004). In this study FAO Penman-Monteith was computed using weather data obtained from the Automatic Weather Stations close to the selected sites which provide all the required parameters.

2.2.2. Scintillometer

The scintillometer is described as an optical instrument that measures the intensity of fluctuations of visible or infrared radiation, after propagation above the plant canopy of interest through a turbulent medium, to work out different meteorological parameters (Hill, 1992; (Savage, Odhiambo *et al.* 2010). The scintillometer methods rely on Monin-Obukhov similarity theory (MOST) and when they are combined they provide path-averaged measurements of sensible heat (*H*) and momentum fluxes over distances of between 50 m and 250 m up to 350 m (Savage, Odhiambo *et al.* 2010; Thiermann and Grassl 1992).

There are three different types of scintillometers that are used to measure water fluxes. The surface layer scintillometers (SLS) comprises two laser beams and either two or four detectors and has a wavelength of 670 nm. The SLS measures sensible heat flux density (*H*) and momentum τ flux density over a path distance of about 50 and 350 m and areas of about 0.25 to 5 ha. They have the receiver aperture size that is less than the Fresnel zone (*F*). The large aperture scintillometers (LAS) and extra large aperture scintillometer (XLAS) are for measuring refractive index structure constant, C^2_n only and they use a near infrared beam wavelength together with horizontal wind-speed measurements required for the estimation of *H* using MOST. The LAS operate over distances of about 250 m up to 3 km and areas that are over 6 ha with receiver aperture size that is greater than *F* (Savage, Odhiambo *et al.* 2010) while the XLAS operate over longer distances of up to 10 km and have a receiver aperture size that is nearly double that of the LAS (Odhiambo and Savage 2009). One of the limitations of using a scintillometer is its high price.

2.2.3. Bowen Ratio Energy Balance Method

The Bowen ratio/Energy balance (BREB) method presents a simple and inexpensive alternative to weighing lysimeter which give accurate measures of ET. BREB is widely used for estimating latent heat flux (λE) over a wide range of natural surfaces such as irrigated wheat, forest, bare soils and some non-ideal sites (Liu and Foken 2001). The BREB method is based on Bowen ratio (Bowen 1926) and the energy balance equation and determines ET using only temperature and humidity measurements, net radiation, and soil heat flux (Rosenberg, Blad *et al.* 1983). The Bowen ratio is the ratio of the sensible heat flux (H) to water vapor flux (H/LE) and it can be estimated from temperature and vapor pressure gradients by:

$$\mathbf{B = \gamma\ (\Delta T / \Delta e)}$$

Where: *y* is the psychrometric constant, ΔT is the air temperature gradient and Δe is the vapor pressure gradient. The basic energy balance model is then calculated from:

$$\mathbf{Rn + G + H + LE = 0}$$

Where: Rn is net radiation, G is soil heat flux, H is sensible heat to the atmosphere, and LE is the evaporative flux.

BREB method was found to be accurate and can be used under semi-arid conditions, however due to recent observations of an imbalance of the surface energy budgets, this accuracy has been questioned (Foken, Kukharets *et al.* 1999). To avoid these imbalances Liu and Foken (2001) proposed a modified Bowen ratio method (MBR) for measuring *H* and λE using a sonic anemometer together with temperature and humidity measurements at two levels (Liu and Foken 2001). Their results showed that humidity and velocity transformations with errors of < 10%, and the latent heat flux with errors of <20% are acceptable when the buoyancy flux is measured with a sonic anemometer (Liu and Foken 2001).

2.2.4. Eddy Covariance

The EC method is applied in many micrometeorological sites to measure CO_2 and H_2O fluxes (Mammarella , Werle *et al.* 2010) and depends on the turbulence of the airflow above and through a canopy. Air travelling over the canopy has a large number of eddies which are small chaotic currents of wind, and these can move at any direction; at any time. The EC system is usually located several meters above canopies and it is made up of an open path infra-red gas analyser (measures CO_2 and H_2O concentrations); a 3-dimension sonic anemometer (determines the velocity in 3-dimensions) and a temperature sensor (measures the air temperature) (Eamus, Hatton *et al.* 2006). EC technique is still the only technique that directly measure gas fluxes to and from the canopy; however like the BREB method they do not discriminate flux from the soil. One of the major limitations of this technique is the complexity of its design, the difficulty to implement and the large volumes of data that it processes (Burba and Anderson 2007). However EC technique has had success in addressing issues like the water and CO_2 budgets of the catchments (Eamus, Hatton *et al.* 2006).

2.3. PLANT PHYSIOLOGY METHODS

2.3.1. Open Top Chamber (OTC)

The initial aim for designing the OTC was to use it in the field for studying the effects of air pollutants, and then later it was modified for use in elevated CO_2 researches (Heagles *et al.*, 1973; Drake *et al.*, 1989). Eamus et al., (2006) have shown how the OTC can also be used for measuring the actual ET from low lying vegetation by summing up the water lost from the vegetation and soil within the chamber. The OTCs are inexpensive, easy to construct (making them easily replicable and replaceable) and transport. The design of the OTC has a cylindrical base and the cone shaped top which are covered using Melinex® that is basically polyethylene terephthalate film with high mechanical strength, good heat resistance, good flexibility, excellent electrical insulating and light transmission properties (http://www.alibaba.com/product-tp/105582310/Melinex_Film.html). A centrifugal fan (size: 100mm; air volume flow rate varies from 0.009 – 0.061 depending on the pressure; the sound and electrical data is stated at 230V 50Hz) blows air into the chamber and this air is monitored when entering and leaving the chamber using probes that can measure wind speed, relative humidity, temperature and dew point (Eamus, Hatton *et al.* 2006). More specifications of the OTC design are detailed in Chapter 3. Then T from the vegetation within the chamber is calculated from the following equation:

$$\mathbf{E} = \frac{\mathbf{\Delta e - Fa}}{\mathbf{Al}} \qquad (1)$$

Where **E** is transpiration rate (mol m^{-2} s^{-1}); **e** is the difference in water vapour concentration (mol m^{-3}) between the inlet and outlet of the OTC; $\mathbf{F_a}$ is the rate of air flow through the chamber (m^3 s^{-1}) and $\mathbf{A_l}$ is the total leaf area (m^2) within the chamber at the time of measurement (Eamus, Hatton *et al.* 2006).

2.4. THE APPLICATION OF REMOTE SENSING TECHNIQUES FOR ESTIMATING ET

Most of the above-mentioned methods are better suited to homogenous surfaces at micro-scale, and remote sensing technology was developed in the late 1970's which provided the option for spatial modeling of water use. Remote sensing technology provides synoptic surface information, making it possible to estimate surface ET at large areal extent through empirical/statistical relationships that use remotely sensed vegetation indices (VIs) (Carlson, Capehart *et al.* 1995; Kustas and Norman 1996). Also there are physical models that can estimate ET from remotely sensed data which are based on solving surface energy balance (SEB) equations through remotely sensed land surface temperature estimates (Kustas and Norman 1996; Overgaard, Rosbjerg *et al.* 2006). In general, remote sensing techniques can only measure E or ET indirectly (AGU, 1995). Some of the new remote sensing techniques that can assist in estimating ET include the Moderate Resolution Imaging Spectrometer (MODIS) sensor system on the Terra satellite (Glenn, Huete *et al.* 2007a).

2.4.1. **Satellite Pour l''Observation de la Terre** (SPOT)

SPOT is a high-resolution, optical imaging Earth observation satellite system that is operated by the SPOT Image in Toulouse, France. It was first initiated in the 1970's by the Centre National d''Etudes Spatiales- the French space agency (CNES) and developed in association with the Belgian Scientific, Technical and Cultural Services (SSTC) and the Swedish National Space Board (SNSB). The SPOT has a series of optical remote sensing satellites with the main objective to obtain Earth imagery for land-use, agriculture, forestry, geology, cartography, regional planning, water resources and GIS applications. A single SPOT satellite flies over the same point within 26 days and provides global coverage between 87 degrees north latitude and 87 degrees south latitude. SPOT 1, 2 and 3 were launched on 22 February 1986, 22 January 1990 and 26 September 1993 respectively. SPOT 3 is no longer functioning The SPOT 1 & 2 have two identical High Resolution Visible (HRV) sensors with a 20 m spatial resolution and three spectral bands sensor resolution: two visible bands, the green (0.5-0.59 μm) and the red (0.61-0.68 μm) and one near infrared band (0.79-0.89 μm). SPOT 4 was launched on the 24 March 1996 and has a High Resolution Visible Infrared (HRVIR) sensor with 20 m spatial resolution and has four spectral bands, two visible bands, the green (0.50–0.59 μm) and the red (0.61–0.68 μm); one near infrared (0.78–0.89 μm) and the shortwave infrared (1.58–1.75 μm). The most recent one, SPOT 5 was launched on the 04 May 2002 and has two High Resolution Geometric (HRG) sensors that were inferred from SPOT 4's HRVIR and has a 10 m spatial resolution (CRISP 2001; Khalaf 2010; Aboelghar, Arafat 2011).

Spot images provide more spatial details and have longer time series than other data sets such as MODIS since it was first launched in 1986. However some limitations in relation to their spatial resolution have been reported that they are not always suited for small plots (Khalaf 2010; Gers and Schmidt 2001).

2.4.2. **Moderate Resolution Imaging Spectrometer** (MODIS LAI)

The MODIS instrument was first developed after the Engineering Model was completed in mid-1995. Since then, it has become the key instrument aboard the Terra (EOS AM) satellite launched in 1999 and Aqua (EOS PM) satellite launched in 2004. The MODIS instrument has been built according to the specifications of NASA by the Santa Barbara Remote Sensing Centre (NASA 2009) and it makes it possible to expand ground truthed ET measurements to larger scale with satellite imagery (Glenn, Huete *et al.* 2007a). MODIS data is useful for the estimation of ET and surface soil water availability using vegetation index such as the normalized difference vegetation index (NDVI) and LAI (Nagler, Cleverly *et al.* 2005; Nishida, Nemani *et al.* 2003; Venturini, Bisht *et al.* 2004). These data can also be used to estimate canopy water stress index from the reflectance of MODIS multispectral bands (Fensholt and Sandholt 2003) and provide physical models with remote sensing based information such as LAI (Zhou, Liang *et al.* 2004). MODIS began delivering 1 km global scale LAI products at an 8 day interval after the launch of the EOS Terre satellite in March

2000. The MODIS LAI product has been used in many validation studies and its accuracy is 0.66 LAI units RMSE when all plants are included and it is 0.5 LAI units RMSE when broadleaf forests are excluded (NASA 2009). The validation of MODIS LAI product have two parts, firstly the validation of LAI Radiative Transfer algorithm and secondly the accuracy of LAI product by using empirical method (Cohen, Maierpserger *et al.* 2003; Tian, Woodcocka *et al.* 2002). These are being analysed at several sites over the world (Kim and Lee 2003). It has been found that the earlier versions of MODIS LAI were over-estimating the LAI product in forest, whereas they were under-estimating them in grasslands and crop lands (Cohen, T.K. *et al.* 2006). These irregularities have been corrected in Collection 4 (Tan, Hu *et al.* 2005) which is an improvement on simple band products (Fuentes, Palmer *et al.* 2008). The MODIS LAI has since been improved to Collection 5 which gives better quality retrievals over broad leaf forests (Hill, Senarath *et al.* 2006).
According to Knyazikhin et al (1998) the retrievals are affected by three random variables which are: uncertainties in surface reflectance product (due to corrections for atmosphere effects); landcover identification (due to biome identification) and georegistration. Due to variations caused by uncertainities the algorithm does not guarantee an accurate LAI value in one pixel and this can be reduced by averaging over a homogenous area or take the best value of parameters to estimate the most probable value of LAI. Since the algorithm provides the distribution of LAI values as if they were derived from ground based measurements, it is therefore important to use statistical techniques that can compare field measured and satellite-derived LAIs to validate the MODIS LAI product. Ground based validation techniques play a vital role in measuring uncertainties in the MODIS LAI product. Fuentes *et al*. (2008) used ground-truthed measurements of canopy LAI obtained using gap fraction analysis of upward-looking digital photographs at eight sites in Australian *Eucalyptus* woodland to validate MODIS LAI (Fuentes, Palmer *et al.* 2008; Macfarlane, Hoffman *et al.* 2007).

Palmer et al (2010) validated the predictions by the MODIS LAI-Stand Water Use (MODIS LAI-SWU) model they developed using data obtained from two catchments. The one in Northern Territory (Howard River), Australia had ground truth measurements from EC, sapflow and OTC techniques which were compared with the MODIS LAI-SWU model predictions. From the other one which was a gauged quaternary catchment in South Africa, ET was calculated from the available rainfall and runoff data and also compared with the predictions by MODIS LAI-SWU model (Palmer, Fuentes *et al.* 2010). Their results showed an acceptable comparison between the MODIS LAI-SWU model predictions and the EC data which led to the conclusion that the model can improve catchment scale estimates especially in ungauged catchments (Cook, Hatton *et al.* 1998; Palmer, Fuentes *et al.* 2010).

Studies done by Leuning *et al* (2005) showed that MODIS LAI has an ability to approximate the stomatal conductance component (g_s) of the Penman Monteith equation and it was used in this study as an input into the Penman–Monteith equation (Leuning, Cleugh *et al.* 2005). The MODIS LAI estimates obtained are ground truthed using the OTC that sums up the water lost from the vegetation inside the chamber. MODIS was selected in this study because it has a higher radiometric resolution than any other high temporal resolution imagery (Khalaf 2010).

CHAPTER 3

METHODS AND MATERIALS

3.1. SITE SELECTION:

3.1.1. Site selection Criteria

Sites considered suitable for this study were quaternary catchments that have dams that supply water to the urban areas and the rural water schemes. The selected sites were either of high or low biomass cover for comparison. Rivers, dams and quaternary catchments were downloaded from the Department of Water Affairs and Forestry website: http://www.dwaf.gov.za/iwqs/gis_data/river/rivs500k.html and the map of the Local Municipalities of the Eastern Cape (EC) from the Municipal Demarcation Board website: http://www.demarcation.org.za/. These were downloaded as ARCView shapefiles and then imported to IDRISI (Version I32.11, Clark Labs, Clark University, Worcester, Massachusetts) where they were saved as vector files. Rivers, dams and quaternary catchments were displayed as overlays on the MODIS LAI product from the growing season in 2009 to select quaternary catchments suitable for further study. Images from Google Earth were also used to visually confirm the cover and biomass state of the selected sites. Four quaternary catchments were selected in the following Local Municipalities of the Eastern Cape, South Africa: Emalahleni, Sakhisizwe and Intsika Yethu (quaternary catchment S20C and S50E) and Makana Local Municipalities (quaternary catchment Q91C and P10A).

3.1.2. Site Description

3.1.2.1. Kei River Primary Catchment

Two quaternary catchments were selected within the Kei River Primary Catchment (figure 2 and 3), S50B (31.72°S, 27.58°E) which represents a high biomass (HB) condition and S20C (31.69°S, 27.39°E) which represents a low biomass (LB) condition (Appendix 1 provides physical details of these catchments). Quaternary catchment S50E, near Tsomo, contains the Emalahleni and Sakhisizwe Local Municipalities which are both under the Chris Hani District Municipality. This catchment supplies the Ncora dam on the Tsomo River. The Ncora dam was established in 1975; has a capacity of 150 x 10^6 m^3 and a surface area of 1392 ha. Quaternary catchment S20C, near Qamata in the Emalahleni Local Municipality, is within the Chris Hani District Municipality. The catchment supplies water to the Lubisi dam on the Indwe River. The Lubisi dam was established in 1968, it has a capacity of 158 x 10^6 m^3 and a surface area of 1129 ha. Both the Lubisi and Ncora dam are maintained by DWA.

3.1.2.2. Bushmans River Primary Catchment

Two quaternary catchments (P10A and Q91C) were selected in the Bushmans River Primary (figure 2 and 3) as they contained examples of judicious and high intensity grazing. The primary catchment has an area of 2675 km and 4% of this catchment is degraded bushland, 90% is natural vegetation and comprises forest, succulent thicket, shrubland and grassland. One percent of the catchment is urban, including residential and industrial development. Two 1 km pixels were selected from P10A and Q91C quaternary catchments. The 1 km pixel (33.29°S, 26.49°E) selected from P10A represents a high biomass state that is lightly grazed by domestic livestock and wild herbivores and the 1 km pixel selected from Q91C (33.27°S, 26°.60°E) represents a low biomass state that is intensively grazed under communal management. Both these quaternary catchments are located near Grahamstown in the Makana Local Municipality (Cacadu District Municipality). There are two small dams that receive water from quaternary catchment P10A, namely Milner and Jameson dams. There is no dam in the Q91C quaternary catchment; however water is supplied by the Great Fish River.

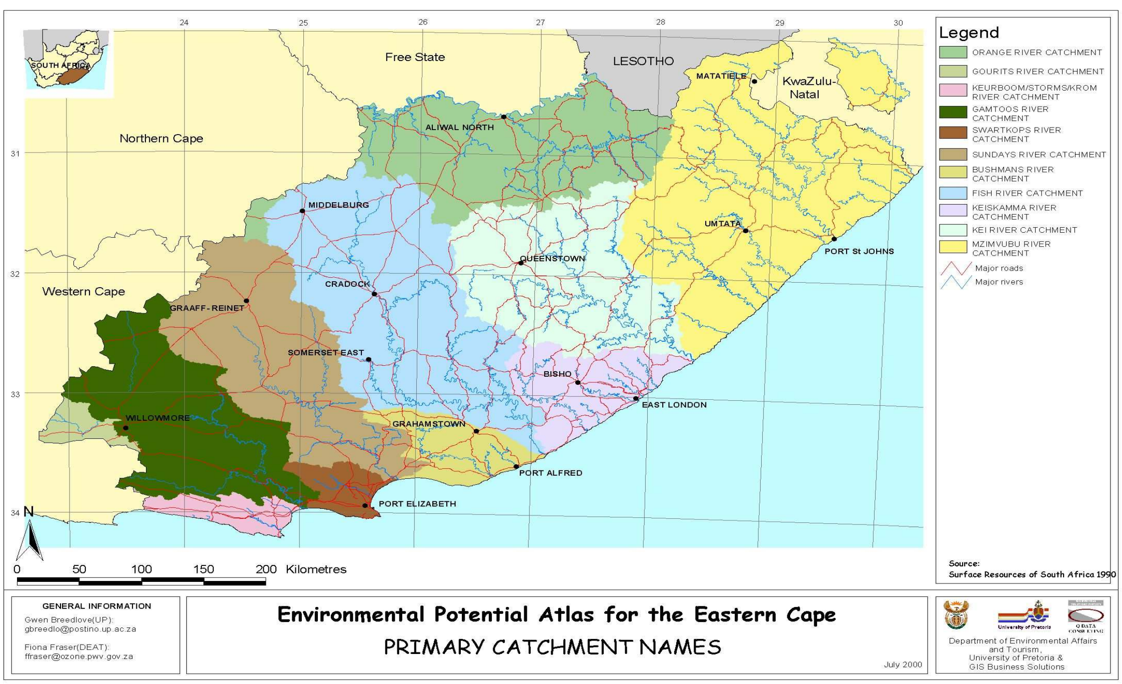


Figure 2: Map showing the Primary Catchments of the Eastern Cape downloaded from the Enviro-Info-2001 on www.environment.gov.za/enviro-info/prov/ec/ecpcat.jpeg

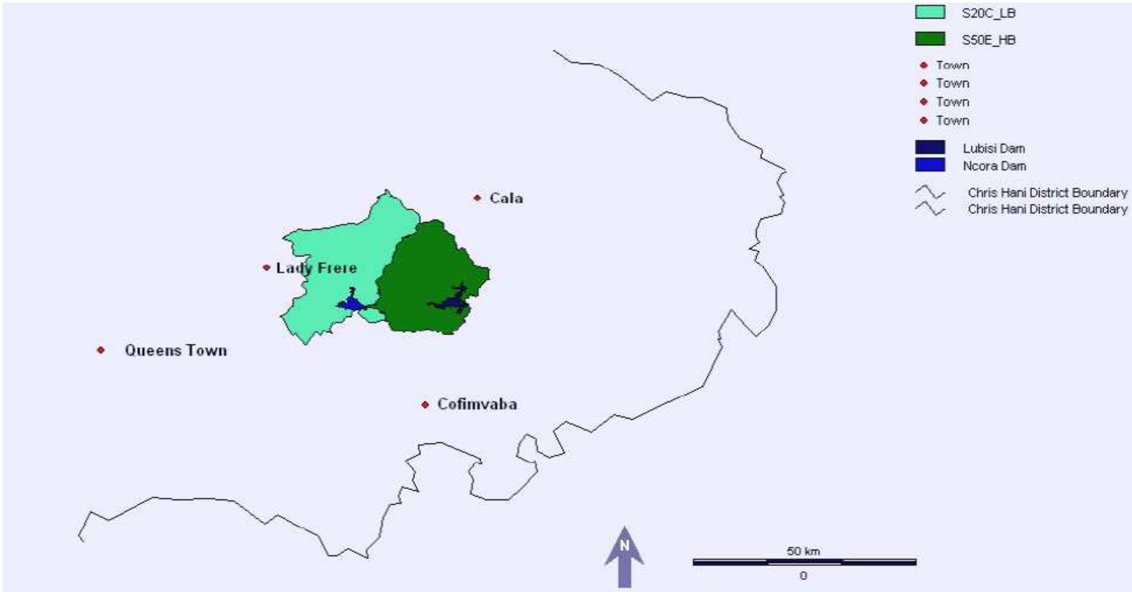


Figure 3(a): Map showing the selected quaternary catchments within the Chris Hani District Municipality with the dams and the surrounding towns.

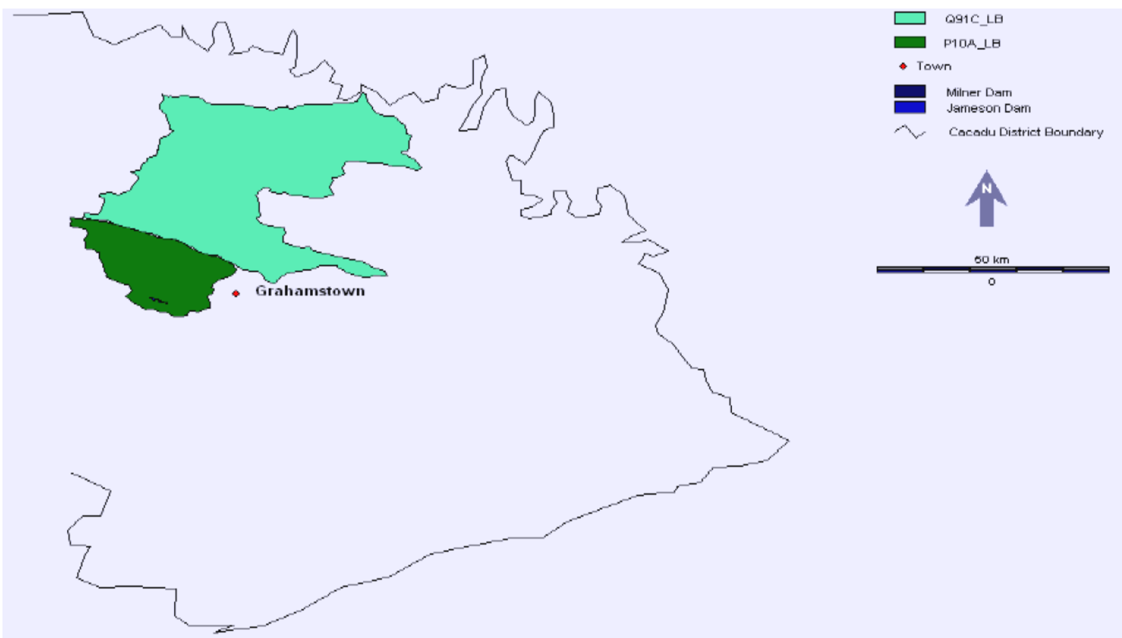


Figure 3(b): Map showing the selected quaternary catchments within the Cacadu District Municipality with the dams and the surrounding towns.

3.2. EVAPOTRANSPIRATION ESTIMATES

3.2.1. Actual ET (ET_a) Quality Assessment

In order to ensure accuracy when estimating ET using remote sensing techniques, it is necessary to validate the remotely sensed ET using ground truthed measurements from instruments such as Bowen-ratio energy balance (BR), eddy-covariance system (EC), Large Aperture Scintillometer (LAS) and Open Top Chambers (OTC). (Leuning, Zhang *et al.* 2008) (Tsouni, Kontoes *et al.* 2008). The strength of the quality of the remotely sensed ET depends on the availability of these validation instruments. Therefore a critical assessment of the quality levels of ET_a obtained from each selected catchment was done based on the proximity of the AWS to the catchment and the availability of BR, EC, LAS, or OTC equipment to validate the modeled ET. The quality was rated:

- Very high where the AWS (inside the catchment) + EC or BR or LAS or OTC + MODIS LAI were available for validation.
- High where the AWS (inside the catchment) + OTC + MODIS LAI were available.
- Moderate where AWS (outside the catchment) + OTC + MODIS LAI were available.
- Low where AWS (outside the catchment) + MODIS LAI were available and
- Very Low where only MODIS LAI was available.

The quality levels of ET_a calculated for the selected quaternary catchments in this study are shown in the in Table 2 below.

Table 2: Quality of ETa for quaternary Catchments S20C; S50B; Q91C and P10A

Catchment	Year	AWS (in)	AWS (out)	EC	LAS	OTC	MODIS LAI	Rating
S20C	2009	-	X	-	-	-	X	Low
S50B	2009	-	X	-	-	-	X	Low
Q91C	2000-2008	-	X	-	-	-	X	Low
Q91C	2009-2010	-	X	-	-	X	X	Moderate
P10A	2000-2008	-	X	-	-	-	X	Low
P10A	2009-2010	-	X	-	-	X	X	Moderate

3.2.2. Acquiring MODIS LAI Data

Eleven years of the MODIS 8-day 1 km Collection 5 (MOD15A2) composite LAI/FPAR product for the period March 2000 to December 2010 have been acquired from the NASA Distributed Active Archive Centre. Images were extracted from the archive using the MODIS reprojection tool (HegTool, HDF Group, University of Illinois Research Park, Champaign, Illinois) and imported into IDRISI (Version I32.11, Clark Labs, Clark University, Worcester, Massachusetts) image processing package to create a 11-year data stack with 451 layers.

MODIS LAI has been used in previous studies to estimate ET. Cleugh et al (2007) estimated E using the P-M equation (Monteith 1965) with a simple model for surface conductance to E given by:

$$Gs = c_L L_{ai} + G_{s,min} \quad (2)$$

Where L_{ai} is the leaf area index obtained from MODIS remote sensing and c_L is a constant and $G_{s,min}$ is the surface conductance controlling soil E. They found that these results were more acceptable than the poor comparison they found when the multi-seasonal time series of E estimated using MODIS measurements of the radiative surface temperature was compared with the resistance surface energy budget approach (Cleugh, Leuning *et al.* 2007).

3.2.2.1. Selecting the most appropriate model for calculating ET_a

Palmer et al (2010) examined the relationship amongst MODIS LAI (Collection 5), pre-dawn leaf water potential (a surrogate for plant water availability), vegetation water use (ET) and pan evaporation (E_0) in forest, evergreen woodland, open shrubland and savanna in Australia (New South Wales, Western Australia and the Northern Territory) in the period of 2002 – 2008. A regression model was prepared from a maximum value composite of MODIS LAI and the pre-dawn water potential in the savanna of Northern Territory (Palmer, Fuentes *et al.* 2008). However as the present study is confined to homogenous grasslands, the regression model was deemed inappropriate as it only applied to Australian woodlands (Palmer, Fuentes *et al.* 2010).

A model was developed in order to improve ET estimates by exploring the potential of MODIS (MOD15A2) to factorize the surface conductance term in the P-M equation (Cleugh *et al* (2007). Palmer and Weideman (2011) proposed a simple surface conductance model that can be used to predict ET_a in a semi-arid savanna site in the Kruger National Park (KNP) using MODIS LAI values to inform the P-M equation of the surface vegetation processes. To achieve, this hourly meteorological data from a nearby automatic weather station was obtained and ET_0 was calculated using FAO56. Then maximum LAI (LAI_{max}) values were extracted for a single MODIS pixel retrieved in the KNP (25.05°S 31.51°E) for year 2007. An eddy covariance (EC) system (FLUXNET) that records fluxes at 30 min intervals at the KNP site was used to validate the predicted ET_a by MODIS LAI. Clean EC data for 173 days of 2007 which were assumed to be the true reflection of actual ET were extracted for both the wet and dry season. Then MODIS LAI was used to parameterize the P-M equation using the following function:

$$\mathbf{ET_a = ET_0 * (LAI / LAI_{max})} \qquad (3)$$

Where:

LAI is the MODIS LAI for the 8-day period, LAI_{max} is the maximum retrieved at the site over the whole data record (~500 records) and ET_0 was calculated from an hourly meteorological data from Malekuta AWS for 2007 using the revised Penman-Monteith equation (FAO56) (Allen et al. 1998).

During the dry season, ET obtained from Eq. (3) had to be further adjusted by an optimized scaling factor of 0.65 as it was observed that MODIS tends to over-predict LAI during this season. The results showed a close correlation between the ET obtained from the EC (ET_{EC}) (147.6 mm) and ET obtained from Eq. (3) (ET_{MODIS}) (139.2 mm) (Figure 4)

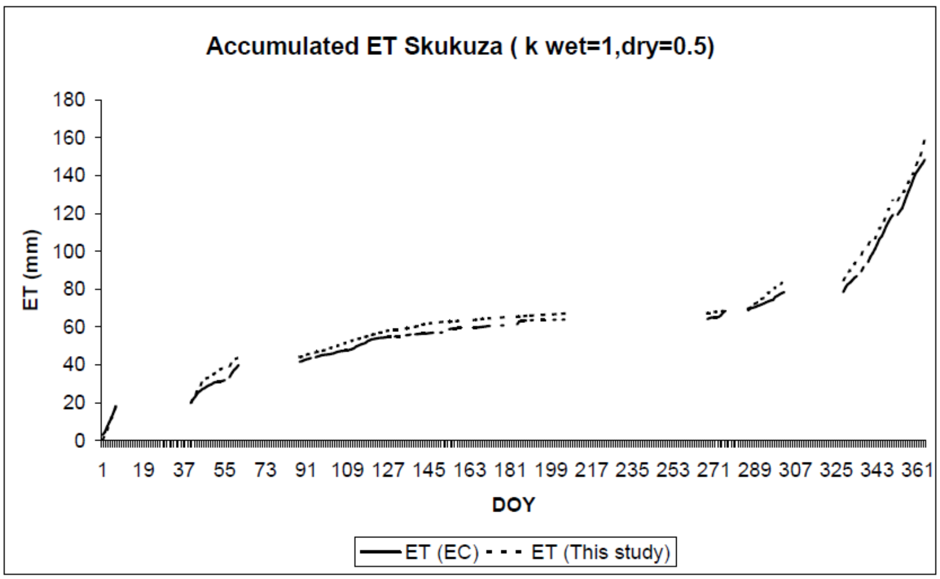


Figure 4: Accumulated ET in 2007 for the site in KNP. Source: (Palmer & Weideman 2011)

To further validate the model Palmer and Weideman (2011) used daily estimates of ET_a from a Large Apperture Scintillometer (LAS) for two week periods in 2005. The LAS ET_a (ET_{LAS}) estimates were obtained for a week in the growing season (February) and a week in the dry season (May) of 2005 and a strong correlation was observed when these were compared with the MODIS LAI ET_a (ET_{MODIS}) obtained from Eq. (3) (figure 5a and 5b).

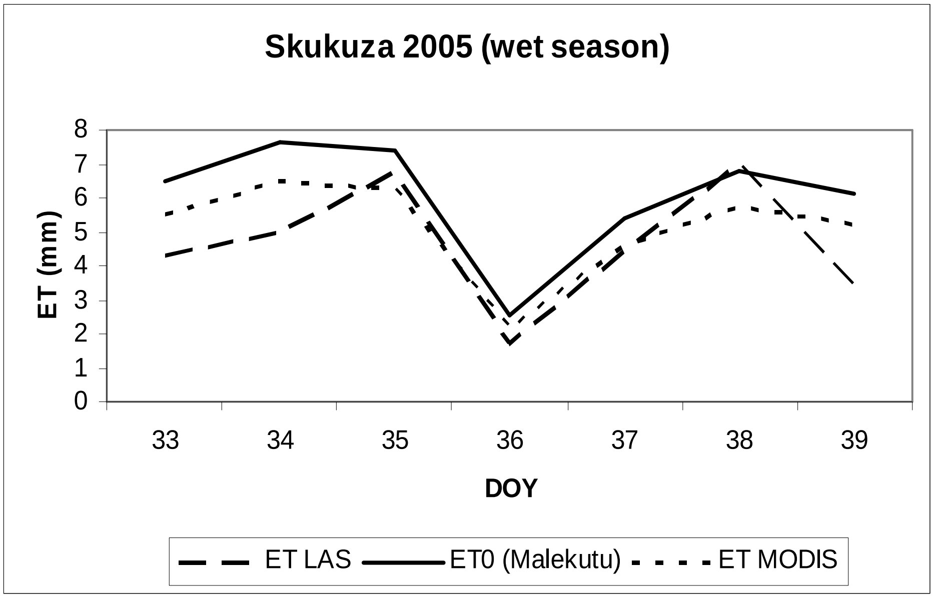


Figure 5(a): Plot of $ET_{LAS,}$ ET_{MODIS} and ET_0 for Skukuza flux site in the wet season of 2005. Source: (Palmer & Weideman 2011).

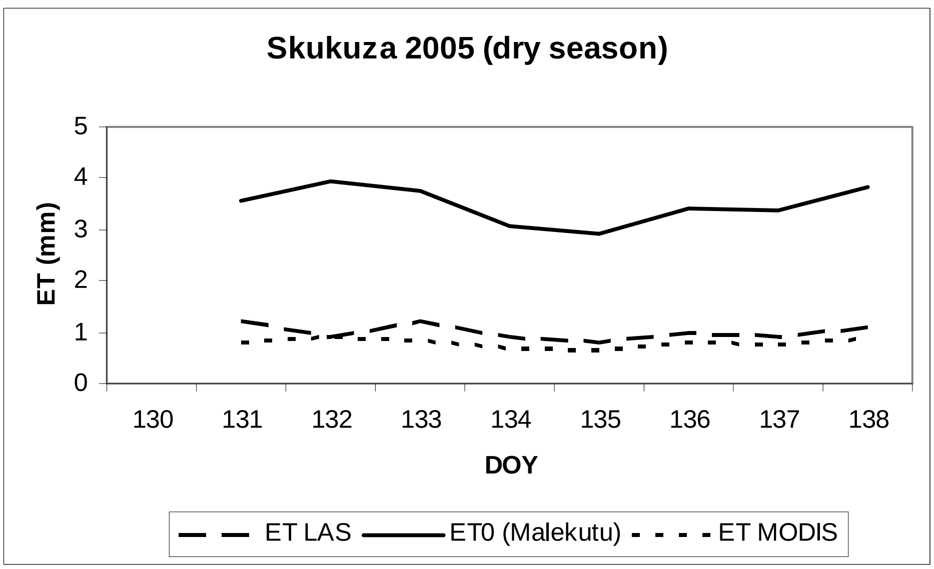


Figure 5(b): Plot of $ET_{LAS,}$ ET_{MODIS} and ET_0 for Skukuza flux site in the dry season of 2005. Source: (Palmer & Weideman 2011).

As the ET_{MODIS} model provided the most parsimonious result of the possible ET models evaluated, Eq. (3) was used to calculate daily ET for the quaternary catchments selected in the present study (Q91C; P10A; S20C and S50E). ET_0 was calculated for each catchment using the stations listed (Table 3).

Table 3: Locations of the weather stations and the years the data was available

Weather Station	Period	Co-ordinates
Qamata AWS	2006 – 2010	- 31.98 27.44
Bucklands MWS	2000 – 2010	- 33.1 26.72
Rhodes University AWS	07/2008 – 2011	- 33.18 26.30

Data from the AWS stations hourly data for: T_{max} and T_{min}; RH_{max} and RH_{min}; U; R_s ; wind direction; rainfall data and ET_0. The accuracy of the ET_0 calculated internally by the data logger on these Campbell Scientific automatic weather stations was verified by manually computing ET_0 using the data and FAO56 computer program (Allen, Pereira *et al.* 1998). Daily data is provided by the manual weather station (MWS) at Bucklands, and the FAO56 for daily data was used to calculate daily ET_0.

The ET_{MODIS} model (Palmer & Weideman 2011) was applied to all further estimates of ET_a. The resulting ET_{MODIS} was further validated using ET obtained from the OTC (ET_{OTC}) (see details in 3.4.).

3.2.3. Mean annual ET for P10A (HB) and Q91C (LB) 1 km pixels

Estimation of ET_{MODIS} for the 1 km pixels was done by firstly digitizing the boundaries of quaternary catchment Q91C and P10A as polygons. Then within each quaternary catchment the selected 1 km pixels were digitized as polygons (figure 6).

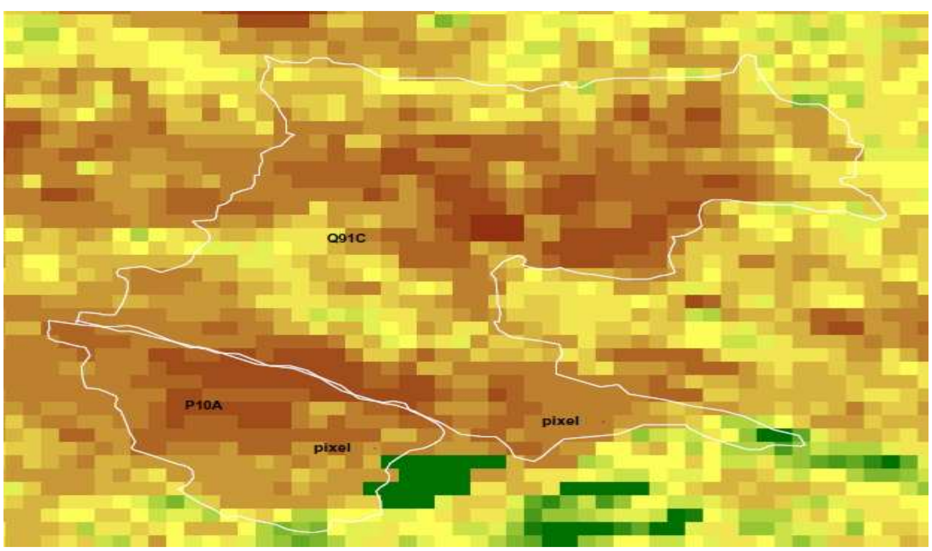


Figure 6: MODIS LAI Image 2009017 showing the catchment boundaries of Q91C and P10A and the 1 km pixels within each quaternary catchment.

LAI was then extracted from an 11 year data stack of MODIS LAI (March 2000-March 2011) for each 1 km pixel (high biomass and low biomass). The actual annual ET for each 1 km pixel was calculated by adjusting the ET_0 data from Bucklands MWS (2000-2008) and Rhodes University WS (2009-2011) with the MODIS LAI product using the Eq. (3). In Statistica version 9, ANOVA (Analysis of Variance) was used to check if there was any significant difference between the mean annual ET_{MODIS} estimates over the 11 year period. Where mean annual ET_{MODIS} was significantly different the Tukey-Honestly Significantly Different (HSD) Post-hoc test was used.

The resulting ET_{MODIS} estimates for the growing season of September 2010 – March 2011 were validated using the OTC measurements obtained from the two 1 km pixels.

3.3. OPEN TOP CHAMBER

Ground truthed estimates of ET were obtained using an open top chamber (OTC) which is small and semi-portable, constructed following methods described by (Eamus, Hatton *et al.* 2006). The OTC sums the water lost from vegetation and soil within the chamber and was used in this study to validate the ET_{MODIS}.

3.5.1. Design of the Open Top Chamber:

The OTC is designed to be portable (Figure 7). It consists of a round cross-section of clear Mellinex® which is used because of its good light transmission properties, with a tapered top. The OTC has two sections – a lower cylindrical base of 0.77 m diameter and 1.23 m height, and a metal frame supporting a Mellinex® cone mounted on top of this base. Total chamber height is 2 m and the volume enclosed is 0.78 m^3. A 12 volt 100 Amp hour battery was used to power the fan supplying air to the chamber. The OTC had one input pipe at the cylindrical base and the cone shape top, and an exit pipe at the cone shaped top and each had a vent for instruments that measure the temperature, wind speed and relative humidity. The exit pipe at cylindrical base had an in-line valve which could be adjusted to increase or decrease the rate of air entering the chamber.

Figure 7: Photo of the open top chamber

3.5.2. Method

The OTC was tested from the grasslands of the two 1 km pixels selected from the quaternary catchments P10A and Q91C and during the growing season of September 2010 – March 2011. Measurements were initially taken using a Kestrel 3000 hand-held vane anemometer only; however the quality of its relative humidity and temperature sensors raised some concerns. To improve the quality of relative humidity and temperature, a Vaisala HMP45C RH and TEMP probe was acquired and used together with the Kestrel 3000 anemometer. The parameter measured by the Kestrel 3000 anemometer was the wind speed and Vaisala HMP45C RH and TEMP probe was used to measure relative humidity and temperature. These parameters were measured both at the inlet and the outlet of the chamber at 30 minute interval and this was done on 5 clear, low wind (<6m s-1) and sunny days.

Transpiration was then calculated using Eq. (1):

$$\mathbf{E = ((\Delta \mathit{e})(F_{\mathit{a}}))/ (A_{\mathit{l}})}$$

Where **E** is transpiration rate (mol m^{-2} s^{-1}); Δ**e** is the difference in water vapour concentration (mol m^{-3}) between the inlet and outlet of the OTC; $\mathbf{F_a}$ is the rate of air flow through the chamber (m^3 s^{-1}) and **Al** is the total green leaf area (m^2) within the chamber at the time of measurement. Then a regression analysis was used to prepare a relationship between ET estimates obtained from the OTC and those obtained from MODIS LAI for all days of recording under both treatments.

3.4. LAND-USE SCENARIOS FOR QUATERNARY CATCHMENTS S50E (HB) AND S20C (LB)

To show the impact that changes in the biomass cover can have on ET rates and ultimately runoff/recharge rates, three scenarios were created in IDRISI (Version I32.11, Clark Labs, Clark University, Worcester, Massachusetts) Scenario 1; 2; 3. Two quaternary catchments were selected for this purpose a high biomass catchment (S50E) and a low biomass catchment (S20C).

3.4.1. Scenario 1

In the first scenario, the state of the grazing camps within the selected quaternary catchments was left unchanged, and the status quo was maintained. This was achieved by extracting the 8 day MODIS LAI value (Appendix B) of each of the selected quaternary catchments (S20C and S50E) for the period of 2009. Quaternary catchments S20C and S50E had high values (40 to 255) that had to be re-classed as zeros before extracting the 8 day MODIS LAI values. According to the information available on (http://cybele.bu.edu/courses/estonia/modis-lab-03-ascii.pdf) MODIS LAI/FPAR products distributed in the HDF format (raw/unfiltered), do not only have LAI and FPAR data layers, but also several quality control layers, which include pixel-by-pixel data about cloud, aerosol, snow contamination, algorithm path, overall product quality, etc. Therefore it depends on users to design their custom data mask that will suit their application to filter out the undesired data (http://cybele.bu.edu/courses/estonia/modis-lab-03-ascii.pdf) accessed on 04.01.11.

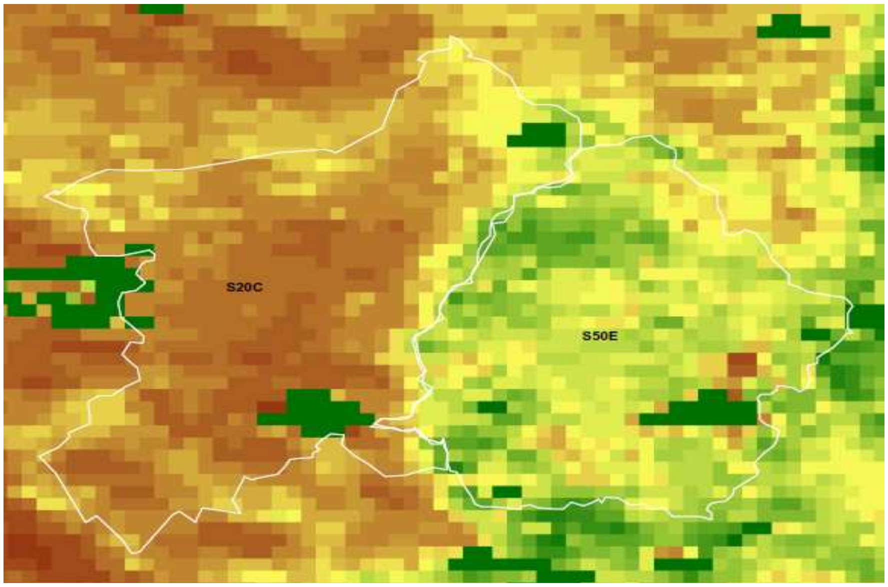


Figure 8: MODIS LAI Image 2009001 showing the difference between quaternary catchment S20C and S50E (the brown to beige pixels are low LAI values and the yellow to green pixels are high LAI values)

The mean annual ET_a for each selected quaternary catchment (S20C and S50E) was calculated using Eq. (3). ET_0 used in the calculations was obtained from Qamata AWS and confirmed using PM-FAO56 and the maximum LAI value of quaternary catchments S20C and S50E for the period of 2009 was used.

3.4.2. Scenario 2

For Scenario 2, MODIS pixels representing 28 km and 14 km were selected in catchments S20C and S50E respectively and the LAI of these pixels was doubled. This scenario represented a state where the standing above-ground biomass would be increased.

3.4.3. Scenario 3

For scenario 3, the LAI of the pixels that were selected for scenario 2 was halved. This scenario represented a state where the above-ground biomass would be decreased. Then actual annual ET for each scenario was calculated from the function used to calculate ET_a for the 1km pixels.

CHAPTER 4

RESULTS

4.1. ET ESTIMATES IN TEST PIXELS IN CATCHMENTS Q91C AND P10A

4.1.1. The annual ET_{MODIS} for 2000 – 2010

The mean annual ET over a ten year period (2000 – 2010) was higher by 78 mm in the high biomass km pixel (P10A) than that obtained in the low biomass km pixel (Q91C). In 2001 the P10A 1 km pixel had the highest annual ET estimate of 610.3 mm, while highest annual ET for the Q91C 1 km pixel was observed in 2006 (534.7 mm). Then the lowest annual ET estimates were observed in 2010 for both 1 km pixels (P10A: 333.1 mm and Q91C: 266.2 mm). ET_0 was highest in 2004 with 1080.7 mm and the lowest ET_0 was 724.5 mm in 2010 the same year both P10A and Q91C 1 km pixel had the lowest annual ET estimates (Table 4). A consistent decrease in annual ET estimates was noticed on both km pixels starting from 2007 to 2010. The Standard Deviation of the mean annual ET_{MODIS} is shown in Figure 9a and 9b for the P10A and Q91C 1 km pixels for the period of 2000 -2010.

Table 4: Mean annual ET_{MODIS}, ET_0 and rainfall for Q91C and P10A 1km (2000 – 2010)

	Q91C - LB	**P10A - HB**		
Year	**ET_{MODIS} (mm)**	**ET_{MODIS} (mm)**	**ET_0 (mm)**	**Rain (mm)**
2000	345.9	448.5	1039.1	541.7
2001	460.2	**610.3**	1046.8	511.7
2002	450.1	566.5	1072.5	592.7
2003	331.5	433.2	1076.4	**318.2**
2004	340	420.6	**1080.7**	419.7
2005	501	517	1049.2	492.9
2006	**534.7**	545.6	979.8	**618.5**
2007	445.7	510.9	1072.2	422.5
2008	376.4	462.8	1065.0	431.1
2009	304.5	385.2	924.1	545.8
2010	**266.2**	**333.1**	**724.5**	516.9
Mean	**396.01**	**475.79**	**1011.84**	**491.97**

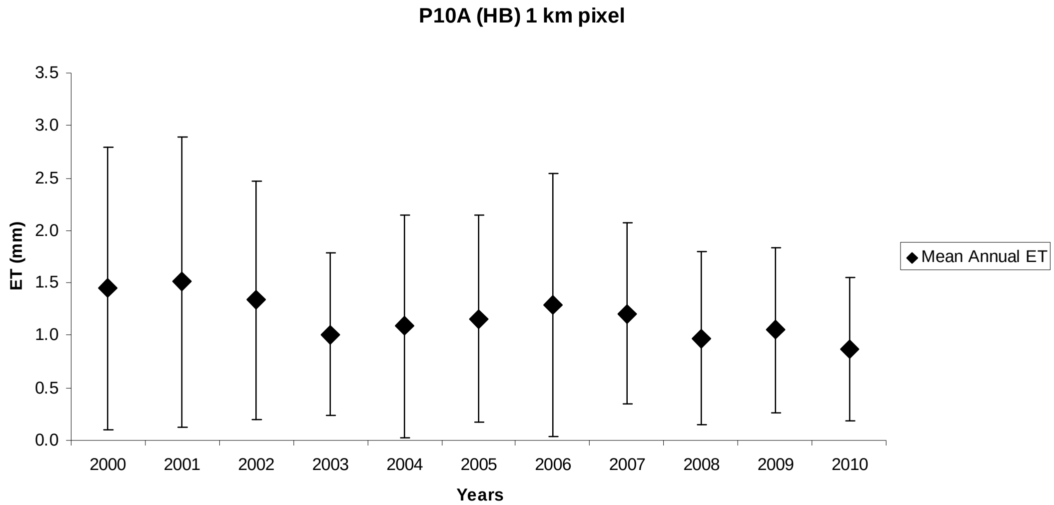


Figure 9(a): Standard Deviation of the mean annual ET of P10A (HB) 1 km pixel for the period of March 2000 – December 2010.

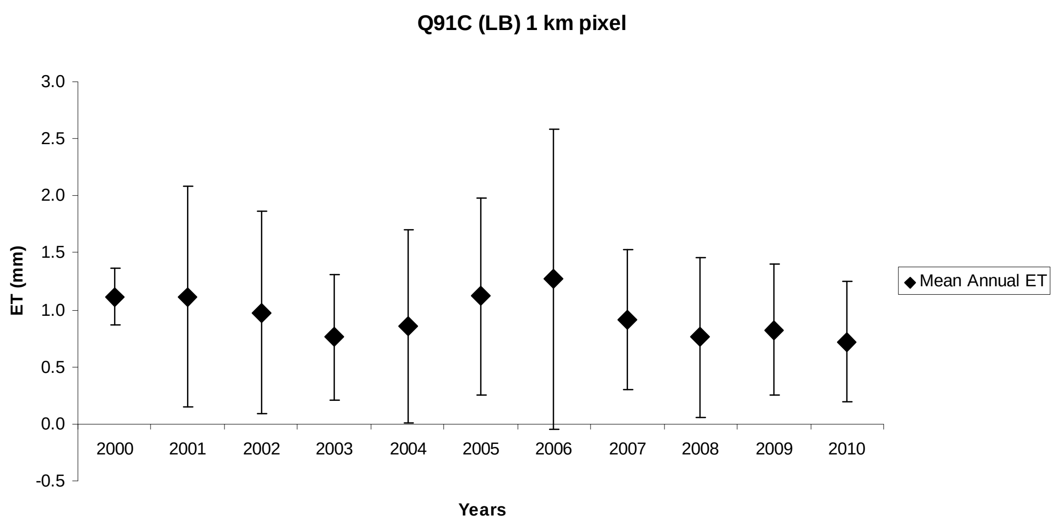


Figure 9(b): Standard Deviation of the mean annual ET of Q91C (LB) 1 km pixel for the period of March 2000 – December 2010.

The ANOVA indicated that the mean annual ET_{MODIS} estimates for the period of 2000 – 2010 were significantly different ($p< 0.05$) for both P10A and Q91C 1 km pixels. The results for the Post Tukey-HSD Post-hoc test are shown in Table 5(a) for P10A 1 km pixel and in Table 5(b) for Q91C 1 km pixel. The p values in bold show which years the mean annual ET_{MODIS} estimates were significantly different for a particular year. For example in Table 5 (a), in year 2000 the mean annual ET_{MODIS} was significantly different to the mean annual ET_{MODIS} obtained for 2004, 2009 and 2010.

Table 5(a): p values showing significant difference for P10A (HB) 1 km pixel for the period of 2000 -2010

Years	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
2000		0.208511	0.976649	0.069979	0.016421	1.000000	0.999973	0.999972	0.518326	**0.000164**	**0.000015**
2001	0.208511		0.922594	**0.000015**	**0.000015**	0.056047	0.499992	**0.029073**	**0.000034**	**0.000015**	**0.000015**
2002	0.976649	0.922594		**0.000295**	**0.000041**	0.842169	0.999773	0.719623	**0.015160**	**0.000015**	**0.000015**
2003	0.069979	**0.000015**	**0.000295**		0.999995	0.137240	**0.006027**	0.224386	0.996842	0.866163	**0.045676**
2004	**0.016421**	**0.000015**	**0.000041**	0.999995		**0.035436**	**0.000881**	0.067155	0.938992	0.985781	0.165636
2005	1.000000	0.056047	0.842169	0.137240	**0.035436**		0.996625	1.000000	0.722912	**0.000370**	**0.000015**
2006	0.999973	0.499992	0.999773	**0.006027**	**0.000881**	0.996625		0.984386	0.133674	**0.000017**	**0.000015**
2007	0.999972	**0.029073**	0.719623	0.224386	0.067155	1.000000	0.984386		0.844741	**0.000952**	**0.000015**
2008	0.518326	**0.000034**	**0.015160**	0.996842	0.938992	0.722912	0.133674	0.844741		0.245581	**0.001270**
2009	**0.000164**	**0.000015**	**0.000015**	0.866163	0.985781	**0.000370**	**0.000017**	**0.000952**	0.245581		0.878458
2010	**0.000015**	**0.000015**	**0.000015**	**0.045676**	0.165636	**0.000015**	**0.000015**	**0.000015**	**0.001270**	0.878458	

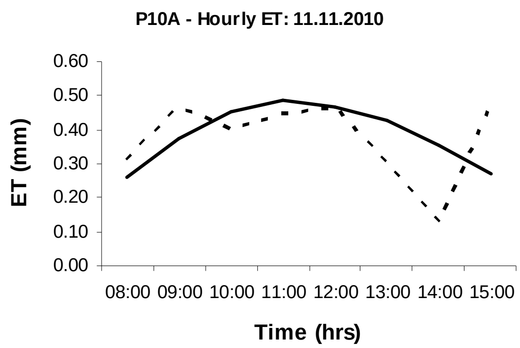
Table 5(b): p values showing significant difference for Q91C (LB) 1 km pixel for the period of 2000 -2010

Years	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
2000		0.609526	0.851274	0.133685	0.260383	**0.013201**	**0.000061**	0.919179	0.982827	**0.004619**	**0.000024**
2001	0.609526		0.999999	**0.000029**	**0.000082**	0.868789	0.099991	0.999968	**0.028426**	**0.000015**	**0.000015**
2002	0.851274	0.999999		**0.000127**	**0.000487**	0.624329	**0.029981**	1.000000	0.095755	**0.000015**	**0.000015**
2003	0.133685	**0.000029**	**0.000127**		1.000000	**0.000015**	**0.000015**	**0.000275**	0.813318	0.992407	0.331827
2004	0.260383	**0.000082**	**0.000487**	1.000000		**0.000015**	**0.000015**	**0.001062**	0.938400	0.953027	0.173763
2005	**0.013201**	0.868789	0.624329	**0.000015**	**0.000015**		0.960731	0.498884	**0.000039**	**0.000015**	**0.000015**
2006	**0.000061**	0.099991	**0.029981**	**0.000015**	**0.000015**	0.960731		**0.016678**	**0.000015**	**0.000015**	**0.000015**
2007	0.919179	0.999968	1.000000	**0.000275**	**0.001062**	0.498884	**0.016678**		0.150156	**0.000016**	**0.000015**
2008	0.982827	**0.028426**	0.095755	0.813318	0.938400	**0.000039**	**0.000015**	0.150156		0.149954	**0.001369**
2009	**0.004619**	**0.000015**	**0.000015**	0.992407	0.953027	**0.000015**	**0.000015**	**0.000016**	0.149954		0.954090
2010	**0.000024**	**0.000015**	**0.000015**	0.331827	0.173763	**0.000015**	**0.000015**	**0.000015**	**0.001369**	0.954090	

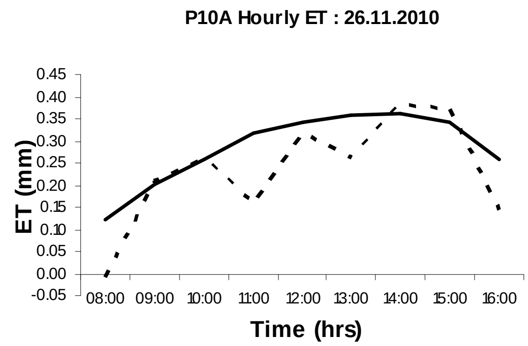
4.1.2. Validation of ET_{MODIS} with ET_{OTC}

The ET_{OTC} obtained using the Kestrel 3000 anemometer for the growing season of (September 2009 – March 2010) were negative for both HB (P10A) and LB (Q91C) 1 km pixels, on most occasions it was measured in the field. No positive correlation was observed when ET_{OTC} was compared ET_{MODIS} for those days, and these results were discarded. When using both the Kestrel 3000 anemometer and the Vaisala HMP45C RH and TEMP probe, positive results were obtained. Since the daily ET_{OTC} estimates was a sum of ±10 hours of the day it was measured, it was deemed important to also calculate the hourly ET_{MODIS} for the same hours as ET_{OTC} on those same days. Figure 10(a - e) and 11 (a – e) show how hourly ET_{OTC} (the actual) performed in the field compared to the hourly ET_{MODIS} (the predicted) for the same days.

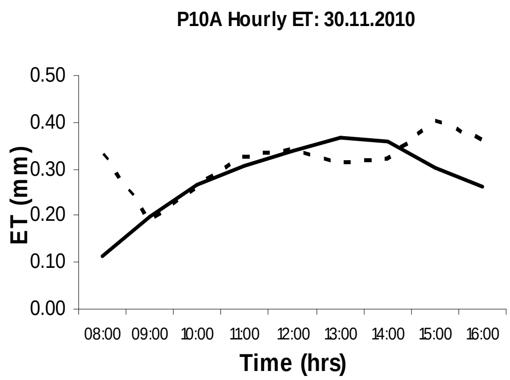
a)



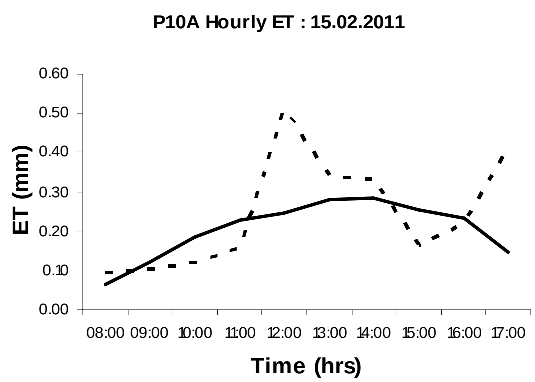
b)



c)



d)



e)

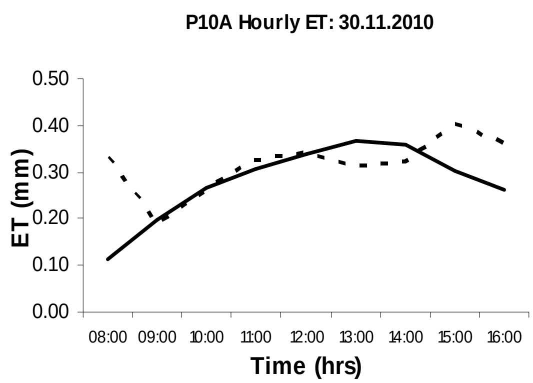


Figure 10(a - e): P10A (HB) hourly performance of ET_{OTC} and ET_{MODIS} on the days ET was measured in the field with the OTC in the growing season of 2010 – 2011. The solid line represents ET-MODIS while the dotted line represents ET-OTC.

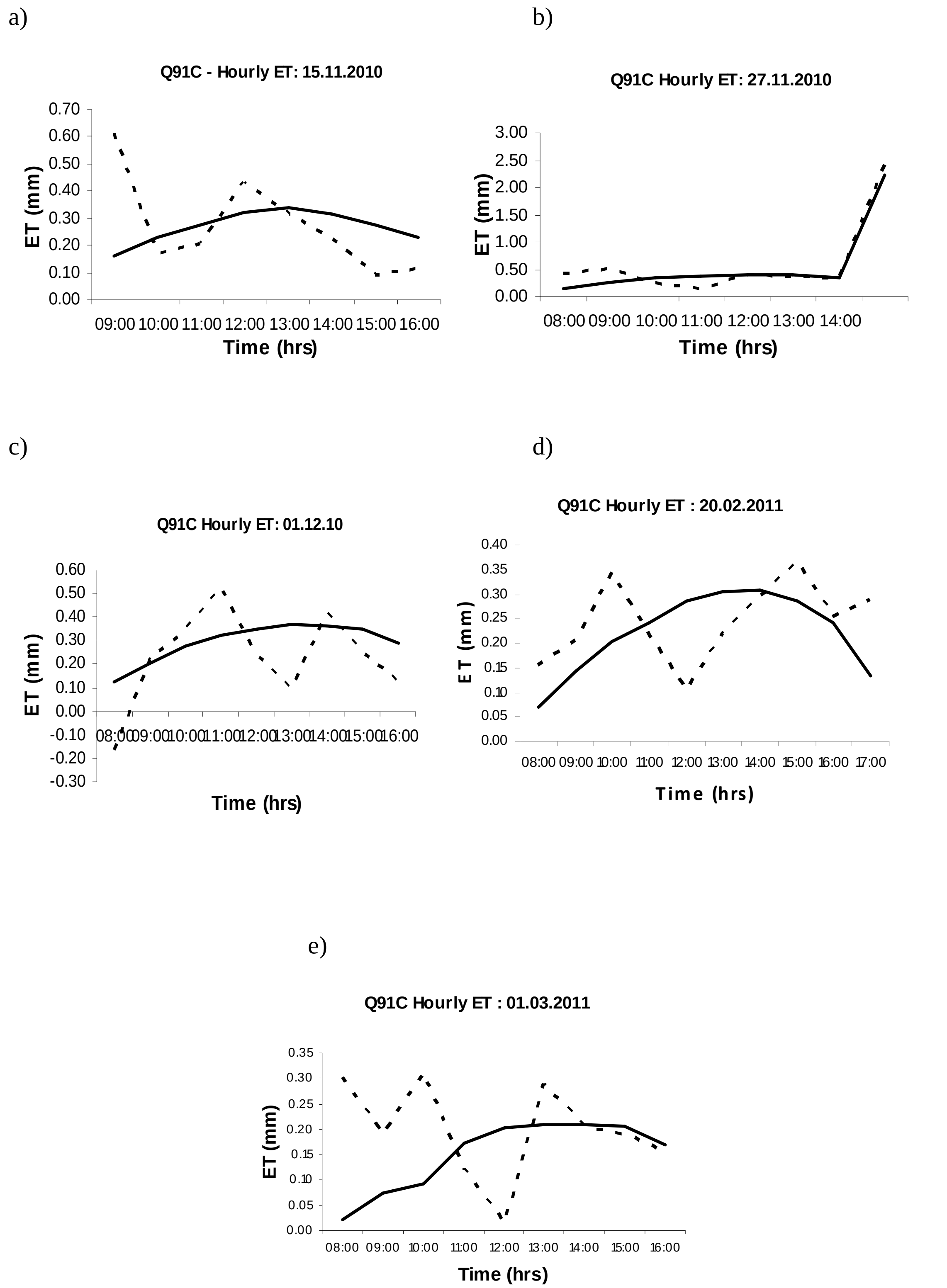


Figure 11(a - e): Q91C (LB) hourly performance of ET_{OTC} and ET_{MODIS} on the days ET was measured in the field with the OTC in the growing season of 2010 – 2011. The solid line represents ET-MODIS while the dotted line represents ET-OTC.

A good relationship was observed between the daily ET_{OTC} and ET_{MODIS} as shown by the linear regression analysis in Figure 12 with the $R^2 = 0.7065$.

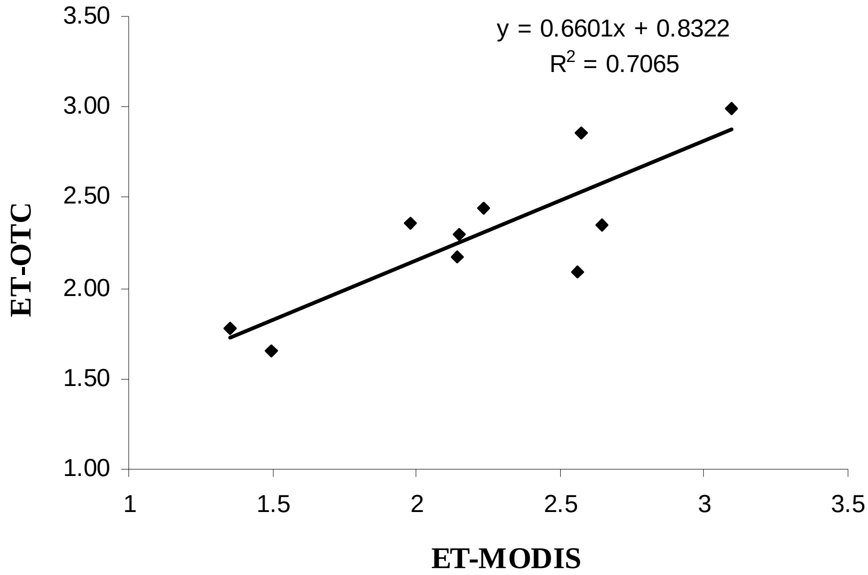


Figure 12: Regression Analysis showing the relationship between ET_{OTC} and ET_{MODIS} for all days.

The relationship observed confirms that ET_{OTC} closely approximates ETMODIS and that the OTC can be used as a tool to validated MODIS LAI ET on clear, low winds and sunny days.

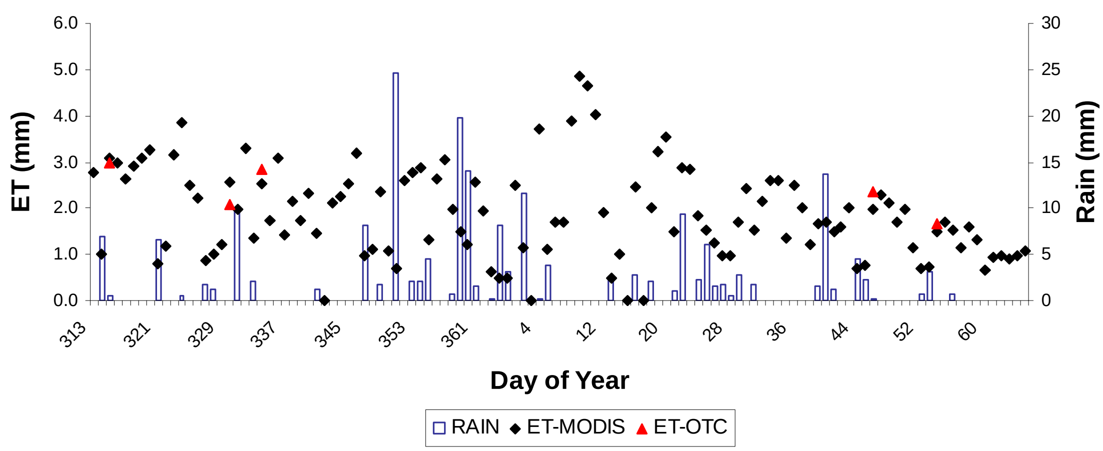


Figure 13(a): Daily estimates of ET_{MODIS} and ET_{OTC} and the rainfall measured from P10A (HB) 1 km pixel for the growing season of October 2010 – March 2011.

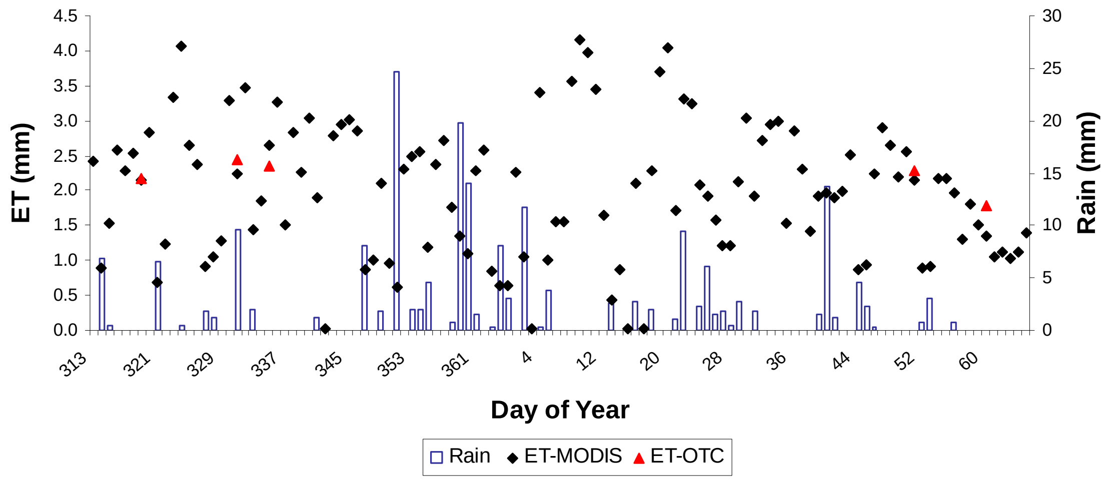


Figure 13(b): Daily estimates of ET_{MODIS} and ET_{OTC} and the rainfall measured from Q91C (LB) for the growing season of October 2010 – March 2011.

4.1.3. The actual leaf area index

Table 6: The actual LAI, ET-MODIS, ET-OTC and ET0

Dates	Sites	LAI	ET0	ET-MOD	ET-OTC
11/11/2010	P10A	0.4423	3.35261	3.094717	2.99
15/11/2010	Q91C	0.3576	3.09369	2.141785	2.17
26/11/2010	P10A	0.3029	3.200624	2.560499	2.09
27/11/2010	Q91C		2.639897	2.233759	2.44
30/11/2010	P10A	0.3954	3.144367	2.575494	2.86
01/12/2010	Q91C	0.6423	3.12263	2.643071	2.35
15/02/2011	P10A	0.3868	3.165128	1.978205	2.36
20/02/2011	Q91C	0.4114	2.732352	2.146848	2.29
23/02/2011	P10A	0.56	2.989981	1.494991	1.66
01/03/2011	Q91C	0.3669	2.706708	1.353354	1.78

4.2. LAND USE SCENARIOS FOR HB and LB QUATERNARY CATCHMENTS

The mean annual ET_{MODIS} estimates obtained in quaternary catchments S50E (high biomass site) were higher by 111mm than those obtained for quaternary catchment S20C (low biomass site). When comparing between the scenarios it was observed that scenario 2 which is the scenario in which the LAI values were doubled had higher ET_{MODIS} estimates than both scenario 1 and 3. Table 7 shows the differences in the ET_{MODIS} between the two quaternary catchments (S50E and S20C) and between the scenarios 1, 2 and 3.

Table 7: Scenario 1-3 for the S50E (HB) andS20C (LB) quaternary catchments in 2009

Catchments	Scenario1 ET(mm)	Scenario2 ET(mm)	Scenario 3 ET(mm)
S50E	426.83	436.36	420.77
S20C	315.81	324.84	314.40

4.2.1. Accumulated ET_{MODIS} for scenario 1-3

The accumulated rates of MODIS LAI ET_a for scenario 1 – 3 are shown in figures 14a and 15a. The differences between the scenarios for quaternary catchments S50E and S20C are clearly shown in Figure 14b and 15b.

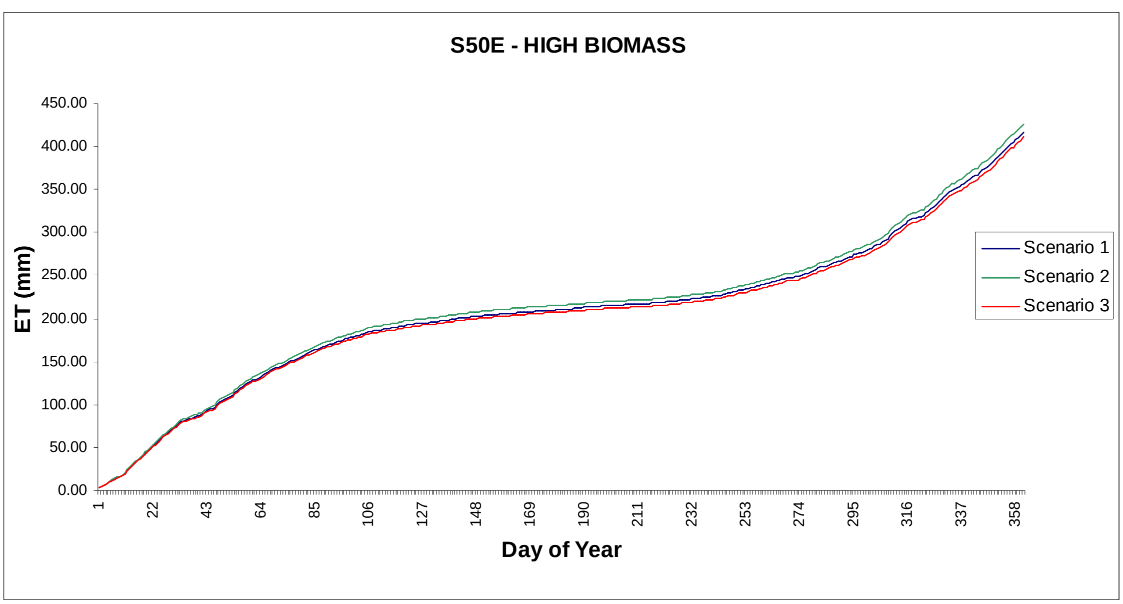


Figure 14(a): Accumulated daily ET_{MODIS} for quaternary catchment S50E showing the difference in ET between scenario 1, 2 and 3.

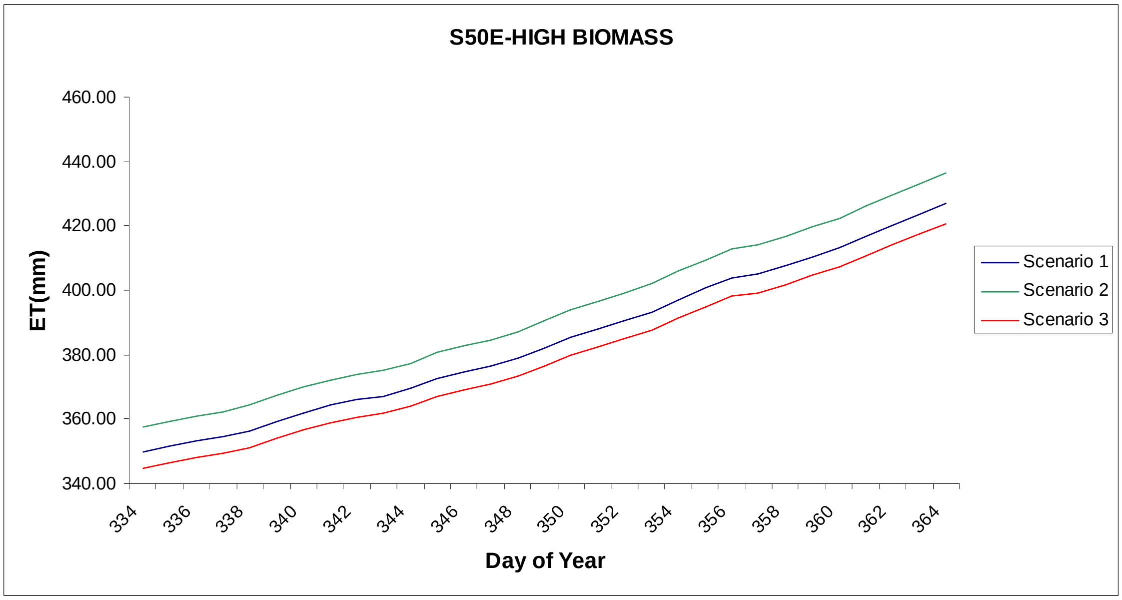


Figure 14(b): Accumulated ET_{MODIS} showing only the 12th month of 2009 for the high biomass 1 km pixel.

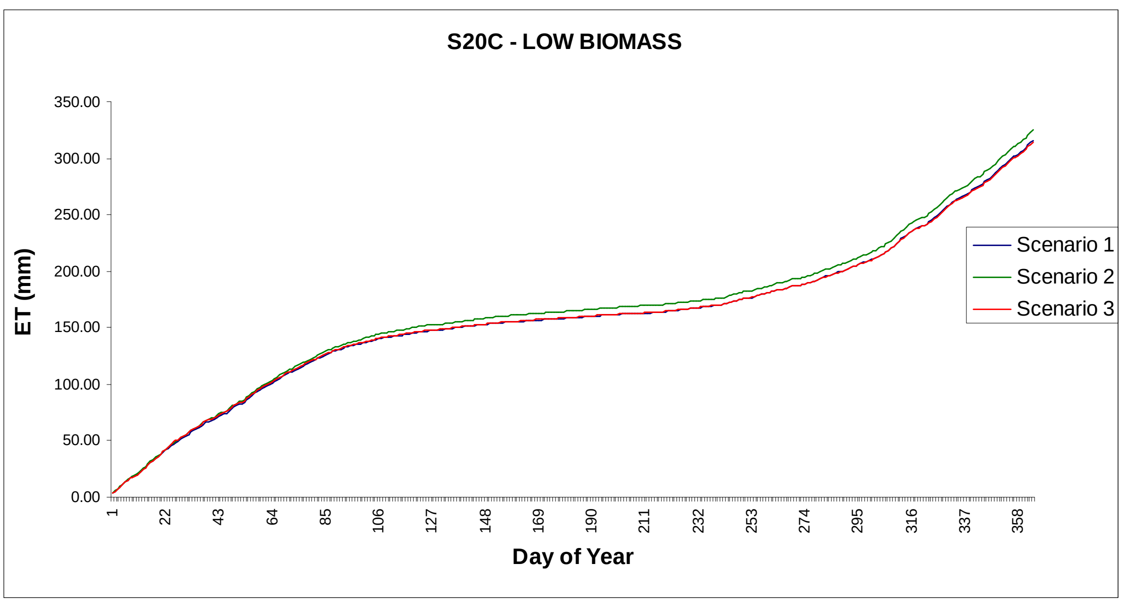


Figure 15(a): Accumulated daily ET_{MODIS} for quaternary catchment S20C showing the difference in ET between scenario 1, 2 and 3.

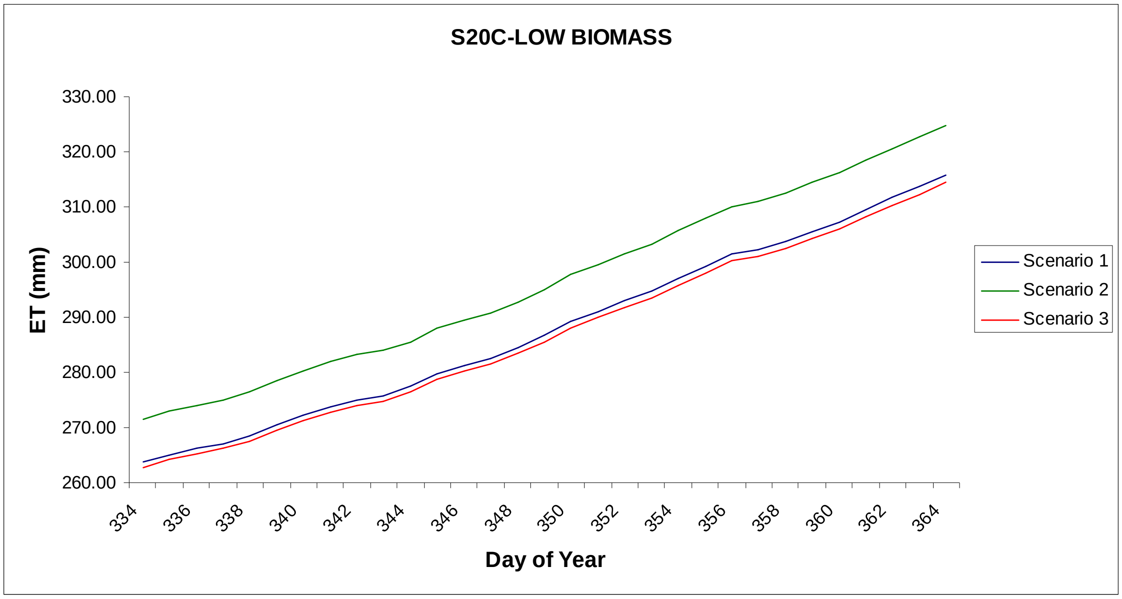


Figure 15(b): Accumulated ET_{MODIS} showing only the 12th month of 2009 for the low biomass 1 km pixel.

CHAPTER 5

DISCUSSION AND CONCLUSION

In this study ET estimates of the grasslands of the Eastern Cape were obtained using MODIS LAI as an input into the Penman-Monteith equation (Palmer and Weideman 2011) and validated using an Open Top Chamber. The aim was to find out how the different management regimes or lack thereof of the grassland catchment affected the rates of ET and ultimately the runoff rates. It was assumed that the mismanagement of the grassland catchments of the Eastern Cape has had an adverse effect on the amount of runoff received annually as it leads to overgrazed land with little biomass cover and soil erosion. Also these overgrazed lands lead to invasion of alien species that usually utilize more water than the native species and lead to high ET rates (Blignaut, Marais *et al.* 2007). The effect of these alien species on ET rates was not explored in this study. Two different grazing strategies (High and low biomass cover) were explore from quaternary catchments selected from Bushmans River Primary Catchment and from Kei River Primary Catchment. First the trend observed for the annual ET estimates over a 11 year period (2000 – 2010) showed that ET has been decreasing in the last four years from both the high and low biomass sites. It was also observed that the high biomass sites had higher ET estimates than the low biomass sites. These results were in agreement with the observation made for the land-use scenarios. High ET rates have been previously associated with the decrease in water supply; however in this study we argue that if these ET estimates are obtained from good condition grasslands then an improvement to the runoff rates is expected.

5.1 THE ANNUAL ET_{MODIS} FOR 2000 – 2010

The results obtained showed that the mean annual ET_{MODIS} obtained for the high biomass 1 km pixel was higher than the mean annual ET_{MODIS} obtained for the low biomass 1 km pixel over the period of 2000 – 2010. When high ET estimates are obtained it is expected that the runoff rates will be reduced. However in cases of grassland catchments though high biomass cover results in high ET estimates which may reduce runoff rates as more water is lost to the atmosphere, high biomass cover also acts as a sponge that catches the summer rainfall and allow the water to be infiltrated in the soil and then be gradually released to the streams. Also high biomass cover reduces the magnitude of storm flows. Whereas in areas with low biomass cover, high runoff rates may result, however infiltration is reduced and storm flows are increased. This also results in soil erosion and siltation of the dams which decreases the capacity of the dams to store water. (DWA 1986; Turpie, Marais *et al.* 2008).

It was also observed that from 2007 up to 2010 there was a consistent decrease of ET for both the low and high biomass 1 km pixel. In an ideal situation decrease in ET rates would mean that less water is lost to the atmosphere and therefore runoff and recharge rates are improved. However where grasslands are concerned this could be true in cases where the high biomass cover is moribund, and the dead grass still allow water to infiltrate the soil. Therefore in this case the decrease of the ET rates is not seen as positive since it was observed for both the high biomass (representing good condition grassland) and the low biomass (representing bad condition grassland).

Factors that could have contributed to this consistent decrease of ET_{MODIS} are at this stage uncertain. However it was noted that for the same period (2007 – 2010), ET_0 was also consistently decreasing. The concept of ET_0 has been used in many studies as a method for estimating ET (Jenson full citation) and in this study ET was estimated by adjusting ET_0 using the 8 day MODIS LAI data (Palmer and Weideman 2011). Therefore the consistent decrease in ET_0 can be viewed as one of the contributing factors to the decrease observed for ET_{MODIS}. Hansen (1984) defined ET_0 as the maximum E and T from a surface with sufficient water available and the amount of energy available for ET is greatly influenced by the surface condition (i.e. whether the surface is well covered with vegetation and well watered or it is lightly covered and water stressed) (Hansen 1984). Therefore it could be argued that over the past four years both the high and the low biomass 1 km pixels have experienced a consistent change in the vegetation cover and soil water availability.

Reynolds et al., (2000) stated that in semi-arid regions where plant growth is limited by water availability, variations in ET rates can be controlled by variability in precipitation at daily to inter-annual timescales (Reynolds, Kemp *et al.* 2000). The lowest annual rainfall was obtained in 2003 and the ET_0 rates obtained for that year are higher than those obtained for 2007 – 2010 and this complicates the effects of rainfall on ET_0. However an answer may be found in the study done by Ferretti et al., (2003) that examined the effect of precipitation variations on the separate fluxes of E and T in short grass steppe. They estimated the average daily E and T fluxes for each time interval by multiplying the fraction of each flux by the total moisture for that interval. The results they obtained showed that for two consecutive years (2000 and 2001) that had similar annual rainfall, the rates for one year were almost double the rates obtained for the other year. They attributed this to the timing of precipitation. The dry spring led a decrease in biomass and when the rain finally came in late August of 2000 it was not used by the short grass. Whereas the spring rains of 2001 increase the biomass leading to high T rates. This then indicates that vegetation growth is not only affected by the rainfall amounts but also by when it is occurring (Ferretti, Pendall *et al.* 2003; Overpeck, Bartlein *et al.* 1991).

5.2. VALIDATION OF ET_{MODIS} ESTIMATES

5.2.1. The variations in the hourly ET_{OTC}

It was observed that for most of the days ET was measured in the field with the OTC, the curve of ET_{OTC} was not as smooth as the one plotted for ET_{MODIS}. ET_{MODIS} was obtained by adjusting ET_0 (a climatic parameter that is estimated from the weather data) by MODIS LAI data (a Remote Sensing technique that measures ET indirectly) and therefore it represented the predicted ET in this study. While ET_{OTC} represents the actual ET as it was measured directly using a micro-meteorological method (Allen, Pereira *et al.* 1998; Breda 2003). ET is the sum of two processes, the direct E of water from open water bodies and moist soils and transpiration through the stomatal pores of leaves (Eamus, Hatton *et al.* 2006). According to Glenn et al., (2007) T of the plants accounts for over 80% of the terrestrial ET. Transpiration depends on the opening and the closing of the stomata which is affected by the increase or decrease in air temperature, RH and U. The decrease in transpiration means that less water is released through the stomata and this also means that the rate of ET will decrease (Eamus, Hatton *et al.* 2006; Glenn, Huete *et al.* 2007b). Therefore as the air temperature RH and U fluctuate throughout the day, the same occurs in the ET rates. This would explain the fluctuating rates of the hourly ET_{OTC}.

5.2.1. Comparison between ET_{OTC} and ET_{MODIS}

ET estimations were obtained in this study using the MODIS LAI as an input into the Penman-Monteith equation (Palmer and Weideman 2011) and validated using the Open Top Chamber. The relationship between the ET_{MODIS} and ET_{OTC} observed from the linear regression analysis (r^2 = 0.7065) showed that ET_{OTC} closely approximates ET_{MODIS} and thus the OTC can be used to validate MODIS LAI ET. ET is a major component of water cycle and obtaining improved estimates of ET is important for determining water budget in and around a region. (Leuning, Zhang *et al.* 2008; Tsouni, Kontoes *et al.* 2008). Remotely sensed data is one of the best ways to determine spatially distributed E fluxes due to their spatial and temporal continuity.

The model of estimating ET using MODIS LAI data as an input into the P-M equation was first proposed by Cleugh *et al.*, (2007) in a study where the 8-day evaporation at 1-km resolution was estimated using gridded meteorological fields and the P-M equation, in which the surface conductance (G_s) was a function in the MODIS LAI (Cleugh, Leuning *et al.* 2007). This was later modified by Mu *et al.*, (2007) who revised the simple model for G_s to account for the response of stomata to temperature and humidity deficit of the air and the results obtained were in good agreement between predictions of ET by the P-M equation and evaporation measurements from a number of flux stations in the USA (Mu, Heinsch *et al.* 2007). Both models for G_s were replaced by Leuning *et al.*, (2008) with a biophysical, two-parameter model for surface conductance that accounted for the sensitivity of the stomatal conductance to the shortage of humidity in the atmosphere and to light. Excellent estimates of evaporation were obtained from this new model for G_s when tested against data sets from 15 flux station sites covering a wide range in climate and vegetation types globally. These results show that the P-M equation is a biophysically sound and robust framework for estimating daily E at regional to global scales using remotely sensed data (Leuning, Zhang *et al.* 2008).

Then Zhang et al., (2008) examined the potential of using remote sensing ET to predict long-term runoff by comparing the runoff values derived from water balance estimates with measured runoff at the 120 gauged catchments in the period of 2001–2005. Their results showed a good comparison between the mean annual run-off estimates calculated by calibrated remote sensing ET and the recorded values. These results lead to a conclusion that remotely sensed ET can be used with rainfall-runoff models to improve the accuracy of estimated runoff in ungauged catchments(Zhang, Chiew *et al.* 2008).

The model used in this study to estimate the actual ET (Palmer and Weideman 2011) which is also a modification of the model developed by Cleugh *et al.*, (2007) was developed around two different data sets (EC and LAS) from different sites (KNP and Malekutu) and in both cases a good relationship was observed between the ET obtained from either data set and ET obtained using the model. The OTC used in this study is a third instrument to be used to ground truth the ET estimates obtained using the model and the advantage of OTC over the other two instruments is that it is easy to construct, replicable and replaceable, easy to transport and inexpensive. Therefore obtaining ET_{OTC} results that closely approximate ET_{MODIS} presents a cheaper and uncomplicated alternative of determining the effects of the different grazing regimes on ET and ultimately on runoff rates using MODIS LAI products.

5.3. LAND-USE SCENARIOS

The results obtained for the land-use scenario showed that the high biomass quaternary catchment had higher ET than the low biomass quaternary catchment and also when comparing between the scenarios, ET estimates were higher in the scenario with the pixels that had doubled LAI values. These results are in agreement with results obtained for the 1 km pixels in which high ET estimates were obtained for the high biomass km pixel than the low biomass 1 km pixel.

The purpose of doing the land use scenarios was to show the impact that changes in land use activity can have on ET and ultimately on runoff rates. The first scenario was the original state of the quaternary catchment. The second scenario showed how ET would be affected if a small area within the quaternary catchment can have an increased LAI and as shown by the results ET would be increased as well. Then the third scenario is the opposite of scenario 2 and resulted in a decrease in ET. The ideal state would be one that has reduced rates of ET (i.e. scenario 3) as this would result in high rates of runoff according to the equation below:

Runoff = Precipitation - ET

However in this case the reduction of LAI in the selected area is assumed to mean that degradation in that area is increasing. This degradation might lead to loss of the above ground biomass which would increase storm flows leading to dam siltation and also reduce surface water infiltration. Therefore though in scenario 3 ET was reduced, increased water supply is not guaranteed instead there is a high possibility that not only would the runoff and recharge rates be decreased but the capacity of the dams would also be decreased due to siltation.

This then denotes that scenario 2 is an ideal state, though high ET rates were obtained as in the case of the high biomass 1 km pixel, the high grass cover can act as a sponge that catches the summer rainfall and allows it to infiltrate the soil and be gradually released to the dam. Also if this state is maintained over the years the above grass can be moribund which could reduce ET rates and continue to allow the infiltration of water (Turpie, Marais *et al.* 2008) (Hogan 2010).

Creating the land use scenarios using the MODIS LAI data was important in this study as this has presented an opportunity to demonstrate how MODIS LAI data can be used to quantify the improvements or further degradation of the vegetation cover within the catchments. This would greatly assist in the application of the payment for ecosystem services as it a step closer to knowing how much water can be expected when the grass cover is improved. The current state of the grasslands of South Africa is of great concern; in arid and semi arid climates overgrazing of rangelands by livestock amongst other things add to land degradation resulting in decline of the soil structure that reduced infiltration and water holding capacity (WMO 1998). This then denotes that there is a need for land use activities to change within the grassland catchments that are also used as rangelands. Livestock owners need to be advised to apply effective management regimes in order to improve the grass cover within the grassland catchments they inhabit to ensure gradual supply of water to the catchments. Then through the PES they can receive direct compensation from the downstream water users for improving the grass cover to improve water supply. In cases where the ecosystem services paid for involve changing land use activities, the costs are higher as opposed to when they are made for retaining them (Engel, Pagiola *et al.* 2008). If the PES can be successfully applied in areas that require change in land use activity in order to improve the above ground biomass which in turn will improve the rates of runoff and recharge then the livestock owner who in this case will be the service providers can expect to be paid more. Although the aim of developing the PES is firstly to meet the environmental objectives and to ensure that natural resources are well managed, the effect on income redistribution is also an important side objective. This is more suited to developing countries where most of the people providing the ecosystem services fall below the poverty line (Hengsdijk, Groot *et al.* 2009).

In the Eastern Cape there is need for land use activities to change within the grassland catchments that are also used as rangelands. Currently these grassland catchments have less grass cover due to inappropriate land practices such as overgrazing. This leads to rapid runoff that silts the dam and also removes the top soil. Livestock owners need to be advised to apply effective management regimes in order to improve the grass cover within the grassland catchments they inhabit to ensure gradual supply of water to the catchments and to reduce their livestock numbers. The PES program that had similar objectives (i.e. the improvement of water supply through change in land use activity) was successfully applied by the Maloti Drankensberg Transfrontier Project (MDTP) in the Thukela and Mzimvubu catchments where they managed to encourage the land owners to change certain land use activities in order to improve water supply. Their results confirmed that application of proper managements system can increase infiltration, reduce summer storm flow and increase winter base flow. These results lead the MDTP to conclude that providing an incentive for land owners for their proper management of the grasslands catchment is efficient and equitable (Mander, Blignaut *et al.* 2007).

Though the PES programs has shown the potential for 'double dividend' payoffs in terms of biodiversity conservation and poverty reduction (van Wilgen, Le Maitre *et al.* 1998), studies done in Costa Rica and Mexico have indicated that participation in the program is not easy for most poor households (Miranda, Porraz *et al.* 2003; Ortiz and Kellenberg 2002; Zbinden and Lee 2005). This is due to the fact that participation in the PES program is limited to households that can provide the desired services and only these household are eligible to receive payment. Constraints such as the formal tenure requirements discriminate against poor farmers who would like to benefit from the program but have no formal rights to the land (Wunder 2005). For instance in Latin America, Southgate and Wunder (2009) found that the PES program was more successful where the service providers had secured land tenures and that cooperation and good compensation were ensured. An example of this is taken from the study by (Varga, Harwood *et al.* 2009). They found that in one of their case studies, knowing who owned the property rights of land upstream, enabled the service buyers to enter into an appropriate contract with the service providers (Varga, Harwood *et al.* 2009).
Another constraint is that in terms of payments, the costs to the ecosystem service buyer are much higher when dealing with many smallholder or a land that is collectively owned by communities compared to when paying only a few big landowners (Smith and Scherr 2002). In this study, where the land users are livestock owners, the above constraint could be experienced since in most cases livestock owners usually own land collectively. Secondly encouraging livestock owners to reduce their livestock numbers would require the ecosystem service buyer or downstream users to ensure that the benefits of participating in the program are higher than the current benefit they receive from their livestock (Pagiola and Platais 2007).

There is another aspect that needs to be looked at that of the differences between private PES programs and national government financed PES programs. In private PES programs land owners or ecosystem service providers can be paid directly by the users of the specific ecosystem service due to a limited geographic scope. For example in a single watershed the downstream hydrological service users can directly pay the upstream service providers (Blackman and Woodward 2009). The advantage of private PES programs is that the ecosystem service buyer and the ecosystem service seller are directly involved meaning they can ensure the efficiency of the system and they are in a better position to renegotiate the agreements (Varga, Harwood *et al.* 2009). Then there are those that have a national scope, these are financed by government who represents the users of that specific ecosystem service throughout the country. This type of PES program has been applied in countries like China, Costa Rica, Mexico and South Africa, while some are still planning to implement them (Pagiola 2007; Wunder 2005). The main advantage of the government financed PES programs is economies of scale, where national programs are able to spread costs over a large number of agents, and reduce some costs. However these are very inefficient, firstly because as opposed to the private PES programs the national governments are not directly involved and do a poor job of identifying providers of important ecosystem services and monitoring the efficiency of the program. Secondly, they depend on national tax revenues and international funds they cannot guarantee long term financing (Blackman and Woodward 2009). One way that could correct this is if the individual service users of a specific ecosystem service would voluntarily contribute to the system by paying for them to the government administrators.

There is a lot in the literature about how the PES programs work for different scenarios and in this study the practical application of the program has not been initiated yet. Only the technique that demonstrate how to identify areas where overgrazing could lead to reduced water supply have been explored. It is not yet clear whether the private PES program or the national government financed PES program will be suitable in this kind of study.

5.4. CONCLUDING REMARKS

It is clear that South Africa has a major shortage of water and the country is at a stage where water demand is exceeding water availability due to population growth (DEAT 2000) (Mukheibhir 2007). Previously water demands were met through a complex system of engineering supply side solutions which included major inter-basin transfer and water pumping schemes (Smakhtin, Ashton *et al.* 2001). However these have become costly and the water available for that has reduced because 12 of South Africa's 19 water catchment areas receive insufficient rainfall (Blignaut and De Wit 2004). This has increased the need to explore cheaper and less complicated alternatives for increasing and conserving water supplies in ungauged catchments (Ashton and Seetal 2002). This study set out to explore the effect of two different grazing strategies on ET rates using MODIS LAI data since changes in ET rates also affect the quantities of water supply. The results obtained showed that high biomass sites had higher ET rates and though high ET rates are associated with low runoff rates it was argued in this study that where grasslands are concerned the opposite is true. Since grasslands allow summer rainfall to infiltrate the soil and be gradually released to the dams, it is recommended that the grass cover must be high. As opposed to the previous ways of meeting water demand the use of the MODIS LAI product as an input into the Penman Monteith to estimate the ET rates is a much cheaper and less complicated alternative. Also it's validation using an open top chamber that is inexpensive, easy to construct and transport, makes the process highly replicable. The findings of this study pave a way for the application of the PES model and the approach used has the potential to quantify the benefits to down-stream water users of improving above-ground biomass in catchments.

5.5 FUTURE RESEARCH

In using contrasting land-use scenarios, this study demonstrated that when LAI is decreased, ET estimates also decrease. Although the low biomass scenario can be viewed as a situation when less water is lost to the atmosphere, it was important to note that in most cases the reduction of LAI is associated with increased run-off, higher silt loads and rangeland degradation. On the other hand, increased LAI, which is accompanied by increased ET, could mean that the rangeland is in a healthy state and can lead to the reduction of storm flows and dam siltation since infiltration of the rainfall occurs. These results high-light the challenges associated with balancing biomass production, vegetation cover, soil conservation and water yield (quality and quantity). Determining the income benefit that livestock owners can receive through the PES model for the improvements made to their rangelands will require further research. This will require a clear understanding of how to quantify the annual biomass increments from the selected sites and the impact on water supply. This can be achieved through the development of techniques for modelling net primary production and then water use efficiency. Degradation or improvement of the rangeland can be determined by monitoring the changes in water use efficiency (Holm, Watson *et al.* 2003). Several authors (Palmer *et al* 2010, Snyman 1986, 1994 and Holm, Watson *et al.* 3003) have prepared water use efficiency values for selected vegetation types in Southern Africa, and this research should be pursued further.

REFERENCES

Aboelghar M, Arafat S, Abo Yousef M, El-Shirbeny M, Naeem S, Massoud A and Saleh N (2011) Using SPOT data and leaf area index for rice yield estimation in Egyptian Nile delta, The Egyptian Journal of Remote Sensing and Space Sciences 14, 81-89..

Aboukhaled A, Alfaro A, Smith MRP (1982) Lysimeters. In 'FAO Irrigation and Drainage'. pp. 68. (Rome)

African Adrenalin (2007) Water Conservation in http://www.africanadrenalin.co.za/rattray/Anderson.htm accessed in June 2009

Ainslie A (2002) 'Cattle ownership and production in the communal areas of the Eastern Cape, South Africa. .' School of Government, University of Western Cape, Western Cape.

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration - Guidelines for computing crop water requirements In 'FAO Irrigation and drainage paper 56'. (FAO: Rome)

Arora VK (2002) The use of the aridity index to assess climate changes effect on annual runoff. Journal of hydrology 265, 164-177.

Ashton PJ (2002) Avoiding Conflicts over Africa's Water Resource. Ambio 31, 236-242.

Ashton PJ, Seetal A (2002) Challenges of Water Resource Management in Africa. In 'African Renais-Science Conference'. Durban

Ashton PJ and Haasbroek B (2002) Water demand management and social adaptive capacity: A South African case study. In: AR Turton and R Henwood (Eds), Hydropolitics in the Developing World: A Southern African perspective. African Water Issues Research Unit (AWIRU) and International water Management Institute (IWMI). Pretoria:

Blackman A, Woodward RT (2009) User Financing in a National Payments for Environmental Services Program: Costa Rican Hydropower. In. (Environment for Development: Central America.)

Blignaut J, De Wit MP (2004) (Ed.)^(Eds) 'Sustainable Options.' (UCT Press: Cape Town)

Blignaut JN, Marais C, Turpie JK (2007) Determining a charge for the clearing of invasive alien plant species (IAPs) to augment water supply in South Africa. Water Sa 33, 27-34.

Bowen IS (1926) The ratio of heat losses by conduction and by evaporation from any water surface. Physical Review 27, 779-787.

Boyd J, Banzhaf S (2007) What are ecosystem services? The need for standardized environmental accounting units. Ecological Economics 63, 616-626.

Breda NJJ (2003) Ground-based measurements of leaf area index: a review of methods, intruments and current contoversies. Journal of Experimental Botany 54, 2403-2417.

Briney A (2010) Evapotranspiration. In. (About.com:Geography)

Burba GG, Anderson DJ (2007) Introduction to the Eddy Covariance Method: General Guidelines and Conventional Workflow". In. (Ed. L-C Biosciences) pp. 41

Carlson TN, Capehart WJ, Gillies RR (1995) A new look at the simplified method for remote sensing of daily evapotranspiration:. Remote Sensing Environment 54, 161-167.

Castellvi F, Stockle CO (2002) Comparing the performance of WGEN and ClimGen in the generation of temperature and solar radiation. Trans ASAE 44.

Cleugh HA, Leuning R, Mu Q, Running SW (2007) Regional evaporation estimates from flux tower and MODIS satellite data. Remote Sensing and Environment 106, 285-304.

Cohen WB, Maierpserger TK, Gower ST, Turner DP (2003) An improved strategy for regression of biophysical variables and Landsat ETM+ data. . Remote Sensing of Environment 84, 561-571.

Cohen WB, T.K. M, et al. (2006) MODIS land cover and LAI collection 4 product quality across nine sites in the western hemisphere. . IEEE Transactions On Geoscience And Remote Sensing. 44, 1843-1857.

Cook PG, Hatton TJ, Pidsley D, Herczeg AL, Held A, O'Grady A, Eamus D (1998) Water balance of a tropical woodland ecosystem, Northern Australia: a combination of micro-meteorological, soil physical and groundwater chemical approaches. Journal of Hydrology 210, 161-177.

Cousins B (1997) 'Conditions of entry into the red meat industry for black livestock producers. University of Natal, Draft Report for Research Project on "Restructuring Agriculture in South Africa".

CRISP (2001) SPOT (Satellite Pour l''Observation de la Terre). Centre for Remote, Imaging, Sensing and Processing. France.

Dai A, Yosuke M, Ishgaldan B, Tsokhio A (2004) Estimation of areal distribution of evapotranspiration over Khentii region using a combination of Satellite data and a heat budget model. In '3RD International Workshop on Terrestrial Change in Mongolia'. Tsukuba, Japan

Daily GC (1997) 'Nature's Services: Societal Dependence on Natural Ecosystems.' Washington DC.

de Jesus WC, Jr., do Vale FXR, Coelho RR, Costa LC (2001) Comparison of Two Methods for Estimating Leaf Area Index on Common Bean. Agron J 93, 989-991.

DEAT (2000) 'State of the Environment: Report 1999.' Department of Environmental Affairs and Tourism, Pretoria, RSA.

DEAT (2007) Factors Affecting availability and quality. In. (Ed. DoEAa Tourism).

DWA (1986) 'Management of the Water Resources of the Republic of South Africa.' Department of Water Affairs, Pretoria, South Africa.

DWAF (2002) 'Proposed First Edition of National Water Resource Strategy.' Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (2004) National Water Resource Strategy:. In. (Ed. P Department of Water Affairs and Forestry).

Eamus D, Hatton T, Cook Pa, Colvin C (2006) 'Ecohydrology: Vegetation Function, Water and Resource Management.' (CSIRO: Collingwood, Australia)

Engel S, Pagiola S, Wunder S (2008) Designing payments for environmental services in theory and practice: An overview of the issues. Ecological Economics 65, 663-674.

Falkenmark M (1994) The dangerous spiral: near-future risks for water-related eco-conflicts. In 'International Committee of the Red Cross: Water and War: Symposium on Water in Armed Conflicts'. Montreux, Switzerland p. 16

Falkenmark M, Widstrand C (1992) Population and Water Resources: A Delicate Balance. In 'Population Bulletin'. (Population Reference Bureau: Washington, DC.)

Fan L, Gao Y, Brück H, Bernhofer C (2009) Investigating the relationship between NDVI and LAI in semi-arid grassland in Inner Mongolia using in - situ measurements. Theoretical and Applied Climatology 95, 151-156.

Fensholt R, Sandholt I (2003) Derivation of a shortwave infrared water stress index from MODIS near- and shortwave infrared data in a semiarid environment. Remote Sensing of Environment 87, 111−121.

Ferretti DF, Pendall E, Morgan JA, Nelson JA, LeCain D, Mosier AR (2003) Partitioning evapotranspiration fluxes from a Colorado grassland using stable isotopes: Seasonal variations and ecosystem implications of elevated atmospheric CO2. Plant and Soil 254, 291–303.

Foken T, Kukharets VP, Perepelkin VG, Tsvang LR, Richter SH, Weisensee U (1999) The influence of the variation of the surface temperature on the closure of the surface energy balance. In 'Proc. 13th Symposium on Boundary Layer and Turbulence'. Dallas pp. 308-309

Fraser G (1989) Agricultural marketing in less developed areas with reference to livestock. In 'Annual Symposium of the South African Society of Animal Production, Developing Areas Branch'. Pretoria, South Africa pp. 29-38

Fraser G (2004) 'Obstacles to agricultural development in the communal areas of the Eastern Cape.' Economic Growth and Development Working Group, East London.

Fuentes S, Palmer AR, Taylor D, Zeppel M, Whitley R, Eamus D (2008) An automated procedure for estimating the leaf area index (LAI) of woodland ecosystems using digital imagery, MATLAB programming and its application to an examination of the relationship between remotely sensed and field measurements of LAI. Functional Plant Biology 35, 1070-1079.

Gers C, & Schmidt E (2001) Using SPOT4 satellite imagery to monitor area harvested by small scale sugarcane farmers at Umfolozi, 75th South African Sugar Technologists' Association (SASTA) (pp. 28−33).

Glenn EP, Huete AR, Nagler PL, Hirschboeck KK, Brown P (2007a) Integrating Remote Sensing and Ground Methods to Estimate Evapotranspiration. Critical Reviews in Plant Sciences 26, 139-168.

Glenn EP, Huete AR, Nagler PL, Hirschboeck KK, Brown P (2007b) Integrating Remote Sensing and Ground Methods to Estimate Evapotranspiration. Critical Reviews in Plant Sciences 26, 139 - 168.

Hansen S (1984) Estimation of Potential and actual evapotranspiration. Nordic Hydrology (Copenhangen) 15, 205-212.

He Y, Guo X, Wilmshurst JF (2007) Comparison of different methods for measuring leaf area index in a mixed grassland. Canadian Journal of Plant Science 87, 803-813.

Hengsdijk H, Groot A, Van Driel J, Kidanemariam Jembere, Van Uum J, Boone P (2009) 'Towards a sustainable future of the western shoreline of Lake Ziway.' Participatory land use plan development workshop, Plant Research International report 234, Ziway.

Hill RJ (1992) Review of optical scintillation methods of measuring the refractive-index spectrum, inner scale and surface fluxes. Waves in Random Media 2, 179 - 201.

Hill MJ, Senarath U, Lee A, Zeppel M, Nightingale JM, Williams RJ, McVicar TR (2006) Assessment of the MODIS LAI product for Australian ecosystems. Remote Sensing of Environment 101, 495-518.

Hoffman MT, Ashwell A (2001) 'Nature divided.Land degradation in South Africa.' (University of Cape Town Press: Cape Town)

Hogan CM (2010) Overgrazing. In 'Encyclopedia of Earth'. (Eds S Draggan and CJ Cleveland). (National council for Science and the Environment: Washington, D.C)

Holm AM, Watson IW, Loneragan WA, Adams MA (2003) Loss of patch-scale heterogeneity on primary productivity and rainfall-use efficiency in Western Australia. Basic and Applied Ecology 4, 569-578

Hughes D (2002) The development of an information modelling system for regional water resource assessments. In 'Fourth International FRIENDS Conference'. pp. 11-18. (International Association of Hydrological Sciences Publication: Cape Town)

Kairu EN (1991) A review of methods for estimating evapotranspiration GeoJournal 25, 371-376.

Kim SH, Lee KS (2003) Local validation of MODIS global Leaf Area Index (LAI) product over temperate forest. Korean Journal of Remote Sensing 19, 1-9.

Khalaf AJ (2010) Spatial and Temporal Distribution of Groundwater Recharge in the West Bank Using Remote Sensing and GIS Techniques. Doctoral thesis, Durham University.

Kroes JG, Van Dam J.C, (2003) Reference manual SWAP version 3.03, Alterra Green World Research, Alterra Report 773, Wageningen University and Research Centre, Wageningen, The Netherlands,.

Kustas WP, Norman JM (1996) Use of remote sensing for evapotranspiration monitoring over land surfaces Hydrological Sciences Journal 41, 495 - 516.

Le Maitre D, Versfeld D, Chapman A (2000) The impact of invading alien plants on surface water resources in South Africa: a preliminary assessment. Water SA 26, 397-408.

Leuning R, Cleugh HA, Zegelin SJ, Hughes D (2005) Carbon and water fluxes over a temperate Eucalyptus forest and a tropical wet/dry savanna in Australia: Measurements and comparison with MODIS remote sensing estimates. Agricultural and Forest Meteorology 129, 151-173.

Leuning R, Zhang YQ, Rajaud A, Cleugh H, Tu K (2008) A simple surface conductance model to estimate regional evaporation using MODIS leaf area index and the Penman-Monteith equation. Water Resource Research. 44, W10419.

Liu H, Foken T (2001) A modified Bowen ratio method to determine sensible and latent heat fluxes. Meteorologische Zeitschrift 10, 71-80.

Macfarlane C, Hoffman MT, Eamus D, Kerp N, Higginson S, McMurtrie R, Adams M (2007) Estimation of leaf area index in eucalypt forest using digital photography. . Agricultural and Forest Meteorology 143, 176-188.

Mammarella I, Werle P, Pihlatie M, Eugster W, Haapanala S, Kiese R, Markkanen T, Rannik Ua, Vesala T (2010) A case study of eddy covariance flux of N2O measured within forest ecosystems: quality control and flux error analysis. Biogeosciences 7, 427-440.

Mander M, Blignaut J, et al. (2007) 'An Ecosystem Services Trading Model for the Mnweni/Cathedral Peak and Eastern Cape Drakensberg Areas.' Development Bank of Southern Africa, Department of Water Affairs and Forestry, Department of Environment Affairs and Tourism, Ezemvelo KZN Wildlife, INR Report IR281., South Africa.

Marion GM, Henry GHR, et al. (1997) Open-top designs for manipulating field temperature in high-latitude ecosystems. Global Change Biology 3, 20-32.

Mengistu MG, Savage MJ (2010) Surface renewal method for estimating sensible heat flux. Water SA 36, 9-18.

Millenium Ecosystem Assessment MEA (2005) 'Ecosystems and Human Well-being.' Island Press, Washington DC.

Miranda M, Porraz IT, Moreno ML (2003) 'The Social Impacts of Payments for Environmental Services in Costa Rica. A Quantitative Field Survey and Analysis of the Virilla Watershed.' International Institute for Environment and Development (IIED), London:.

Monteith JL (1965) Evaporation and environment. Symposia of the Society for Experimental Biology 19.

Moran MS, Scott RL, Hamerlyck EP, Green KN, Emmerich WEa, Collins CDH (2009) Soil evaporation response to Lehmann lovegrass (Eragrostis lehmanniana) invasion in a semi-arid water shed. . Agricultural and Forest Meteorology. 149, 2133-2142.

Mu Q, Heinsch FA, Zhao M, Running SW (2007) Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. Remote Sensing of Environment 111, 519−536.

Mucina L, Rutherford MC (2006) 'The vegetation of South Africa, Lesotho and Swaziland.' (South Afican National Biodiversity Institude: Pretoria)

Mugabi B (2010) Water utilization and population demography in South Africa: Key ethical and human rights issues. University of Witwatersrand.

Mukheibhir P (2007) The impact of climate change on small municipal water resource management: The case of Bredasdorp, South Africa. University of Cape Town.

Muller M (2009) Attempting to do it all: how a new South Africa has harnessed water to address its water development challenges. In 'Earthscan': London)

Nagler PL, Cleverly J, Glenn E, Lampkin D, Huete A, Wan ZM (2005) Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. Remote Sensing of Environment 94, 17-30.

NASA (2009) Status for: LAI/FPAR (MOD15). In. (MODIS Land Team)

Nilson T (1971) A theoretical analysis of the frequency of gaps in plant stands. Agricultural Meteorology 8, 25-38.

Nishida K, Nemani RR, Running SW, Glassy JM (2003) An operational remote sensing algorithm of land surface evaporation. Journal of Geophysical Research: Atmospheres 108, 4270.

Odhiambo GO, Savage MJ (2009) Surface layer scintillometry for estimating the sensible heat flux component of the surface energy balance. South African Journal of Science 105, 208-216.

Ongwenyi, Kithiia SM, Denga FO (1993) An overview of the soil erosion and sedimentation problems in Kenya. In 'Sediment Problems: Strategies for Monitoring, Prediction and Control '. Yokohama, Japan. (International Association of Hydrological Sciences Publication)

Ortiz E, Kellenberg J (2002) Program of payments for ecological services in Costa Rica. In 'International Expert Meeting on Forest Landscape Restoration'. Heredia, Costa Rica

Otieno FAO, Ochieng GNM (2004) Water management tools as a means of averting a possible water scarcity in South Africa by year 2025. Water SA 30, 120 - 124

Overgaard J, Rosbjerg D, Butts MB (2006) Land-surface modelling in hydrological perspective â€“ a review. Biogeosciences 3, 229-241.

Overpeck JT, Bartlein PJ, Webb III T (1991) Potential magnitude of future vegetation change in eastern North America: comparisons with the past. Science 254, 692-695.

Pagiola S (2007) Using Markets to Preserve Forests and the Services They Provide. In 'International Union of Forest Research Organizations (IUFRO) Symposium'. Saariselkä, Finland.

Pagiola S, Platais G (2007) 'Payments for Environmental Services: From Theory to Practice.' World Bank, Washington.

Palmer AR, Fuentes S, Taylor D, Maccinis-Ng C, Zeppel M, Yanusa I, February E, Eamus D (2008) The use of pre-dawn leaf water potential and MODIS LAI to explore seasonal trends in the phenology of Australian and southern African woodlands and savannas. Australian Journal of Botany 56, 557-563.

Palmer AR, Fuentes S, Taylor D, Macinnis-Ng C, Zeppel M, Yunusa Ia, Eamus D (2010) Towards a spatial understanding of water use of several land-cover classes: pre-dawn leaf water potential, stand water use, aridity index and MODIS LAI. Ecohydrology 3, 1-10.

Palmer AR, Short A and Yunusa IAM (2010) Biomass production and water use efficiency of grassland in KwaZulu-Natal, South Africa. African Journal of Range and Forage Science 27, 163-169.

Palmer AR, Weideman CI (2011) Exploring trends in evapotranspiration in the KNP: towards a water use efficiency model for rangeland production in semi-arid savannas. . In ' IXth International Rangelands Congress'. Rosario, Argentina p. 248.

Penman HL (1948) Natural evaporation from open water, bare soil and grass. In 'Proceedings of the Royal Meteorological Society (series A)'. pp. 120-146.

Proctor W, Köllner T, Lukasiewicz (2008) 'Equity Considerations and Payments for Ecosystem Services.' University of Cambridge, Switzerland.

Reynolds JF, Kemp PR, Tenhunen JD (2000) Effects of Long-Term Rainfall Variability on Evapotranspiration and Soil Water Distribution in the Chihuahuan Desert: A Modeling Analysis. Plant Ecology 150, 145-159.

Richmond A, Kaufmann RK, Myneni RB (2007) Valuing ecosystem services: A shadow price for net primary production. Ecological Economics 64, 454-462.

Rosenberg NJ, Blad BL, Verma SB (1983) 'Microclimate: The Biological Environment, 2nd edn ' (John Wiley and SonsJohn: New York).

Ross J (1981) 'The radiation regime and architecture of plant stands.' (Dr. W. Junk Publishers: The Hague-Boston-London).

Sadoff CW, Muller M (2009) 'Better water resources management - greater resilience today, more effective adaptation tomorrow. A climate and water perspectives paper ' Global Water Partnership.

Savage MJ, Everson CS, Odhiambo GO, Mengistu MG, Jarmain C (2004) 'Theory and Practice of Evapotranspiration. Measurement, with Special Focus on SLS as an Operational Tool for the Estimation of Spatially-Averaged Evaporation.' Water Research Commission, 1335/1/04, Pretoria (South Africa).

Savage MJ, Odhiambo GO, Mengistu MG, Everson CS, Jarmain C (2010) Measurement of grassland evaporation using surface-layer scintillometer. 36, 1-8.

Schleppi P, Conedera M, Sedivy I, Thimonier A (2007) Correcting non-linearity and slope effects in the estimation of the leaf area index of forests from hemispherical photographs. Agricultural and Forest Meteorology 144, 236–242.

Scholes R (2001) 'Regional Implementation Plan for South Africa ' Global Terrestrial Observing System, South Africa.

Schulze RE (1990) Climate change and hydrological response in Southern Africa - Heading towards the future. South African Journal of Science 86, 373-381.

Seckler D, Amarasinghe U, Molden D, de Silva R, Barker R (1996) 'World Water Demand and supply, 1990 - 2025: Scenarios and issues ' International Water Management Institute, Research Report 19.

Smakhtin V, Ashton PJ, et al. (2001) Unconventional Water Supply Options in South Africa: possible solutions or intractable problems? Water International 26, 314-334.

Smith J, Scherr S (2002) 'Forest carbon and local livelihoods: assessment of opportunities and policy recommendations.' Center for International Forestry Research Occasional Paper No. 37, Bogor, Indonesia.

Snyman HA, van Rensburg WLJ (1986) Effects of slope and plant cover on run-off, soil loss and water use efficiency of natural veld. Journal of Range and Forage Science 16, 108-117.

Snyman HA (1994) Evapotranspiration, water-use efficiency and quality of six dryland planted pasture species and natural vegetation, in a semi-arid ramgeland. African Journal of Range and Forage Science 11, 82-88.

Southgate D, Wunder S (2009) Paying for Watershed Services in Latin America: A Review of Current Initiatives. Journal of Sustainable Forestry 28, 497-524.

StatistcsSA (2010) 'Mid-year population estimates.' Statistic South Africa, Pretoria, SA.

Stockle CO, Kjelgaard E, Bellocchi G (2004) Evaluation of estimated weather data for calculating Penman-Monteith reference crop evapotranspiration. Irrigation Science 23, 39-46.

Stockle CO, Nelson R (1999) 'ClimGen: a weather generator program.' Department of Biological Systems Engineering. Washington State University.Pullman, Wash. USA.

SWCC (1990) Proceedings from the Second World Climate Conference. In 'Second World Climate Conference'. Geneva. (World Meteorological Organisation)

Tan B, Hu J, Huang D, Yang W, Zhang P, Shabanov NV, Knyazikhin Y, Nemani RR, Myneni RB (2005) Assessment of the broadleaf crops leaf area index product from the Terra MODIS instrument. Agricultural and Forest Meteorology 135, 124-134.

Teixeira AHC (2010) Determining Regional Actual Evapotranspiration of Irrigated Crops and Natural Vegetation in the SÃ£o Francisco River Basin (Brazil) Using Remote Sensing and Penman-Monteith Equation. Remote Sensing 2, 1287-1319.

Thiermann V, Grassl H (1992) The measurement of turbulent surface layer fluxes by use of bichromatic scintillation. Boundary Layer Metereology 58, 367-984.

Tian Y, Woodcocka CE, et al. (2002) Multiscale analysis and validation of the MODIS LAI product II. Sampling Strategy. Remote Sensing of Environment 83, 431-441.

Tsouni A, Kontoes C, Koutsoyiannis D, Elias P, Mamassis N (2008) Estimation of Actual Evapotranspiration by Remote Sensing: Application in Thessaly Plain, Greece. Sensors 8, 3586-3600.

Turpie J, Winkler H, Spalding-Fecher R, Midgley G (2002) The impact of climate change in SA:A preliminary analysis of unmitigated damage costs. University of Cape Town.

Turpie JK, Heydenrych BH (2000) (Ed.)^(Eds) 'Economic consequences of alien infestation of the Cape Floral Kingdom's fynbos vegetation.' The economics of Biological Invasions (Edward Elgar: Cheltenham)

Turpie JK, Heydenrych BJ, Lamberth SJ (2003) Economic value of terrestrial and marine biodiversity in the Cape Floristic Region: implications for defining effective and socially optimal conservation strategies. Biological Conservation 112, 233-251.

Turpie JK, Marais C, Blignaut JN (2008) The working for water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. Ecological Economics 65, 788-798.

USGS (2010) The water cycle: Evapotranspiration. In. (U.S. Geology Survey: United States of America)

van Wilgen BW, Le Maitre DC, Cowling RM (1998) Ecosystem services, efficiency, sustainability and equity: South Africa's Working for Water Programme. Trends in Ecology & Evolution 13, 378.

Varga A, Harwood JH, et al. (2009) 'Payments for Ecosystem Services: An Analysis of Cross Cutting Issues in 10 Case Studies ' Colombia University, Colombia.

Venturini V, Bisht G, Islam S, Jiang L (2004) Comparison of evaporative fractions estimated from AVHRR and MODIS sensors over South Florida. . Remote Sensing of Environment 93, 77−86.

Vink N (1986) An institutional approach to livestock development in Southern Africa. University of Stellenbosch.

Walmsley RD, Walmsley JJ, Consultants M, Silbarbuer M, DWAF (1999) 'National State of the Environment: Freshwater Systems and Resources.' Department of Environmental Affairs and Tourism, South Africa.

Wang Y, Woodcock CE, et al. (2004) Evaluation of the MODIS LAI algorithm at a coniferous forest site in Finland. Remote Sensing and Environment 91, 114-127.

Warren RW, Hakonson TE, Bostick KV (1996) The hydrologic evaluation of four cover designs for hazardous waste landfills at Hill Air Force Base. Federal Facilities Environmental Journal Winter, 91-110.

Watson DJ (1947) Comparative Physiological Studies on the Growth of Field Crops: I. Variation in Net Assimilation Rate and Leaf Area between Species and Varieties, and within and between Years. Annals of Botany 11, 41-76.

WMO (1998) 'WMO Statement on the Status of the Global Climate in 1997.' World Meteorological Organization, Geneva - Switzerland.

Wunder S (2005) 'Payments for environmental services: some nuts and bolts.' Center for International Forestry Research, Occasional Paper No. 42, Bogor, Indonesia.

Xiong YJ, Qiu GY, Yin J, Zhao SH, Wu XQ, Wang P, Zeng S (2008) Estimation of Daily Evapotranspiration by Three-Temperatures Model at Large Catchment Scale. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 37, 767-774.

Zbinden S, Lee DR (2005) Paying for environmental services: An analysis of participation in Costa Rica’s PSA program. World Development 33, 255-272.

Zhang Y, Wegehenkel M (2006) Integration of MODIS data into a simple model for the spatial distributed simulation of soil water content and. Remote Sensing of Environment 104, 393-408.

Zhang YQ, Chiew FHS, Zhang L, Leuning R, Cleugh HA (2008) Estimating catchment evaporation and runoff using MODIS leaf area index and the Penman-Monteith equation. Water Resour. Res. 44, W10420.

Zhou SQ, Liang X, Chen J, Gong P (2004) An assessment of the VIC-3L hydrological model for the Yangtze River basin based on remote sensing: A case study of the Baohe River basin. Canadian Journal of Remote Sensing 30, 840−853.

WEBSITES:
http://www.alibaba.com/product-tp/105582310/Melinex_Film.html (Accessed on October 2010)
http://www.dwaf.gov.za/iwqs/gis_data/river/rivs500k.html (Accessed on February 2011)

http://www.demarcation.org.za/ (Accessed on February 2011)
www.environment.gov.za/enviro-info/prov/ec/ecpcat.jpeg (Accessed on February 2011)
http://cybele.bu.edu/courses/estonia/modis-lab-03-ascii.pdf (Accessed on February 2011)

APPENDICES:

Appendix 1: Differences between quaternary catchment S50E (HB) and S20C (LB)

Description of the veld condition of quaternary catchment S50E:

1. High biomass cover dominated by *Eragrostis plana*.
2. The average disc pasture meter reading from three sites was 9.5 cm.
3. Soil is red and deep
4. Fire is used
5. No camp resting
6. There are some Black wattles and Pine plantations

The summary of the point to turf distance:

Season	2011/09/27	
Co-ordinat	27.61809	-31.87008

			Plot	
Camp ID	Species	Data	1	Grand Total
S50E-HB	DIGITARIA	Count of Distance	3	3
		Average of Distance	1.333333333	1.333333333
	ERAG	Count of Distance	1	1
		Average of Distance	0	0
	ERAG PLANA	Count of Distance	24	24
		Average of Distance	0.875	0.875
	FORB	Count of Distance	13	13
		Average of Distance	0.846153846	0.846153846
	HYPA HIRTA	Count of Distance	7	7
		Average of Distance	1.142857143	1.142857143
	SPORO AFR	Count of Distance	1	1
		Average of Distance	0	0
S50E-HB Count of Distance			49	49
S50E-HB Average of Distance			0.897959184	0.897959184
Total Count of Distance			49	49
Total Average of Distance			0.897959184	0.897959184

Season	2011/09/28
Co-ordinat	27.68027 -31.78604

			Plot	
Camp ID	Species	Data	2	Grand Total
S50E-HB	DIGITARIA	Count of Distance	1	1
		Average of Distance	1	1
	ERAG PLANA	Count of Distance	29	29
		Average of Distance	1.344827586	1.344827586
	FORB	Count of Distance	19	19
		Average of Distance	0.526315789	0.526315789
	HETROPOG	Count of Distance	1	1
		Average of Distance	2	2
S50E-HB Count of Distance			50	50
S50E-HB Average of Distance			1.04	1.04
Total Count of Distance			50	50
Total Average of Distance			1.04	1.04

Season	2011/09/28
Co-ordinat	27.68341 -31.77613

			Plot	
Camp ID	Species	Data	3	Grand Total
S50E-HB	CYN DACT	Count of Distance	1	1
		Average of Distance	1	1
	DIGITARIA	Count of Distance	18	18
		Average of Distance	1.111111111	1.111111111
	ERAG PLANA	Count of Distance	4	4
		Average of Distance	2	2
	ERAG SPP	Count of Distance	5	5
		Average of Distance	1.2	1.2
	FORB	Count of Distance	1	1
		Average of Distance	0	0
	HETROPOG	Count of Distance	2	2
		Average of Distance	0.5	0.5
	MISCENTHUS	Count of Distance	10	10
		Average of Distance	2.2	2.2
	SPORO AFR	Count of Distance	5	5
		Average of Distance	1.8	1.8
	THEMEDA	Count of Distance	4	4
		Average of Distance	1.5	1.5
S50E-HB Count of Distance			50	50
S50E-HB Average of Distance			1.46	1.46
Total Count of Distance			50	50
Total Average of Distance			1.46	1.46

Photos showing the biomass cover of Quaternary Catchment S50E (HB):








Description of the veld condition of quaternary catchment S20C:

1. Low biomass cover dominated by *Euryops annae* and some *Cynodon dactylon.*
2. No disc pasture meter readings were taken from this quaternary catchment due to its low biomass
3. The soil is shale and shallow
4. No fire used
5. No camp resting
6. No black wattle or pine plantations were observed

The summary of the point to turf distance:

Season	2011/09/27

			Plot	
Camp ID	Species	Data	1	Grand Total
S20C-LB	ARIS CONG	Count of Distance	12	12
		Average of Distance	9.666666667	9.666666667
	CYM PLU	Count of Distance	38	38
		Average of Distance	4.5	4.5
	CYN DACT	Count of Distance	9	9
		Average of Distance	4.555555556	4.555555556
	ELIO. ARG	Count of Distance	3	3
		Average of Distance	4	4
	ERAG CHL	Count of Distance	31	31
		Average of Distance	4.516129032	4.516129032
	EURY ANN	Count of Distance	3	3
		Average of Distance	3.333333333	3.333333333
	FORB	Count of Distance	3	3
		Average of Distance	3.666666667	3.666666667
	HERB	Count of Distance	1	1
		Average of Distance	2	2
S20C-LB Count of Distance			100	100
S20C-LB Average of Distance			5.03	5.03
Total Count of Distance			100	100
Total Average of Distance			5.03	5.03

Season	2011/09/27
Co-ordinat	27.43350 -31.75260

			Plot	
Camp ID	Species	Data	2	Grand Total
S20C-LB	ARIS CONG	Count of Distance	5	5
		Average of Distance	5.4	5.4
	CYM PLU	Count of Distance	2	2
		Average of Distance	6	6
	CYN DACT	Count of Distance	35	35
		Average of Distance	6.171428571	6.171428571
	FORB	Count of Distance	8	8
		Average of Distance	1.875	1.875
S20C-LB Count of Distance			50	50
S20C-LB Average of Distance			5.4	5.4
Total Count of Distance			50	50
Total Average of Distance			5.4	5.4

Season	2011/09/27
Co-ordinat	27.44275 -31.74145

			Plot	
Camp ID	Species	Data	3	Grand Total
S20C-LB	ARIS CONG	Count of Distance	10	10
		Average of Distance	6.3	6.3
	CYN DACT	Count of Distance	1	1
		Average of Distance	2	2
	ELIO. ARG	Count of Distance	35	35
		Average of Distance	4.457142857	4.457142857
	ERAG CHL	Count of Distance	1	1
		Average of Distance	1	1
	FORB	Count of Distance	2	2
		Average of Distance	1.5	1.5
S20C-LB Count of Distance			49	49
S20C-LB Average of Distance			4.591836735	4.591836735
Total Count of Distance			49	49
Total Average of Distance			4.591836735	4.591836735

Photos showing the biomass cover of Quaternary Catchment S50E (HB):

Appendix 2: A Macro File showing how Scenarios 1 – 3 were created in IDRISI 32

Scenario 1

INITIAL x
c:\gisdata\modis1\eastcape\2009\col5\lai\13951.rst*1*1*0*1*c:\gisdata\modis1\eastcape\2009\col5\lai\2009001.rst*
POLYRAS x c:\gisdata\modis1\eastcape\2009\col5\lai\1395-hca.vct*c:\gisdata\modis1\eastcape\2009\col5\lai\13951.rst
OVERLAY x
3*c:\gisdata\modis1\eastcape\2009\col5\lai\13951.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\2009001.rst*c:\gisdata\modis1\eastcape\2008\col5\lai\13951-1.rst
RECLASS x I*c:\gisdata\modis1\eastcape\2009\col5\lai\13951-1.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13951-2.rst*3*c:\gisdata\modis1\eastcape\2009\col5\lai\1395-1.rcl
RECLASS x I*c:\gisdata\modis1\eastcape\2009\col5\lai\13951-2.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13951-3.rst*3*c:\gisdata\modis1\eastcape\2009\col5\lai\1395.rcl
extract x c:\gisdata\modis1\eastcape\2009\col5\lai\13951-3.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13951-2.rst*2*4

Scenario 2

INITIAL x
c:\gisdata\modis1\eastcape\2009\col5\lai\13952.rst*1*1*0*1*c:\gisdata\modis1\eastcape\2009\col5\lai\2009001.rst*
POLYRAS x c:\gisdata\modis1\eastcape\2009\col5\lai\1395-cat.vct*c:\gisdata\modis1\eastcape\2009\col5\lai\13952.rst
OVERLAY x 1*c:\gisdata\modis1\eastcape\2009\col5\lai\13951-3.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13952.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13952-1.rst.
extract x c:\gisdata\modis1\eastcape\2009\col5\lai\13952-1.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13951-2.rst*2*4

Scenario 3

INITIAL x c:\gisdata\modis1\eastcape\2009\col5\lai\13953-1.rst*2*1*0*1*c:\gisdata\modis1\eastcape\2009\col5\lai\2009001.rst*
POLYRAS x c:\gisdata\modis1\eastcape\2009\col5\lai\1395-hca1.vct*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-1.rst
OVERLAY x 3*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-1.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\2009001.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-2.rst
RECLASS x I*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-2.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-3.rst*3*c:\gisdata\modis1\eastcape\2009\col5\lai\1395-1.rcl
RECLASS x I*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-3.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-4.rst*3*c:\gisdata\modis1\eastcape\2009\col5\lai\1395.rcl
SCALAR x
c:\gisdata\modis1\eastcape\2009\col5\lai\13953.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-0.rst*3*0.5
OVERLAY x 2*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-4.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-0.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-5.rst
OVERLAY x 3*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-5.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-3.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-6.rst
extract x c:\gisdata\modis1\eastcape\2009\col5\lai\13953-4.rst*c:\gisdata\modis1\eastcape\2009\col5\lai\13953-6.rst*2*4