

**GROUND AND SATELLITE-BASED ASSESSMENT OF  
HYDROLOGICAL RESPONSES TO LAND COVER CHANGE  
IN THE KILOMBERO RIVER BASIN, TANZANIA**

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## Abstract

Changes in land use and land cover are a global issue of concern, especially with regard to possible impacts on biophysical processes which affect the hydrological functioning of a system. Tanzania is no exception to this concern. This study, therefore, addresses the implications of land use alterations on the hydrodynamics of the Kilombero River Basin, specifically with regard to the Kilombero Valley's wetlands and water resources, which have been altered and exploited to a great extent.

As its starting point, the study embarked on mapping the current land cover in the Kilombero Basin and the quantification of the historical changes. The study revealed significant changes and, in recent years, increased rates of clearing natural vegetation cover and conversion to agricultural land. The most affected area of the Basin was the Kilombero Valley, a Ramsar Site and formerly extensively inhabited by wildlife, but which now has 62% of its area converted into agricultural and/or human settlements. In line with this observation, the study used two approaches for the impact analysis, a regional scale and a local scale approach. Plant physiology, soil moisture and micro-meteorological measurements were undertaken to quantify the impact of land cover change at local scale. Sensing techniques were then applied to assess the spatial extent of the changes and the basin scale (regional) impact thereof.

Investigation of hydrological processes at a local scale placed emphasis on the implications of forest conversion from indigenous Miombo woodland to exotic Teak (*Tectona grandis*) forests. Field measurements showed the distinctive nature of Teak trees consumptive water use, both in quantity as well as in regard to the seasonal variation as compared to the native Miombo woodland forests. Teak was found to have higher transpiration rates, both during the rainy season (where the rates were approximately 10-fold higher than that of Miombo) and the period immediately after the cessation of rainfall, with consumptive water use rates being four-fold higher than that of Miombo. This contrast in water use was further observed in the measured soil water fluxes which evidenced a large difference in the components of the soil water balance. Less recharge was observed in the Teak forests suggesting significant impacts on the replenishment of groundwater resources in the study area.

Assessment of the basin scale impacts of the land cover changes on the evapotranspiration (ET) regime was undertaken using the Surface Energy Balance System (SEBS) remote sensing model. Validation was provided by the Teak field sites and through the monitoring of ET from sugar cane using a Large Aperture Scintillometer (LAS). Results suggest a decrease

in ET during the dry season. There is a clear transition of ET that follows the land cover transition from the natural and more adaptable vegetation, to rain-fed dependent crops and bare lands, where minimal ET is observed during the dry season. Similar seasonal leafing, and therefore a similar ET pattern, is observed with the conversion of natural forests to deciduous plantation forests. Irrigated crops, on the other hand, were found to have persistently higher ET throughout the year regardless of rainfall variability. This implies that land cover change in the Kilombero Valley is resulting in higher water use and less recharge in the wet season and a correspondingly lower ET (and possibly lower river flow) in the dry season than would occur under natural conditions.

This research provides valuable information relevant to all stakeholders in the Kilombero River Basin (i.e. both smallholders and commercial sugarcane farmers, the forestry industry, Basin Water Authorities etc.). This information will help to inform decision-making around the sustainable management of the water resources in the Kilombero Valley for food security as well as for sustaining livelihoods and ecosystems.

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## PREFACE

The work described in this thesis was carried out in the School of Agriculture, Earth and Environmental Science, University of KwaZulu-Natal, Pietermaritzburg under the supervision of Professor Graham Jewitt. All field work in this study was undertaken at the Kilombero River Basin in Tanzania.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

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## **DECLARATION 2 - PUBLICATIONS**

Details of contribution to publications that form part of and/or include research presented in this thesis (including publications submitted or published, giving details of the contributions of each author to the research and writing of each publication):

### **Publication 1 – Chapter 2 of this thesis**

Munishi, SE and Jewitt, GPW in preparation. Trends of land use and cover changes and their hydrological implications in the Kilombero Valley, Tanzania.

Research for this publication was conducted by SE Munishi, with technical advice from GPW Jewitt. This publication was written in its entirety by SE Munishi and all data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by GPW Jewitt.

### **Publication 2 – Chapter 3 of this thesis**

Munishi, SE and Jewitt, GPW in preparation. Water use characteristics of Miombo and Teak forests in the Kilombero Valley, Tanzania: a comparative analysis.

Data collection and analysis for this publication was conducted by SE Munishi, with technical advice from GPW Jewitt. This publication was written in its entirety by SE Munishi and all data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by GPW Jewitt.

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# 1. BACKGROUND

Changes in land use and land cover are a global issue of concern, especially with regard to the impacts on biophysical processes which affect the hydrodynamics of an ecosystem. Recently, the global water resources community's efforts have been focused on the sustainable management of water resources in the face of increasing demand by a rapidly expanding world population coupled with the quest for more agricultural lands accelerated by advancements in agricultural technology. Recent global trends in flood and drought occurrence have also prompted the scientific community to investigate the role of human-induced land use transformation on these occurrences (e.g. Hirabayashi *et al.*, 2008; Sheffield and Wood, 2008; Orłowsky and Seneviratne, 2012). One of the main drivers of land use change is anthropogenic activity that, in most cases, results in agricultural intensification and urbanisation. It is acknowledged that there are several factors, including national policies and climate variability, which may lead or facilitate such land use change. It is also important to note that the alteration of hydrological regimes is driven by factors such as climatic variability, upstream surface and groundwater withdrawals etc., thus making it more challenging to distinguish the causative force behind a change in hydrological regime (Tomer and Schilling, 2009).

A number of past studies have addressed the impacts of land use transformation on hydrological systems on a global scale (Van Dijk *et al.*, 2009; Ridoutt and Pfister, 2010; Pfister *et al.*, 2011,) and on regional and catchment scales (Petchprayoon, 2010; Noretto *et al.*, 2012). In most of these studies, focus has leaned towards impacts on river flow and groundwater regime modifications since these are regarded as the most affected by land use alterations in the Integrated Water Resources Management Framework (Bonell, 2010). However, sound assessment of human interference in a global water cycle should be carried out by observing trends in all key hydrological variables, though typically trends in stream flow, evaporation, soil moisture variations, precipitation, groundwater, reservoir, lakes and wetlands storage and glacier cover are the focus (Lettenmaier *et al.*, 2009). Consequently, less attention has been paid to the impacts of land use change on other hydrological processes such as evaporation and soil water dynamics, which form the focus of this study. This is due to the Limitations with regard to availability of robust scientific methodologies for quantifying such processes also hindered previous studies; however with the advancement in

remote sensing techniques, studies such as Zhang *et al.* (2012) and Gokmen *et al.* (2013) have addressed such limitations at regional and global scales.

The importance of assessing spatially-variable processes such as evaporation and soil moisture cannot be over-emphasised. These processes are known to be entities that vary spatially, hence studies on climate change, surface water exploitation or land use change have attempted to apply hydrological models that are capable of capturing such hydrological processes at the desired scale. Wagener *et al.* (2010) stress that the future assessment of hydrological impact studies should give more attention to hydrological processes (i.e. understanding water and system dynamics) rather than a general response or an outcome-oriented approach.

A range of studies exist that have investigated the change in hydrological processes originating from human-induced land use/cover changes (e.g. Wang *et al.*, 2007, and Shi *et al.*, 2013, who modelled the hydrological responses of land use and climate change). However, most of these studies have been structured through simplified simulations of the hydrological cycle constructed from climatic and discharge data. Impact assessments through modelling approaches have been shown to yield outputs that are affected by model structure and calibration strategies (Cornelissen *et al.*, 2013). Further, they suffer issues of inaccuracy in representing hydrological processes at the desired scale (Cornelissen *et al.*, 2013). Relatively few studies (e.g. Venkatesh *et al.*, 2011, Bonella *et al.*, 2010 and Harden *et al.*, 2013), have integrated modelling with the ground measurements of hydrological processes, an approach that this study embraces. Notably, most African basins are inadequately gauged for such approaches to be successfully applied. The Kilombero River Basin, where this research study is carried out, is one such ungauged basin suffering from issues of data inadequacy where basic data like rainfall and runoff values are insufficient and of poor quality.

It appears, then, that most existing monitoring networks are not capable of providing up-to-date information on available water resources, consumption and withdrawal patterns. Nonetheless, rapid population growth population and land use transitions, call for more robust methods capable of monitoring the continually changing landscape and watershed degradation at a large spatial and temporal scale relevant for watershed management. In this regard, Wagener *et al.* (2010) proposed the increased use of remote sensing techniques. For the purpose of this study, such techniques offered an opportunity to monitor the spatial and temporal variability of key hydrological variables (such as evaporation fluxes) from land

parcels with mixed land cover types as well as varying canopy height and vegetation density. Moreover, remote sensing methods have successfully been used in the past in ungauged basins, like the Kilombero Basin, where ground-based micrometeorological data are insufficient and of poor quality thereby limiting the drawing of any meaningful conclusions concerning the hydrological state of the basin (Winsemius *et al.*, 2008; Tarpanelli, *et al.*, 2013). However, remote sensing techniques are applied with an understanding of their limitations, especially in mountainous areas where there is persistent cloud cover that compromises the capture of ground signatures by satellite sensors. In spite of these limitations, remotely-sensed signatures can present opportunities for improving the understanding of processes governing the hydrology of large river basins (especially in sub-Saharan Africa where data availability and quality are lacking ) providing the sources of uncertainty around the approach can be easily identified and dealt with (Hrachowitz *et al.*, 2013). It should be noted that the Kilombero River Basin, like many other ungauged watersheds in Tanzania, has not been given adequate attention by the scientific community, mostly due to poor data availability and quality.

In Tanzania, the recent “*Kilimo Kwanza*” (Agriculture First) initiative (an initiative by the Government to prioritise agriculture as a key pillar of the economy) has resulted in agricultural intensification accompanied by the expansion of cropland areas. Wetland areas are often targeted due to their fertility and assurance of soil moisture supply for agricultural crops. The Kilombero Valley has become a focal point for the initiative through the promotion of large-scale farming, including afforestation, especially with Teak (*tectona grandis*), and irrigated agriculture. Private and foreign investors are already acquiring land, especially from the Ruipa, Merera and Kihansi Valley’s wetlands, for large-scale farming. In addition, the productivity of the Kilombero Valley area has attracted a continued influx of small farmers and pastoral migrants from other drier areas of the country. Consequently, the area is currently experiencing significant population pressure and farmer-pastoralist conflicts (Kangalawe and Liwenga, 2005; Mombo *et al.*, 2011). Increased population pressure has also led to substantial clearance of natural vegetation for land acquisition for agricultural activities, grazing and settlements resulting in increased competition for water resources.. Recent rapid population increases in the Kilombero Valley and the accelerated conversion of large areas into agricultural and grazing land, reflect unplanned agricultural development in the Basin and, more importantly, have the potential to disturb the Basin’s hydrological regime and threaten the permanent degradation of the water sources. The Kilombero Valley is a Ramsar

site (Mombo, 2011) and its conservation cannot be ignored. Moreover, more than 80% of the Valley's population is totally dependent on the wetlands for their livelihoods (Kangalawe and Liwenga, 2005).

The "Kilimo Kwanza" initiative is geared towards the transformation of the agricultural sector through the modernisation of technology for increased crop production and the expansion of the area of irrigated land (Lugoe, 2010; Coulson, 2011). In line with this and the current rapid land exploitation, the River Basin Authorities are under pressure to guide the planning of water resources for newly established development activities and the associated land allocation process. This poses a challenge to water management, given the Kilombero Basin's data scarcity and the lack of information on the implications of the already on-going agricultural intensification. Informed decisions have to be made on the trade-off between the utilisation and conservation of a wetland's resources and the tolerance levels of the wetland to utilisation before the sustainability of the water resource is threatened.

This research study is intended to provide a scientifically sound assessment of the current status of the hydrological changes associated with various land uses in the Basin and the extent of the on-going development of the land and Valley wetlands, while providing information on the consumptive water use characteristics of the various dominant land cover types, including irrigated land in the Basin. This study strives to establish a link between the quantified land cover changes and the hydrological processes in the Kilombero Basin using a different approach to previous studies in the Basin which have typically applied scenario analysis to estimate hydrological impact. Most studies use stream-flow changes as an indicator of the impact on the alteration of the hydrological regime whereas his study recognises that stream-flow changes may be driven by a number of other factors. Therefore, the study focused on the quantification evapotranspiration and assessed its variability across different land covers in the Kilombero Basin recognising that evapotranspiration is the most dominant hydrological flux ( $\pm 90\%$  of rainfall) in the region and also the most affected or influenced by anthropogenic activities due to the alteration of vegetation cover.

Due to the size and complexity of the Kilombero Basin, this study narrowed its focus to the Valley area after an initial, rapid analysis of land cover change for the entire Basin. This analysis revealed the Valley as the most vulnerable landscape feature was undergoing rapid transformation in the area. Impact assessments were then carried out in the Valley for specific case studies such. Teak forests establishment and expansion representing the commercial

forestry industry within the Basin, with a special focus on the water use of the replacing versus the replaced forest. Another case study on irrigated sugarcane plantations provided information on irrigated agriculture water use. The respective field sites areas were instrumented for detailed analysis of various biophysical processes. The impact analysis was not only carried out at field-scale (through the case studies) but also at Basin scale by capitalising on the strength of remote sensing techniques to capture such information over a large spatial scale.

A particular focus of this study was to provide scientific evidence of the extent to which hydrological processes are affected by the clearance of Miombo woodlands, the dominant land cover in the Basin, and subsequent replacement with Teak forest plantations. An unpublished report to the Kilombero Valley Teak Company (KVTC) by van Hensbergen and Scott ([www.ssc-forestry.com/fc04part2/files/hydrological.ppt](http://www.ssc-forestry.com/fc04part2/files/hydrological.ppt)) on the potential impacts of the Teak plantations on water supply in the Kilombero Valley, dismissed the possibility of the plantations having negative impacts on the local water resources due to, what they considered, the relatively small size of the envisaged plantations and their location in the Kilombero Valley. However, no attention was given to the Miombo woodland water use characteristics in this tropical area. Malmer and Nybergm (2008) noted that there is inadequate scientific clarity in the knowledge of biophysical processes and a lack of empirical data on basic links between trees and water budgets for Miombo woodlands. Miombo woodland has been documented as being highly susceptible to deforestation for the fuel wood supply in Tanzania (Luoga *et al.*, 2000). Information on the hydrological impacts of converting Miombo to Teak forests is almost non-existent in literature.

## **1.1 Overview of the Study Area**

The Kilombero Basin (Figure 1.1), which is part of the larger Rufiji River Basin, has an approximate area of 40,727 km<sup>2</sup> and is located in the southern central part of Tanzania. The Rufiji Basin has an estimated area of 170,000 km<sup>2</sup>. The estimated average discharge at the outlet of the Kilombero River Basin is 520 m<sup>3</sup> s<sup>-1</sup>, amounting to approximately 65% of the total Rufiji River outflow (Yawson *et al.*, 2005). Figure 1.1 shows the location and overview of the Kilombero River Basin.

The Kilombero Valley is located in the Kilombero Basin, a braided floodplain channel estimated to cover an area of about 7,946 km<sup>2</sup> drained by rivers (Figure 1.1) and with a high variation in seasonal flow. It should be noted that the Kilombero Valley was given Ramsar status in 2002 (Mombo *et al.*, 2011) due to its high biodiversity and ecological significance. The Valley consists floodplains that are seasonally inundated during the wet season (December to May) and that dry up during the dry season (June to November), with the exception of the main river channels and permanent swamps that are a common feature in the Valley. The Valley is also fringed by fragments of Eastern-Arc forests (Burgess *et al.*, 1998; Hall *et al.*, 2009) and large tracts of Miombo woodland (Starkey *et al.*, 2002).

One of the main challenges that this study faced, as mentioned earlier, was the fact that the Kilombero River Basin is poorly gauged, typical of many catchments and basins in less developed countries. Due to the absence of long-term, time series hydrological data, it was not possible to monitor the hydrological response of the landscape-transformed watersheds through the analysis of ground observations (e.g. discharge data, evapotranspiration or groundwater data). For instance, the most downstream gauging station near the outlet of the Kilombero Basin (i.e. 1KB17Kilombero at Swero) has data records starting from 1957 up to December 1981; however more than 20% of this data is missing (Yawson *et al.*, 2005). Remote sensing techniques were found to be extremely useful in this case, especially for a basin scale assessment of the hydrological impacts.

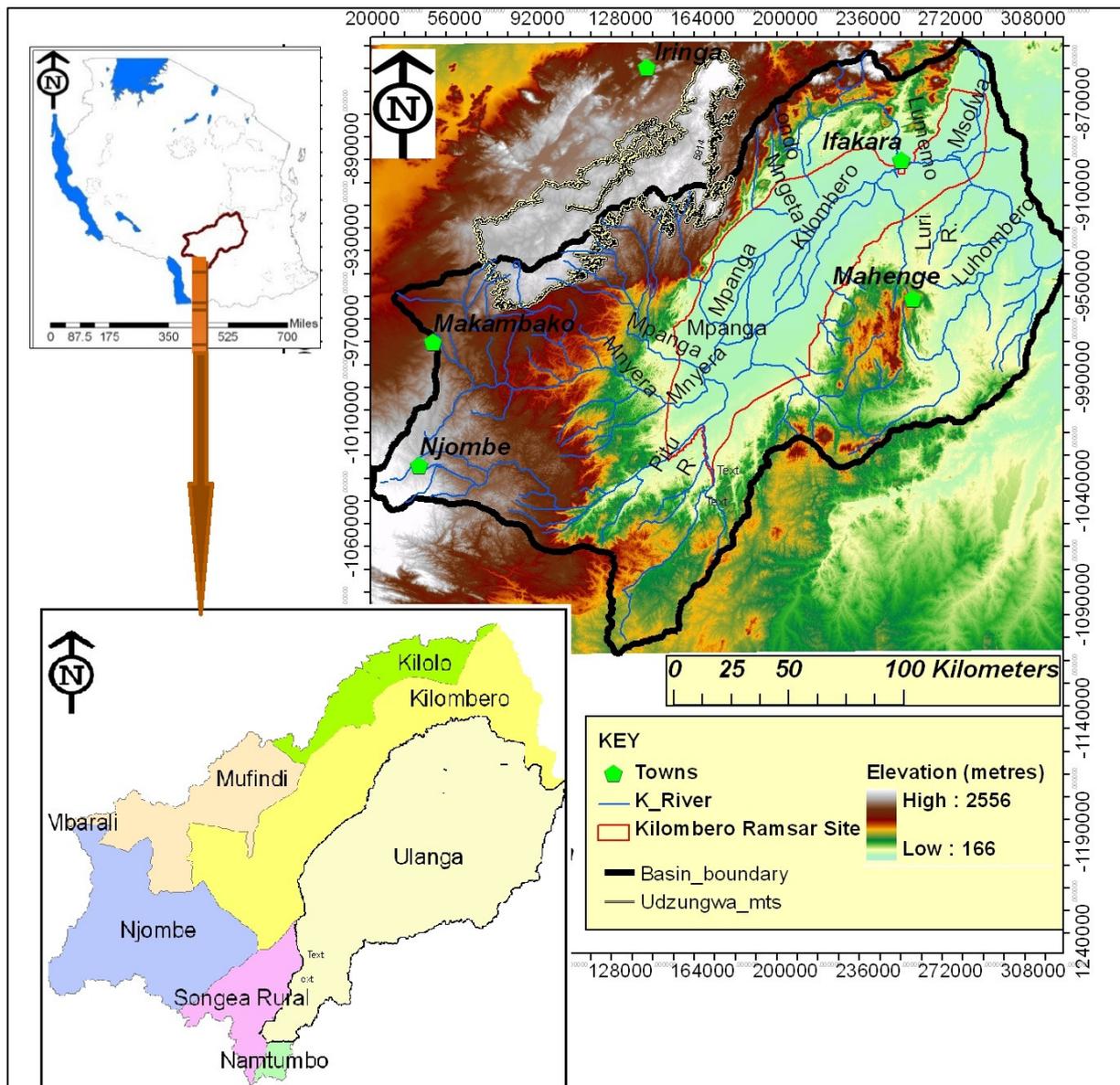


Figure 1.1 Location of Kilombero basin in Tanzania, districts boundaries and the Basin relief characteristics.

## 1.2 Population Dynamics in the Kilombero Valley

Most of the population in the Kilombero district, estimated at 430,135, resides in the low areas (i.e. in the Valley) where there are numerous wetlands (Mombo *et al.*, 2011). This settlement pattern is mainly due to the mountainous nature of the areas on the periphery of the Valley, in addition to the fact that large areas of the district and Basin are under conservation, either as National Parks, forest reserves or game reserves, forcing the majority of the population to move to the lowland floodplains, as indicated in Figure 1.2. Table 1.1 gives a

summary of population dynamics in the two major districts in the basin, Kilombero and Ulanga.

Table 1.1 Population dynamics of the major districts in the Kilombero Valley

District	Population				Inter-censal Growth Rate (%)	
	1978	1988	2002	2012	1978-1988	1988-2002
Kilombero	133,013	187,608	321,611	407,880	3.4	3.9
Ulanga	113,510	138,658	193,280	265,203	2.0	2.4

*Source: National Bureau of Statistics, 1978, 1988, 2002 and 2012 Population and Housing Census*

Over the past two decades, there has been rapid immigration of people from other regions of the country to the highly productive Kilombero Valley which has been a concern to both the Government and conservationists. This movement of people has mainly been driven by unreliable rainfall patterns and population growth in other regions leading to competition for productive land and water resources (Jones, 2006). A 2006 survey on communities in the southern part of the Kilombero Valley established that 71% of the residents were recent immigrants from other parts of the country (Harrison, 2006). A previous survey by Starkey *et al.* (2002) revealed that a large number of pastoralists migrated to the Valley between 1987 and 1997 in search of grazing land, with each pastoralist having herd sizes of between 60 to 200 cattle. It is worth noting that pastoralism also contributes to the on-going widespread conversion of wetlands, forests and woodlands to agricultural and bare lands, the destruction of natural habitats and the cutting-off of most of the traditional migration routes of wild animals.

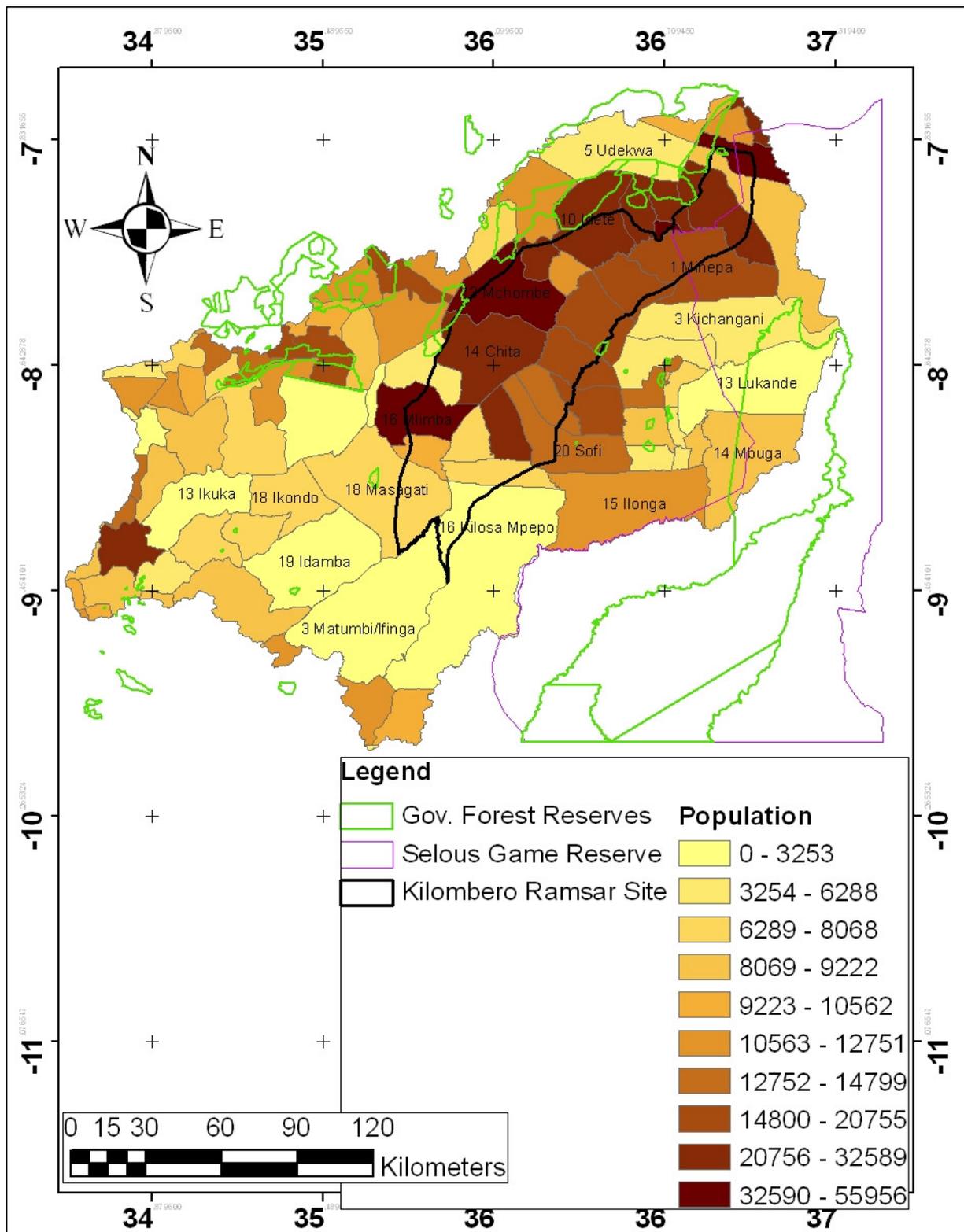


Figure 1.2 Spatial distribution of population across the Basin as per 2012 Population Census

### 1.3 Hydro-Environmental Concerns

The Kilombero Valley has numerous wetlands that serve as a source of water for farming, livestock, fishing and other domestic uses for the residing population (Kangalawe and Liwenga, 2005). It is noteworthy that the game-controlled area in the Valley is home to the largest number of Puku (*Kobus vardonii*) in Africa, accounting for about 76% of the world's remaining population of these animals (Corti *et al.*, 2002). Recent studies have shown a declining trend in biodiversity in the Kilombero Valley (Frontier, 2002). This indicates the importance of sustaining the agro-hydrological balance in the Valley for the benefit of the local community and the ecosystem.

Moreover, the survival of the Puku in the Valley has been linked to the existence of Miombo forests and the status of the human population in the Kilombero Valley (Corti *et al.*, 2002). However, recent land grabbing and agricultural expansion, both in large-scale commercial and small-scale farming, has posed a threat to the existence of wildlife and their movement corridors. For example, in 1992 14,000 ha of the natural Miombo forests were leased to the Kilombero Valley Teak Company (KVTC), which has expanded to a total area of about 28,229 ha for the establishment of commercial Teak plantations (Frontier Tanzania, 2002). A technical report by the International Institute for Environment and Development (IIED, 1992) highlighted some environmental concerns associated with the clearing of the Miombo plantations and replacing them with the exotic Teak forests. Other large-scale farmers of significance in the area, whose link and approach to land and water resources exploitation largely determine the sustainability of the Valley wetlands, are as listed in Table 1.2 and as illustrated in Figure 1.3.

Table 1.2 Large scale cash crop producers in the Kilombero District (after GOT, 2007)

Crop	Producer	Area (ha)
Sugarcane	Illovo Co.	7,919
	Ulanga Company	
	Mbega farm	212
	New Sanje estate	140
	Kiberege Prison	2,800
Rice	Idete Prison	10,000
	Chita JKT	15,000
	Kambega farm	4,000
	Mang'ula farm	100
	Dustan Chiduo	236
	KPL	5,800
Rice/ Maize	Mbigu sisters	3,600
	Udzungwa Plantations	140
Maize	Ifakara Secondary	8,100
	D.Balali	400

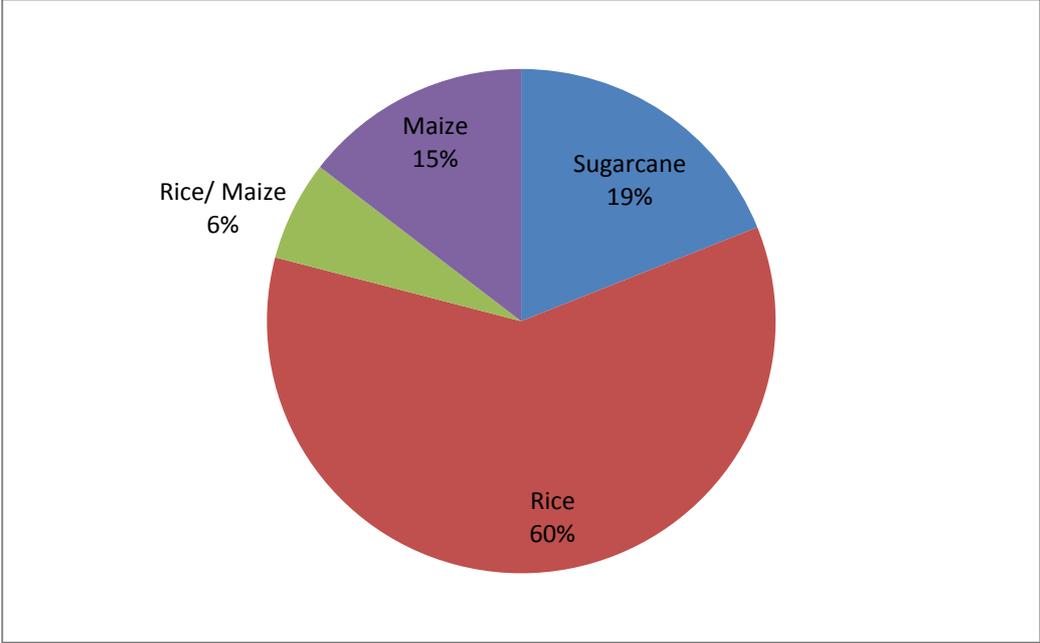


Figure 1.3 Percentage potential crop production distributions by major large scale farmers in the Kilombero District.

The Kilombero Valley has been identified as one of the agricultural baskets of the country and Table 1.3 provides an overview of total land acreage under food crop cultivation in the two major districts of the Kilombero Basin.

Table 1.3 The historical trend of acreage of two major food crops (areas in ha) cultivated in the main districts of the Basin (after GOT 2007)

District	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06
<b>Rice (Ha)</b>								
Kilombero	21,308	24,717	23,792	29,698	35,246	38,488	38,269	38,969
Ulanga	28,614	44,648	11,831	3,061	22,159	27,792	34,055	26,404
<b>Maize (Ha)</b>								
Kilombero	13,585	10,548	14,214	14,501	17,138	20,261	18,879	16,307
Ulanga	25,250	34,945	12,533	15,302	26,326	20,508	23,117	20,744

From Figure 1.3 and Table 1.3, it is clear that rice is the most significant of the food crops produced in the Valley. The area under paddy cultivation (mainly by small holder farming systems) has been increasing. According to Mombo *et al.* (2011), a large part of the commercial agricultural land in the Valley is under Teak forests (43%), while the Escarpment Forest Company occupy 23% and Illovo Sugarcane plantations 11%. Despite the clear evidence of hydrological alterations associated with such land use change in the Kilombero Valley, very little effort has been made towards gaining understanding, supported by authenticated field data, of the potential hydrological dynamics associated with such human interventions. This study strives to contribute to this shortcoming, by providing field evidence and detailed analysis on the hydrological dynamics of land cover changes in the Kilombero Valley through the application of innovative remote sensing and ground measurement techniques, as reported in subsequent sections of this thesis.

#### 1.4 Motivation of the Study

For more than a decade, the Kilombero Valley has been under population pressure due to the immigration of people, especially pastoralists searching for new grazing and farming land. The driving factor behind migration and the search for new grazing and farming land is the availability of water resources. The perceived attractions of the Kilombero Valley are, therefore, not surprising. As mentioned earlier, such uncontrolled migration has led to conflicts between farming communities and livestock keepers. Recently, the conflicts have taken a new dimension with pastoralists resisting a Government eviction order imposed in October 2012. A previous eviction order by the Government was issued in March 2006,

targeting the immigrant smallholder farmers and pastoralists in the Valley (Lankford *et al.*, 2009).

The impact of population pressure, especially in the Valley floodplains, manifests itself in different forms including deforestation for fuel wood. Starkey *et al.* (2002) estimated that an average of 0.88 m<sup>3</sup> of dry wood was harvested from the floodplain weekly for fuel wood supply. Direct measurements of biomass energy use per household, conducted by Mombo *et al.* (2013), revealed that the Kilombero Valley residents use about 528,000 m<sup>3</sup>.yr<sup>-1</sup> of wood. This is estimated to cause deforestation at a rate of between 3.37 and 21.59 ha daily (Mombo *et al.*, 2011). Large herds of cattle exist in the area and tree cutting, as a means of controlling the Tse-tse fly, has been reported to leave some areas with bare land. The settlement around and within the Valley, is also an emerging issue of concern that impacts on the sustainability of the wetlands. According to Mombo *et al.* (2013), even though the Land Policy of 1995 and the Act of 1999 legally protect the wetlands, in practice there are households with legal occupancy of wetland areas. All this has resulted in the degradation and clearance of marginal woodland and wooded grassland of the Valley (Starkey *et al.*, 2002).

The community residing in the Valley is totally dependent on the Valley for their livelihood (Kangalawe and Liwenga, 2005). Currently, wetland agriculture alone provides between 66% and 80% of the household annual cash income of the livelihoods residing near them (Wood *et al.*, 2013). The on-going establishment and expansion of agricultural fields in the area results in increased agricultural water demand.

Furthermore, there has been emergence of commercial agriculture, such as the establishment of 10,000 ha of sugarcane plantations in 1999, which expanded to about 17,930 ha by 2004-2005. It has been reported that approximately 18.7 million litres of water are used daily for irrigation by the Kilombero Sugar Co. Ltd. (GoT, 2006). Moreover, there has been an increase in the number of rice irrigation schemes in the Valley, with some schemes having an area of up to 10,000 ha. Other commercial farms in the Valley include the above mentioned Teak plantations managed by the Kilombero Valley Teak Company (KVTC), which has 28,229 ha of woodland. The Teak plantations were, and continue to be, established after clearing the native Miombo woodland (Frontier Tanzania, 2002). It is useful to note that information from this study, particularly on water use characteristics of the Miombo and Teak forests, has been sought by the Rufiji Basin Water Office on several occasions in an effort to facilitate informed decision-making on water resource management in the Basin. All these

human investments and interventions in the Valley are thriving as a result of being directly associated with the use and/or availability of water resources in the Valley. This highlights a critical need to understand the potential hydrological impacts of the land use changes in the Valley. Figure 1.4 summarises the main research challenges in the Basin and clearly indicates the focus of this research study.

All the above developments have the potential to alter the hydrological regime of the Valley and the basin as a whole. For example, the Kibasira swamp (8° 19' 59.99S; E 36° 18' 0.00E) has been significantly reduced, while others swamps (e.g. Njagi Swamp) have been totally converted into agricultural land. The Valley's hydrological sustainability is of paramount importance to the inhabitants who totally depend on farming activities. The motivation of this study, therefore, was to obtain a good understanding of the interaction between the land use change processes in the Kilombero River Basin and hydrological regime to broaden the understanding of the impacts of management decisions. Such a detailed analysis has never been undertaken in the study area and results from this study will be valuable to water resource managers and conservationists in the Basin. Past efforts to quantify the hydrological impacts of land use change in the Kilombero Basin have been compromised by several drawbacks and uncertainties, including inadequate hydrological data due to the remoteness and distance from the main towns in Tanzania. There are a few point measurements of hydrological processes of interest (e.g. manual rain gauges) but with scant data. Thus, in this study an automatic weather station had to be installed in the study area, to provide useful climatic data at the desired scale. However, these point measurements, including the weather station, do not provide the spatial variability of the hydrological dynamics across scales necessary to the study. Thus, remote sensing techniques were applied to capture the hydrological dynamics of interest across both spatial and temporal scales.

Lastly, inadequate knowledge exists on tested tools and approaches (methodology) in quantifying and mapping the potential hydrological dynamics of the on-going large-scale land use change in the Kilombero River Basin. This study makes a contribution in this regard by testing and applying a combination of remote sensing and ground based techniques in the study area.

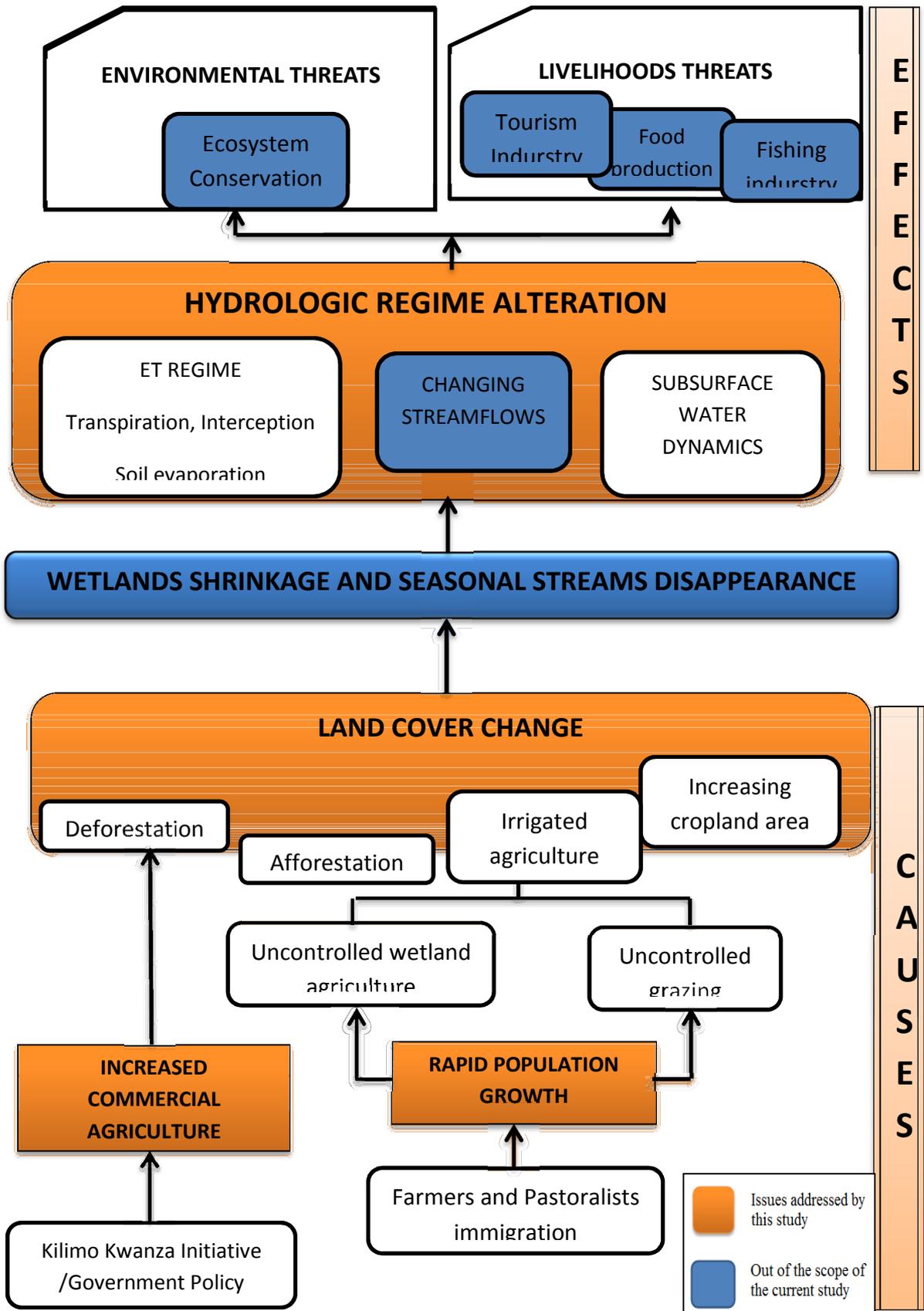


Figure 1.4 A schematic depiction of the research problem analysis

## **1.5 Research Questions, Objectives and Relevance of the Research**

### **1.5.1 Research objectives**

This research study is geared towards assessing the extent of Kilombero River Basin land cover alterations and the associated implications with regard to Basin water resources. This being a poorly gauged basin, it provides a platform for assessing the suitability of remotely sensed estimates of evapotranspiration for Basin water resource management and decision-making. The questions that drove the study are:

- Has there been a significant change in land cover and land use in the Kilombero Valley over the last 30 years?
- How much of the indigenous forest area has been converted to commercial plantations and domestic farmland?
- Do the changes have a potential impact on the basin ET regime?
- What are the dominant land uses in the Basin that have the highest evaporative water use?
- What are the water use characteristics of the native Miombo woodlands compared to those of exotic Teak plantations?
- How useful/suitable is remote sensing as a tool in hydrological studies in data-scarce watersheds?

These questions were used to define and elaborate on the specific objectives of the study which were divided into two main themes. The first theme was establishing the usefulness of remote sensing as a tool in data-scarce areas where the following specific objectives were addressed:

- To quantify the land cover changes in the Basin over the past 30 years using high resolution, remote sensed data; and
- To characterise the spatio-temporal variation of evapotranspiration in the Basin using remote sensing techniques.

The second theme was analysing the hydrological dynamics of the land use changes, with the following specific objective:

- To establish the possible impacts of changing land covers and land uses on the evapotranspiration regime in the Kilombero Basin using remote sensing and ground-based techniques.

### **1.5.2 Research contribution to local water resource management institutions**

The Rufiji Basin Water Office (RBWO) has expressed concern over the uncertainty regarding the impact of the on-going exploitation of water and land resources in the Kilombero Valley particularly in relation to the establishment of commercial private plantations, the consumptive water use of which has not been established. These include the recently established Kilombero Valley Teak Forest Plantation Company and the Farm Forest Company Limited that has established pine and eucalyptus plantations (information supplied through personal communication with the Rufiji Basin Manager). This study therefore was geared towards addressing some of the concerns by the Basin Water Office and is expected to contribute to decision-making processes within the Ministry of Water in Tanzania. As mentioned in previous sections of this thesis, the RBWO has been seeking scientific evidence to support its decision-making processes with regard to managing water resources in the Basin.

This study provides first-hand information on the progressive land use changes over time, including the current status in the Kilombero Valley and surrounding areas. No such detailed study with a documented methodology has yet to be produced for the study area. Furthermore, the information derived from this study provides a guide to the prioritisation of allocation of land parcels for development activities, especially plantation forestry and agricultural activities, taking into consideration that the Kilombero Valley has crucial wetlands with a Ramsar status. It is recognised that these wetlands are very sensitive to land use changes. With the on-going intensification of farming activities at the expense of natural forest areas, this study provides an insight into the consumptive water use of dominant land uses in the Basin and hence points to the implications of land use allocations with regard to the sustainability of water resources in the larger Kilombero River.

### **1.5.3 Scientific contribution of the research study**

This study provides three major contributions:

1. It contributes to addressing the inadequacy of hydrological data to represent both the spatial and temporal variability of hydrological processes in ungauged and poorly gauged areas in developing countries. In many developing countries, available hydrological data tends to be sparse point measurements which are unreliable. This study tested and applied remote sensing techniques for estimating evapotranspiration across landscapes. The estimates were verified with ground measurements, hence future studies could build on the documented approach for further analysis.
2. The study contributes to a better understanding of the hydrological dynamics of land use and land cover changes in the Kilombero River Basin, and other similar landscapes. In particular, this study documents and analyses the potential hydrological dynamics of intensifying Teak forest plantations at the expense of the Miombo natural forests in the Kilombero River Basin in Tanzania. The current state of knowledge in the Basin Water Office with regard to the water use characteristics of both Miombo and *Tectona Grandis* is poor.
3. Being one of the earliest attempts in the Kilombero River Basin to quantify evapotranspiration from satellite data, it provides a guide and insight into the challenges and opportunities of using such remote sensing techniques in the Basin.

### **1.6 Structure of the Thesis**

This thesis is structured so that the historical trend analysis of the study area, the Kilombero River Basin, with regard to population dynamics and land uses is captured at the beginning, as illustrated in Figure 1.5 and 1.6. The analysis is mainly through the application of remote sensing techniques, with ground measurements being used to verify the information derived from satellite sensors. It is useful to note that, generally, the study applied various remote sensing tools and techniques in the analysis. These remote sensing techniques were applied while recognising the limitations of the ground monitoring techniques in capturing the hydrological dynamics across spatial scales. Thus, the papers presented in this thesis (as chapters) are a derivative of detailed analytical procedures based on remote sensing and/or

ground-based techniques applied at different scales, i.e. local or basin scale (Figure 1.6), with each paper addressing one or two specific objectives. The thesis has been organised in seven main chapters, as described below. An overview of the study area, including the challenges the Basin is facing, issues of concern with regard to water resource management, the motivation of the study and research objectives, are highlighted in Chapter One. The main analytical assessments and findings of the study are contained in Chapters Two to Five and organised in paper format for submission to relevant scientific journals. In accordance with the regulations of the University of KwaZulu-Natal, it should be noted that, using this structure means that some degree of repetition is inevitable, particularly with regards to site description and the like.

Chapter Two gives an analysis of the current and historical land cover status of the Kilombero Valley and the possible hydrological implications of such land use changes. This Chapter provides an insight into the anthropogenic activities of the study area and the accompanying pressure such activities are exerting on the water resources in the Basin. Chapter Three provides a comparative analysis of consumptive water use between the indigenous Miombo woodlands and the exotic Teak forest plantations, with the view to detailing the possible hydrological dynamics of the on-going replacement of the Miombo with Teak forest plantations in the study area. This analysis was accomplished by monitoring the transpiration rates of the two types of forest stands through field experiments, as detailed in the paper. Chapter Four highlights and discusses the vertical soil water profile beneath the indigenous Miombo and the exotic Teak forests plantations following intensive field measurements on soil water dynamics undertaken and modelled using WAVES (Water, Vegetation, Energy and Solute balance). The modelling exercise was adopted in an effort to establish a link between the changes in the subsurface dynamics and the evaporative water use of the larger extents of Teak, Miombo and other dominant land uses, as described in Chapter Five. The impact of converting forest covers on subsurface hydrology is also highlighted in this Chapter.

Chapter Five details the application of the Surface Energy Balance System (SEBS) model framework and the measurement of the various components of the surface energy balance in the study area. The computation of evapotranspiration, and subsequently the evaporative water use of various land uses in the Basin, are detailed in this Chapter as well. An analysis of diurnal and seasonal trends of the measured and estimated fluxes is also presented.

Chapter Six provides an integrated perspective of all the Chapters in achieving the stated objectives as summarised in Figure 1.5. Chapter Seven is a summary of the key findings, thus drawing overall conclusions of the research study, while highlighting the challenges faced and recommendations for further research.

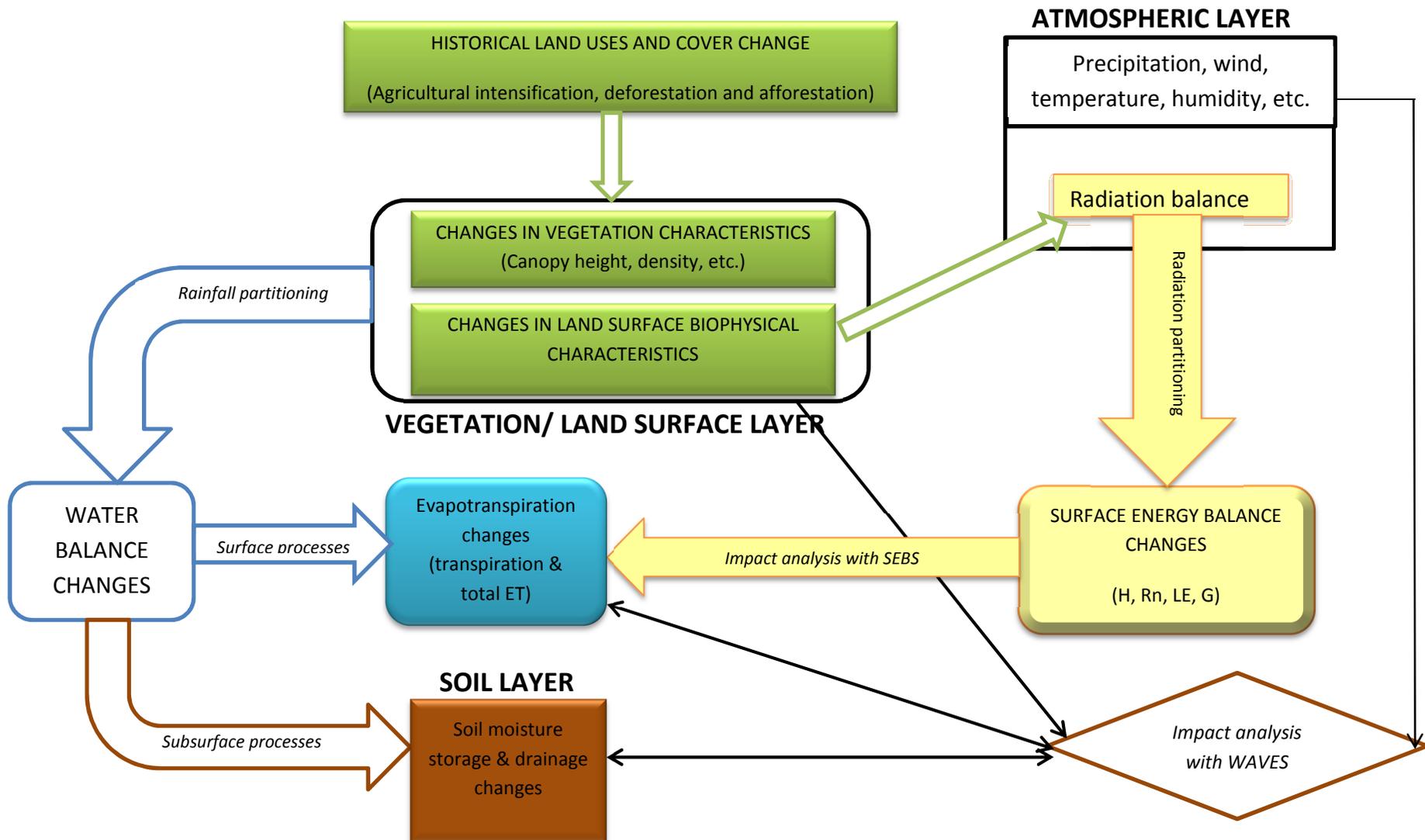


Figure 1.5 Conceptual framework of the study

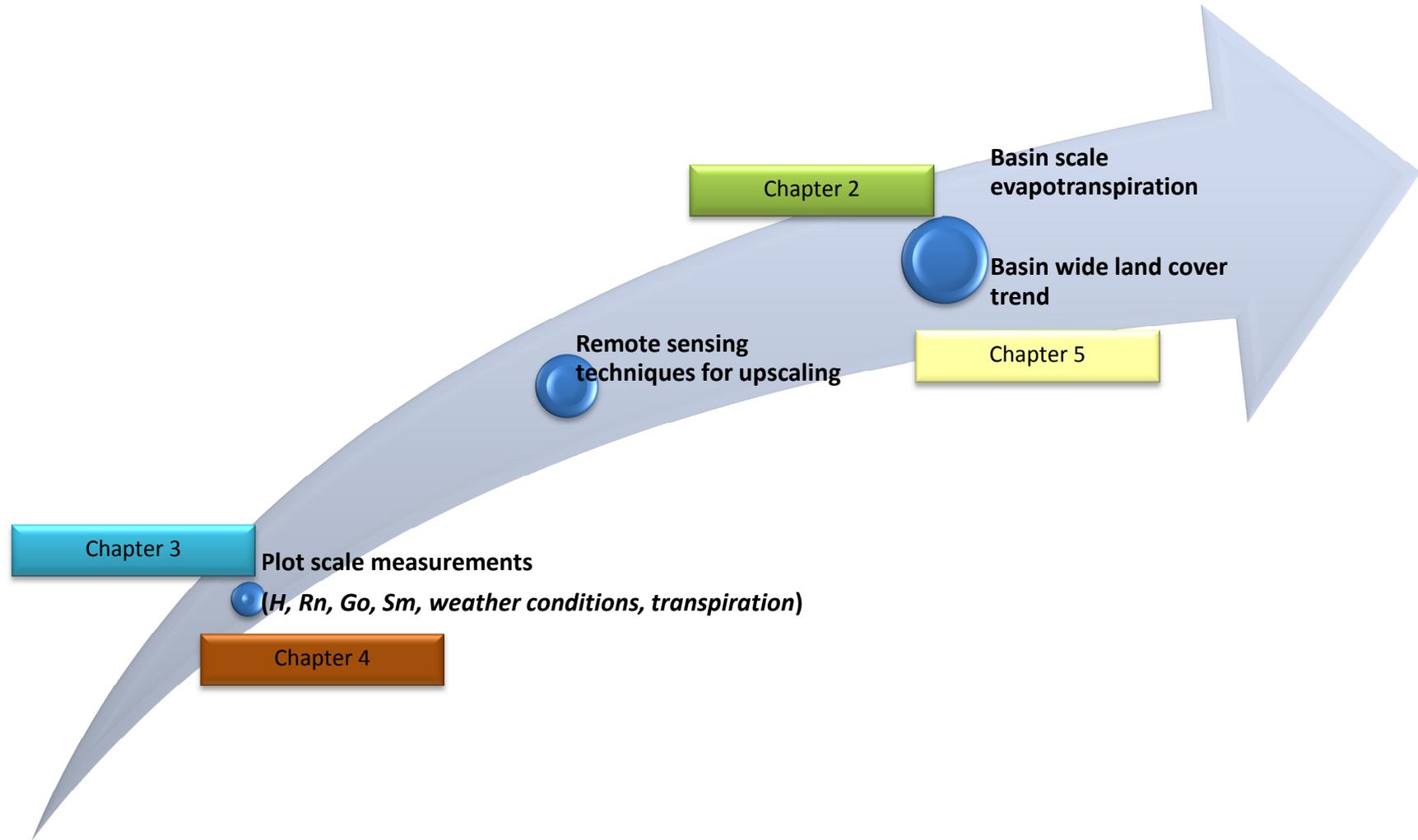


Figure 1.6 Methodological approach to the research study

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## 2. TRENDS OF LAND USE AND COVER CHANGES IN THE KILOMBERO VALLEY IN TANZANIA

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### **Abstract**

Population dynamics and unfavourable climatic conditions in southern Africa have led to changes in land management practices, including changing land use patterns. Unprotected wetlands and river valleys have often been encroached upon by communities for pastures or agricultural lands, as has been the case with the Kilombero Valley, a Ramsar site, in Tanzania. The encroachment and exploitation of the wetlands in the Kilombero Valley by local and immigrating communities is a concern to both the scientific and local communities due to the potential environmental and economic impacts of loss of biodiversity from wanton land use changes. The Valley, initially home to wildlife including large mammals, has currently been converted to agricultural lands and is one of the main bread baskets of the country.

Various research initiatives have been carried out in the Valley on the impact of land use changes on wildlife distribution, disturbance and migration patterns. However, there is no case study in literature on the assessment of the trends and extent of land use and land cover changes over the years, as reported herein.

In this study, the land use and land cover changes in the Kilombero Valley were analysed over a span of 30 years. Fourteen Landsat (ETM and TM) images, covering the years 1975, 1990, 2002, 2009 and 2010, were used to generate land use maps for the study area and were analysed for quantitative changes over these years.

Post-classification change detection analysis revealed that there has been an extensive exploitation of natural land cover across the valley through agricultural activities. In 1975, the valley floor was dominated by woodland (42%) and seasonal wetlands (37%). However, this has changed over the years and in 2008, 36% of the valley area was under intensive

cultivation and 29% was occupied by a mixture of settlement, grazing and cultivated areas. While the riverine forests appear to be stable, the rate of loss of wetland is significant.

### **Key words**

*Kilombero Valley, land use, remote sensing, Ramsar site, anthropogenic activities, water resources.*

## **2.1 Introduction**

Studies on land use and land cover changes have been of significant importance over the years, due to the fact that land cover change entails the exploitation of natural resources, most often for the purpose of catering for immediate human needs (economic and social). Moreover, most of the land use changes have been at the expense of (future) ecosystem functioning and sustainability. Foley *et al.* (2005) highlights that the land cover transition of most regions begins with conversion of the natural ecosystems to subsistence farming and settlement areas. With increasing population demands and needs, accompanied by the adoption of modern technology, this eventually leads to the conversion of a landscape to intensive agricultural activities, as well as the establishment and expansion of urban and recreational areas.

While it may be inevitable for changes to occur in a landscape due to population growth and advances in technology, it is important to note that ecosystems services provision is entirely dependent on, and governed by, the local land cover system and therefore any alteration in the land cover has direct impacts on the ecosystem's capability to cater for future human needs (Foley *et al.*, 2005; Millennium Ecosystem Assessment, 2005).

Land cover changes lead to the alteration of hydrological cycles through changes in the partitioning of incoming precipitation to evapotranspiration, infiltration and overland flow components. This results in changes in the subsurface water dynamics, water table level and, ultimately, streamflow. In this regard, the main interest for the scientific community has been the potential impacts of land use and land cover changes on the ecosystem services and provision, while analysing the driving forces behind the land cover modifications. Various studies, including Li *et al.* (2007); Poff *et al.* (2006) and Mayomi (2009), have linked land use and land cover changes to anthropogenic activities, particularly food production, urbanisation

and energy demand. Wood *et al.* (2004) and Martínez *et al.* (2011) grouped the main drivers of land use and cover changes into biophysical (e.g. flooding, climatic change, landslides, etc.), socio-economic/human-induced (e.g. agricultural activities, population growth, tourism, etc.) and natural loss of biodiversity. Human mediated changes of land use and their potential impacts on ecosystems have been given much attention in the recent past, including studies by Wood *et al.* (2004), Britton and Fenton (2007), Martínez *et al.*(2011) and Mendoza *et al.* (2011).

The ability to study the pace and the magnitude of land cover change over the years has been facilitated by the emergence and continued development of satellite remote sensing science. This provides the scientific community with an opportunity to not only study the change over a long period of time, but also over larger spatial extents. Remote sensing is relatively cheaper than field-based studies in characterising land use changes, even though the accuracy is often questionable. Numerous studies in literature have used remote sensing techniques in mapping or monitoring land use and land cover changes. Specifically, the use of Landsat satellite images in land use and land cover studies has been increasing, due to its availability over the past three decades with a useful 30 m pixel size resolution (Tayyebi *et al.*, 2008; Podeh *et al.*, 2009;Ioannia and Meliadis, 2011). A number of wetland mapping studies have also indicated the suitability of Landsat satellite images with an accuracy of between 80% and 90% (Baker, 2004; Jiang *et al.*, 2008). In this study, Landsat images were used to characterise land use changes over a 30-year period in the Kilombero Valley in Tanzania, as detailed in subsequent sections of this paper.

The Kilombero Valley, in south-central Tanzania (Figure 2.1) is relatively flat, lowland at an elevation of about 400 masl. and characterised by riparian wetlands adjacent to the main Kilombero River channel. The River is braided at the floor of the valley. The riparian area is located in the valley between the Kilombero River and the Eastern Arc Block Mountains located on either side of the valley, as indicated in Figure 1.1. In this study, both the riparian zone and adjacent wetlands are addressed, using the common term “wetland”, as is the case with other similar studies e.g. Baker (2004), since the ecological characteristics of the two are similar. In this case, the riparian zone is composed of grassland and open woodland forest along a broad, braided Kilombero River floodplain. The riparian zone encompasses the natural vegetated corridor along a stream bank and the land uses within a restricted elevation or distance from the floodplain and mostly represents the transition zone between aquatic and terrestrial ecosystems (Green *et al.*, 2011). Wetlands, on the other hand, are defined by Article

1.1 of the Ramsar Convention as areas of marsh, fen, peatland or water, natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the low tide depth of which does not exceed 6 m (Ramsar Convention on Wetlands, 1971).

The importance of wetland conservation has long been on the agenda of the scientific and local communities and policy-makers alike. Wetlands are known for their variety and richness in biodiversity as well as their susceptibility to human alterations. However, it is useful to note that the sustainability of wetlands depends on the hydrodynamics of the contributing system (Auterives *et al.*, 2011). Hydrological alterations, resulting in changes in the saturated conditions of the wetland to unsaturated conditions, can cause a total change of wetland ecology and functioning.

Available studies in literature on the impact of land cover on riparian and wetland areas include Zacharias *et al.* (2004), who reported a 71% loss of wetland area in four decades in the Trichonis Lake Catchment, Greece, with an associated 50% agricultural land increase. These activities subsequently led to an increase in urbanisation, resulting in a 7% annual increase in evapotranspiration (*ET*), with highest *ET* values being observed in farming areas. Another study by Jensen (2002) reported a 98% loss of wetland area to agricultural land of the lower Murray Valley wetland in Australia. Again, Yu *et al.* (2010) also reported a 92% loss of wetland area to agricultural land located in the Sanjian Plain marsh China, and Taylor *et al.* (1995) noted a loss of 90% of wetland area in the Thukela River Basin and 58% from the nearby Mfolozi Catchment in South Africa.

Striking a balance between conservation of wetlands and their exploitation raises the question of the extent to which their natural land cover can be altered whilst minimising the possible impacts, notably the hydrological impacts. Floodplain wetlands are good buffer zones, they have hydrological systems that are useful in controlling floods and erosion; they enable water purification, detoxification and ground water recharge (Kashaigili *et al.*, 2006; Zhao *et al.*, 2011); and they remain ecologically important as habitat for wildlife.

During this study, a reconnaissance survey of the Kilombero Valley (wetlands) revealed the on-going clearance of woodland for the establishment of new agricultural lands and fuel-wood supply for both domestic and commercial consumption. Another study in the Ruvu and Sigi Catchments in Tanzania (Yanda and Munishi, 2007) reported extensive land cover

conversion from forest and woodland to farmlands and grassland, which resulted in diminished dry season flows and reduced soil water storage capacity.

Agricultural practices, particularly the adoption of modern technology that enables greater yield on the same arable land (intensification), are known to cause negative impacts on ecosystem goods and services through the degradation of water quality and quantity, resulting in the drying up of some rivers and the salinisation of soils (Foley *et al.*, 2005). More specifically, farming practices often lead to a reduction in the water storage capacity of the soil's overland flow, driven by saturation excess which causes an increased surface runoff and a reduced infiltration volume, resulting in a reduced base-flow (Buytaert *et al.*, 2006; Wijesekara *et al.*, 2011). Thus, the extensive adoption of such agricultural practices, especially in a wetland area, will often lead to significant alterations in partitioning of rainfall, and is likely to be the case with the Kilombero River Basin. Uncontrolled burning and grazing of livestock also causes soil crust formation that leads to increased overland flow and reduced infiltration (Buytaert *et al.*, 2006). Deforestation has been reported to cause an increase in the runoff volume, while afforestation, especially with woody trees, has a negative effect on the base-flow (Buytaert *et al.*, 2006, Li *et al.*, 2007). Other studies, e.g. Calder *et al.* (1995) and Zimmermann *et al.* (2006), have provided more insight into the potential hydrological impacts of land use and land cover changes.

This research aimed to study the land cover changes, with particular focus on the pace and magnitude of the wetland exploitation in the Kilombero River Basin and the associated hydrological impacts. As a result, it creates an awareness of the extent of exploitation of the Valley wetlands (Ramsar site) and the threats to their survival for policy- and decision-makers, particularly the local Rufiji River Basin Water Authority (RBWO) which manages the Kilombero Basin. Proper land use management and water resource allocation requires a basic knowledge of the land cover status of the area, as provided by this study.

## **2.2 Study Area**

The Kilombero Valley is a floodplain in southern-central Tanzania, covering an area of about 7000 km<sup>2</sup> (see Figure 2.1). The Valley is located in the Kilombero District, and partly in Ulanga District. The main Kilombero River channel is braided and has more than 10 tributaries, most of which are seasonal. The Kilombero Valley floodplain was bestowed

Ramsar status on 24<sup>th</sup> April 2002 (Ramsar site 1TZ003) due to its high biodiversity and ecological significance (Ramsar Bulletin Board, 2002). The Valley bottom is an extensive, relatively flat plain and most often flooded during the wet season (see Figure 2.1 and 2.2). The Valley is fringed by the Udzungwa Eastern-Arc Forest Mountains on the north-western side and the Mahenge Mountains with large tracts of Miombo woodland on the southern-eastern side, as shown in Figure 1.1.

Kilombero receives mean annual rainfall of about 1300 mm. The basin is known for its stable rainfall regime, with no significant trend for the past thirty years. According to Balama *et al.* (2013), who carried out a rainfall trend analysis, between 1980 and 2010, the rainfall trend was not statistically significant at  $p > 0.05$ . The reliability of the rainfall in this area, most likely due to the cloudy forests on the nearby Udzungwa and Mahenge Mountains, has made the Valley even more popular. The Kilombero Valley wetlands are mainly used for agricultural (Figure 2.2) and fishing activities. Owing to their fertility and moisture availability, the Valley wetlands attract farmers from nearby areas and regions, as they provide assured crop yields throughout the year. The main crop cultivated in the wetlands is rice, while maize is mainly found in the adjacent drier areas. Rice is also the main cash crop in the District.

The greater part of the population and settlements in the Kilombero and Ulanga Districts are confined to the Valley strip of the floodplain since other adjacent areas are government protected lands, as shown in Figure 2.2. The population in the Valley relies, to a large extent, on the existence of the wetlands for their economic and social provisions which provide 98% of their food security (Mwakaje, 2009).

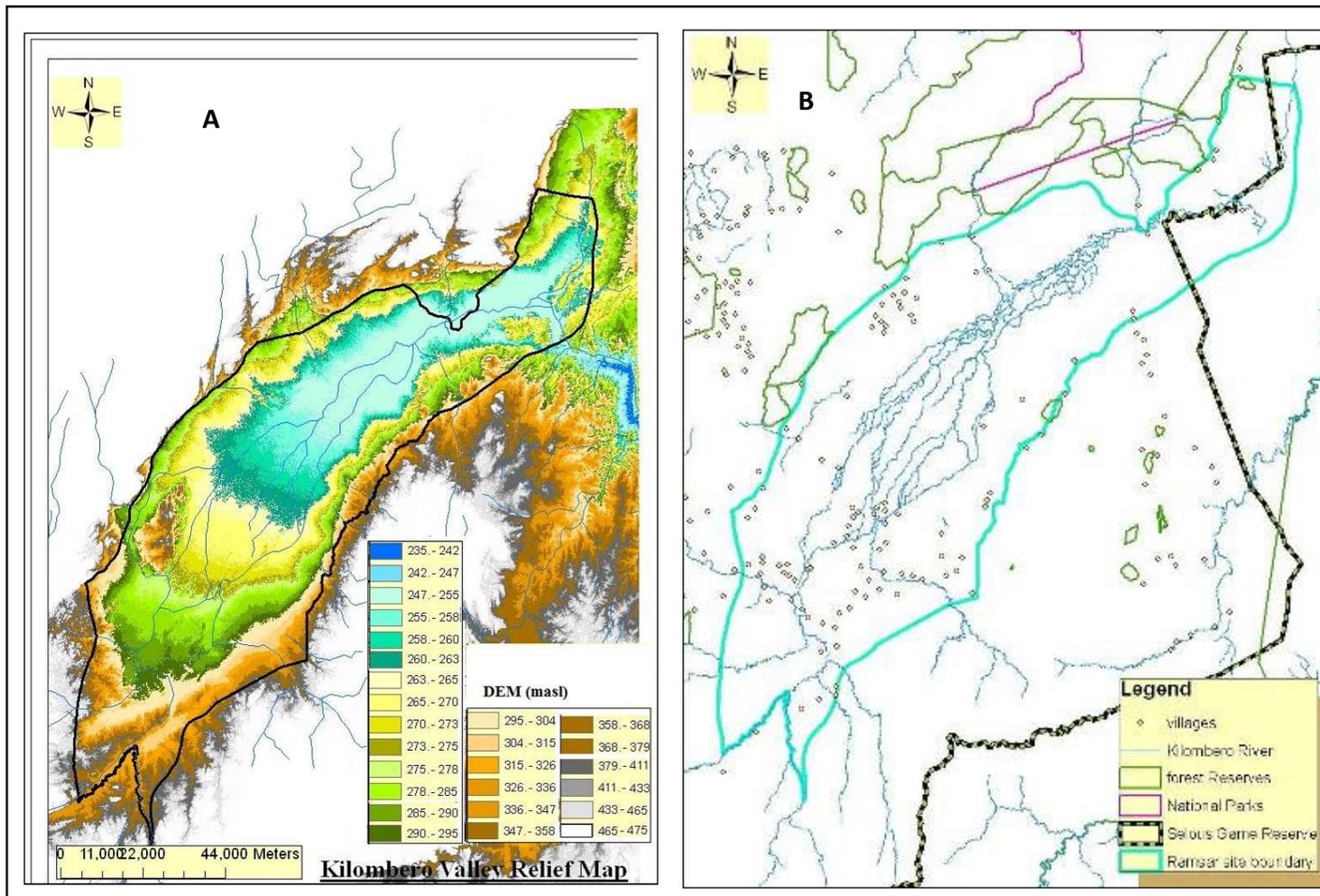


Figure 2.1 Relief map of the Kilombero Valley floor (A) and government conserved areas in the Kilombero Valley (B)



Figure 2.2 The Kilombero River showing a typical, seasonally flooded grassland and human activities in the Valley (November 2009)

Recently, population pressure in the Kilombero Valley has become an issue of concern, arising from the immigration of people searching for farming and grazing land (Haule *et al.*, 2002; Kangalawe and Liwenga, 2005; Jones, 2006). A survey by Harrison (2006) on communities in the southern Kilombero Valley, highlighted that 71% of the residents were recent immigrants from other parts of the country. Another survey by Starkey *et al.* (2002) revealed that a large number of pastoralists migrated to the valley between 1987 and 1997 in search of grazing land, with each pastoralist having herd sizes of between 60 to 200 cattle. This has resulted in the widespread conversion of wetlands and woodland to agricultural and grazing lands, thus destroying the natural habitats of the ecosystem.

The land cover characterisation carried out in this study, through a field survey in 2008 and 2009, established that the Valley comprises mainly of smallholder agricultural farms, floodplain Miombo woodland (also reported by Jenkins and Roettcher, 2001), as well as herbaceous and grassland vegetation, which are located on the Valley floor and are frequently covered by seasonal swamps, as indicated in Figure 2.2. The Miombo woodlands cater for the household fuel wood demand of the locals and are a source of income generation through the sale of timber products (Abdallah and Monela, 2007). In this study, it was also noted that the frequent burning of vegetation was commonly practiced as a means of preparing the land for farming (Figure 2.2).

Policy- and decision-makers are faced with the challenge of making a trade-off between exploitation and conservation of the Valley area. While the Valley's Ramsar status stresses its conservation importance, its agricultural potential makes it vulnerable to further exploitation. Recently (2010) the Tanzania Government earmarked the Kilombero District as a target region for the implementation of a national initiative, commonly known as "*Kilimo Kwanza*" (meaning Agriculture First). This initiative has the objective of encouraging investment by both local and private investors in commercial and large-scale farming and is already being implemented by the Southern Agricultural Growth Corridor of Tanzania (SAGCOT). The latter is in the process of establishing, among other projects, a 3200 ha rice plantation near the Mbangala and Fimbo villages in Ulanga District, 470 ha of irrigated rice at Sonjo, as well as installing an irrigation system to the 4000 ha of the existing outgrower area and more than 5000 ha in Ruipa Valley ([www.africacorridors.com/sagcot/](http://www.africacorridors.com/sagcot/)). All these areas are in the Kilombero Valley.

Other commercial farms in the Valley include the Kilombero Plantations Limited (KPL) rice scheme (see Appendix 2.11.12), established in 1985 by clearing and draining more than 5800 ha of the floodplain wetlands. The Kilombero Valley Teak Company (KVTC), that owns and manages 28,229 ha of native woodland in the Valley, is progressively converting the woodlands to Teak forest plantations (Frontier Tanzania, 2002). Other new establishments are still emerging, such as the Illovo Sugar Company Limited which is in the process of finalising the acquisition of more than 9,000 ha of the Ruipa River Valley for irrigated sugarcane agriculture (Chachage, 2010).

However, despite previous and on-going developments leading to land use changes in the Kilombero Valley, no study in literature exists analysing the trends of land use changes, especially on the floor of the Valley, over the past 30 years as detailed in this study.

### **2.3 Methodology**

Landsat satellite images covering the period 1975 to 2009 were used to generate land use maps for the Kilombero Valley. Efforts were made to obtain quality images in the same season. In this case, the dry season was preferred, due to the fact that the Valley and surrounding mountains are normally covered by cloud in the wet season which affects the quality of satellite images. Vegetation cover is also easier to assess in the dry season. Table 2.1 shows the number of images obtained and processed during this study

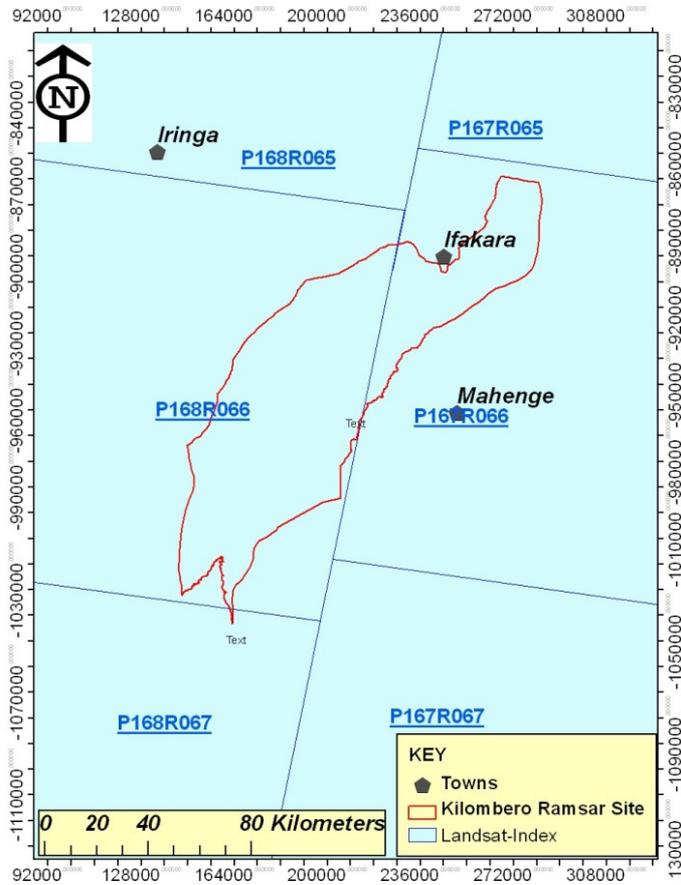


Figure 2.3 Landsat grid coverage of the Kilombero Valley

Table 2.1 Acquired Landsat images

S/N	Acquisition dates	Path/Row	Platform	Season
1	1975/07/27	179/66	MSS	Dry
2	1975/10/26	179/67	MSS	Dry
3	1979/07/25	180/66	MSS	Dry
4	1979/07/25	180/67	MSS	Dry
5	1973/09/04	181/66	MSS	Dry
6	1991/06/05	168/67	TM	Dry
7	1991/06/05	167/66	TM	Dry
8	1990/07/11	168/66	TM	Dry
9	2000/07/07	167/65	ETM	Dry
10	2002/05/10	167/66	ETM	Dry
11	2002/06/18	168/66	ETM	Dry
12	2008/09/07	167/66	ETM+	Dry

13	2009/09/29	168/66	ETM+	Dry
14	2008/09/07	167/65	ETM+	Dry

NB: MSS is the Multispectral Scanner, TM stands for Thematic Mapper and ETM is the Landsat Enhanced Thematic Mapper.

### 2.3.1 Image processing

The main image pre-processing steps, using an ERDAS Imagine (Leica Geosystems, Atlanta, Georgia, USA) and ArcGIS 10 (Redlands, CA: Environmental Systems Research Institute) platform, involved geometric correction, image-to-image registration, as well as the mosaicking and resampling of the acquired satellite images. The geometric correction of Landsat MSS scenes was carried out using Ground Control Points (GCPs) extracted from topographical maps with a scale of 1:50000. The selection of GCPs was done considering features such as road junctions and river confluences. The correction process had a Root Mean Square error (RMS) of 0.91 pixels. This was acceptable when compared to the recommended RMS value of less than 1, as suggested by Clarks Lab (2001). To ensure that all images perfectly overlay each other, geo-registration of the images to the baseline 1975 image was carried out with the RMS of less than 0.5 pixels. Bilinear re-sampling was also done in the pre-processing procedure to align all the images from different Landsat sensors to the same pixel resolution.

Supervised classification, using the maximum likelihood technique, was applied, where the identification of known land-cover types of interest in the image was performed (training sites development). This was then followed by signature development, where a statistical relationship of the reflectances of each land cover category is developed. Clouds and cloud shadows were masked in this analysis to avoid errors and reduce uncertainty.

The land cover categories that best represented the Kilombero Valley were: riverine forest, woodland, agricultural land, built-up areas and seasonally inundated land, as shown in Table 2.2. During land cover categorisation, consideration was given to the spectral reparability of different signatures in the satellite images for the various land cover classes in the area due to the influence of the surrounding mountains on the spectral reflectance and the limitations of the high altitude satellite images used (Landsat).

Table 2.2 Land cover categorisation and description in the Kilombero Valley

No	Land cover class	Description
1	Riverine forest	Evergreen forest along rivers and streams, forested wetland
2	Grassland	Grasses, pasture, herbaceous rangeland
3	Woodland	Open and closed woodland, intermediate between woodland and grassland
4	Intensive cultivation	Cropland under cultivation, drained wetlands with crops, cultivated wetlands
5	Settlement/cultivation	Residential areas, roads, Mixed urban areas, barren land, idle agricultural areas
6	Seasonally inundated land	Marsh areas, inundated grassland, inundated woodland and wetland vegetation
7	Water	Rivers, open water ponds, streams and reservoirs

The Kilombero Valley riparian area is comprised of different zones, starting from open water areas, to vegetation that sits on water, vegetation on saturated soil and, finally, vegetation on dry land close to the mountain ranges on either side of the Valley. The transition in these zones was a challenging to identify due to the inability to clearly separate the relevant spectral signatures. This is a common problem for land cover of this nature, a fact also recognised by U.S. Geological Survey classification guide (USGS, 1976). Another challenge encountered was the inability to distinguish spectral signatures of bareland and idle agricultural land, a common problem when using medium resolution satellite images (Kashaigili *et al.*, 2006). Difficulties were also experienced in separating the spectral signatures of informal and irregular village settlement areas that were surrounded by bareland. This was due to the lack of clear settlement pattern in the area, with some houses having thatched roofs and, in most cases, occupying a very small area and being quite isolated from each other. In effect, this makes it more difficult to capture and interpret such signatures at a 30 m resolution so they were lumped with the bareland areas (USGS, 1976; Guo *et al.*, 2009). Similar challenges were observed in other studies including Zhao *et al.* (2011) and Jiang *et al.*, (2008). The latter noted “confusion” between area spectral signatures of farmland, natural grassland and paddy rice, hence knowledge-based methods (i.e. using common knowledge and understanding of the area) were used to correct the errors in that study. For this

study, the barren land, abandoned agricultural land, settlement and built up areas were lumped as one class category (S/n 5), as indicated in Table 2.2.

Teak forests were derived from a separate classification exercise where care was taken to distinguish them from the other woodlands, specifically the Miombo within which the Teak plantations are found. In previous (presented) classification, the signatures for Teak and Miombo were merged together with the rest of the deciduous woodlands. The locations and plantation boundaries were obtained through ground field surveys and shapefiles sourced from the company databases which showed some of the old plantation sites. The data were then used to train and verify the land cover maps produced.

### **2.3.2 Land cover change detection and accuracy assessment**

The land cover change detection technique applied in this study was the post-classification comparison approach (Lambin, 1999; Lu *et al.*, 2004) and it was implemented in an IDRISI platform. The change detection was done to determine the change in area of the different classified land covers over a period of 30 years.

Accuracy assessment focused on analysing the accuracy of each of the classified images (final classified map for each year), since the accuracy of post-classification change detection depends entirely on the accuracy of each of the individual land cover images used for change detection. Thus, the accuracy of land cover detection entailed verifying the generated land cover maps using field data (for 2008/9 images). For 1975 image; the Toposheets generated from aerial photography, airborne profile recording and other supplementary control surveys conducted between 1969 and 1972 to 1977 were used. For the 1991 image, use was made of the national land cover and landuse map (shapefile) generated from band 3, 4 and 5 of the Landsat TM satellite images taken between 15/07/1994 and 23/06/1995. Further, for all the maps generated, use was made of other readily available secondary data such as Landsat images that had not been used for generating the land cover maps to be assessed. Moreover, Google Earth maps were sought for those areas where high resolution Quickbird images covering the study area were available. Google Earth images have been used as reference data in a similar study by Knorn *et*

*al.* (2009) and Gutierrez *et al.* (2011). Ground truthing data (ground reference data) for the 2008/09 land cover maps were collected in the dry seasons of 2008 and 2009.

Ground truthing was aimed at determining what is actually on the ground at a given location in order to verify the derived land cover product. The ground truthing exercise was carried out between October 30<sup>th</sup> and November 20<sup>th</sup> 2008 (just before the short rains) and repeated on 25<sup>th</sup> June and 5<sup>th</sup> July 2009 (dry season after the long rains). The survey entailed recording the land cover type observed and taking their respective location using hand held global position system (GPS) device. The first campaign was conducted with sampling done on the periphery of the roads and foot paths. For the second field campaign, effort was made to adhere to the random stratified sampling scheme in data collection where possible; however, the nature of the terrain in the study site made this difficult. In both of the campaigns, a continuous homogeneous land cover of at least 30 m by 30 m was identified and the dominating land cover type recorded.

A total number of 775 and 836 reference points for the years 1975 and 2008 respectively were generated using a random stratified sampling scheme, where samples for each generated land cover class were obtained. 167 were verified through field visits and the rest through Google Earth data and other sources as mentioned above. This was carried out with the help of the geo-statistical analyst tool in ArcGIS platform.

An error matrix was generated using ArcGIS and Microsoft Access database where overall errors, as well as errors of omission and commission, were tabulated. Errors of omission are the percentage of pixels that should have been included in a particular class, but were not, while errors of commission are the percentage of pixels that are wrongly placed or mistakenly included in a category that they do not belong to (Stehman and Czaplewski, 1998.; Congalton and Green, 1999). The overall accuracy is the percentage of correctly classified pixels that represent those pixels that are in agreement with the generated land cover map and the ground reference data.

## 2.4 Results and Discussion

### 2.4.1 Accuracy assessment

The accuracy assessment indicated that the land cover maps satisfactorily represented the actual situation on the ground, with an accuracy of 89% for the 1975 thematic map (see Table 2.7) and an 85% overall accuracy for the 2008 land cover map.

Table 2.3 Error matrix for the 1975 land cover map

LC Map1975	Reference Data					Total sample	User's Accuracy	COMISSION ERROR
	R. Forest	Grassland	Woodland	Seasonally Ind.	Water			
R.Forest	93	3	8			104	89%	11%
Grassland		111	11	2		124	90%	10%
Woodland	9	8	254	12		283	90%	10%
Seasonally Inund.	4	11	7	182	6	210	87%	13%
Water				7	47	54	87%	13%
Total sample points	106	133	280	203	53	775		
Producer's accuracy	88%	83%	91%	90%	89%		89%	
OMISSION ERROR	12%	17%	9%	10%	11%			

The land cover class specific errors indicated that, for the 1975 land cover map, 12% of the pixels that were supposed to be classified as forest, were either classified as woodland or seasonally inundated land. On the other hand, 11% of pixels were mistakenly included in the forest class.

Generally, the land cover mapping exercise was accomplished with acceptable accuracies.

Uncertainty occurred, especially when trying to distinguish the spectral signatures of the intensive cultivation class and the settlement/cultivation class. However, in this study, the class-specific user's and producer's accuracies in generating the various land cover maps were fairly good and ranged between 80 – 90%.

Table 2.4 Error matrix for the 2008 land cover map

LC MAP 2008	Reference Data							Total sample	User's Accuracy	COMISSION ERROR
	R. Forest	Grassland	Woodland	Intens. Cultv	settle./cultv.	Seasonally Ind.	Water			
R.Forest	84	3	7					94	89%	11%
Grassland	6	115	2	8		7		138	83%	17%
Woodland	12	10	97	6	3			128	76%	24%
Intens. Cultv		3	3	142	17			165	86%	14%
settle./cultv.				21	192	2		215	89%	11%
Seasonally Inund.				4	1	62	5	72	86%	14%
Water						2	22	24	92%	8%
Total sample points	102	131	109	181	213	73	27	836		
Producer's accuracy	82%	88%	89%	78%	90%	85%	81%		85%	
OMISSION ERROR	18%	12%	11%	22%	10%	15%	19%			

### 2.4.2 Area changes of the land cover types

Generally, the generated thematic land cover maps showed significant land cover transformation over time. Figure 2.4 shows the land cover maps from 1975 to 2008/09. The 1975 land cover map indicates limited human activities, with most parts of the Valley area covered by woodland or grassland vegetation. These are the areas that used to be seasonally flooded by the braided Kilombero River. Therefore, in this study, the 1975 land cover was regarded as the baseline land cover map upon which other comparative analyses were based.

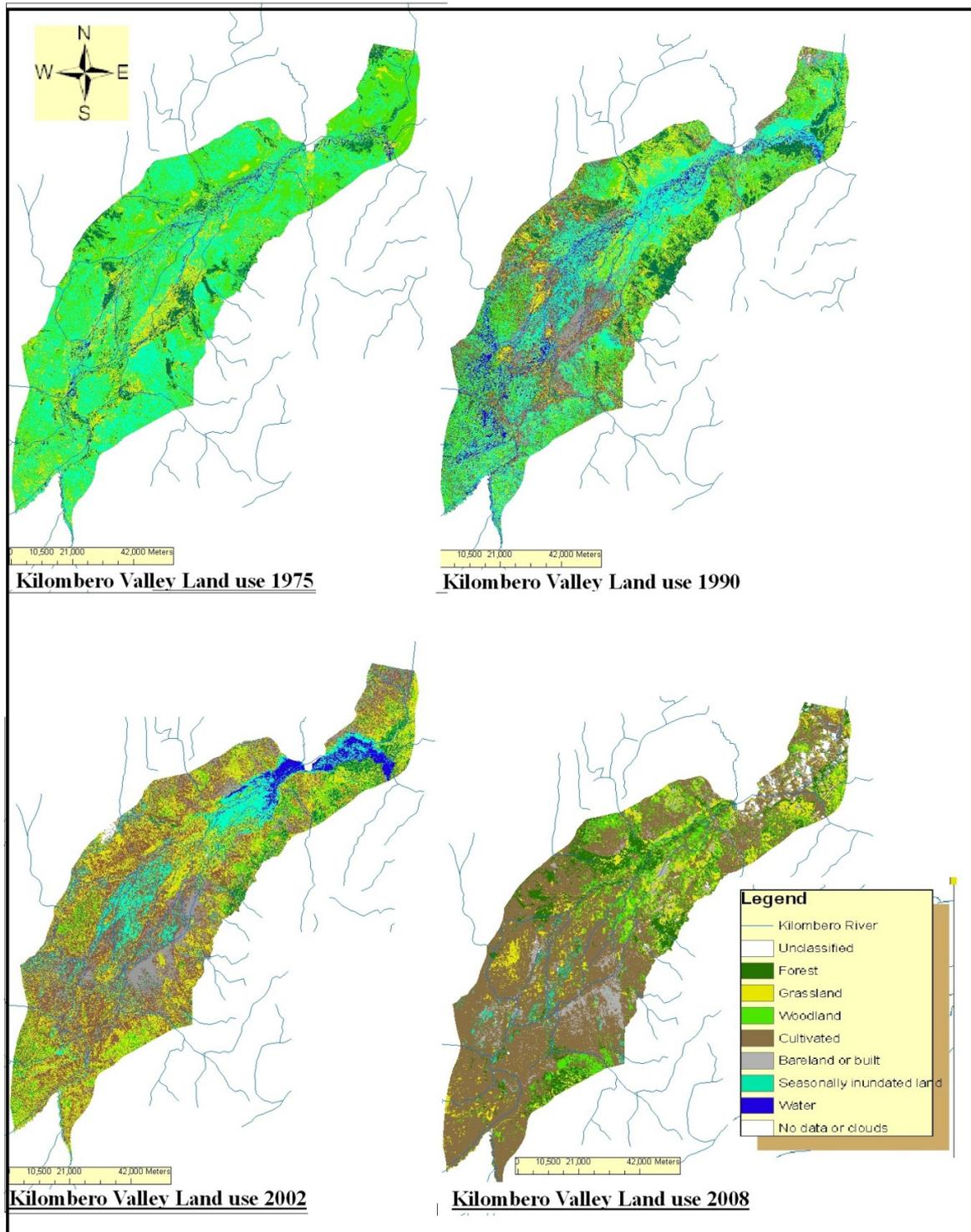


Figure 2.4 Land cover map showing the baseline situation of 1975, 1990, 2002 and 2008/9

Analysis shows that, particularly over a span of twelve years between 1990 and 2002, the Valley appears to have been progressively transformed into an agricultural and settlement area (Figures 2.4). This transformation process was accompanied by the progressive encroachment and exploitation of the riparian zone, as indicated in Figures 2.4A and B, with a gradual conversion of the native Miombo woodland zone into other land covers, particularly farmlands. A summary of the statistical land cover transformation over a span of 35 years (i.e. 1975 to 2008) is given in Table 2.3 and Figure 2.6 in which it is evident that there has been a dramatic loss of Miombo woodland, increased human disturbance and decreased area under the seasonal swamps. Figure 2.6 summarises land cover changes as mapped using Landsat satellite images from 1975 to 2009.

Table 2.5 Land cover status in the Kilombero Valley over a 30 year period

LC Category	1975	1990	2002	2008/9
	Area (Km <sup>2</sup> )			
Riverine Forest	582	699	340	407
Grassland	1,051	1,317	2,119	1,575
Woodland	3,347	1,290	627	541
Intensive cultivation	1	1,482	3,035	2,760
Settlement/ cultivated land	-	417	793	2,214
Seasonally inundated	2,860	2,336	821	144
Water	123	415	210	210
Cloud coverage	4	12	23	116

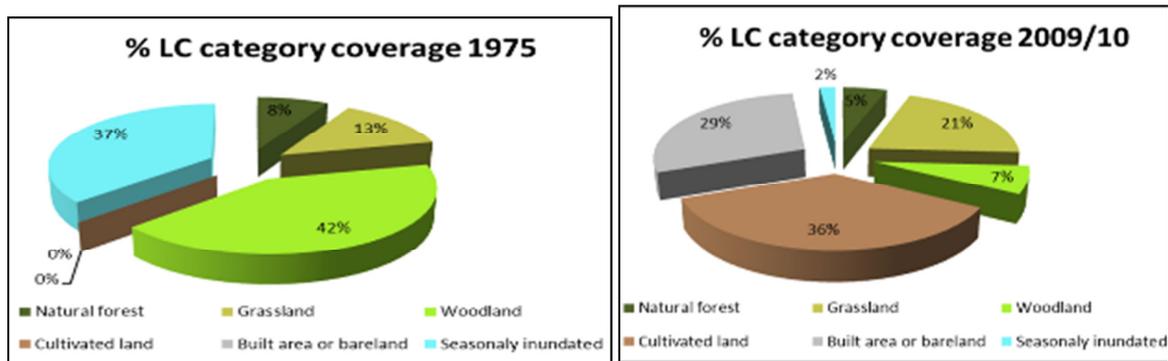


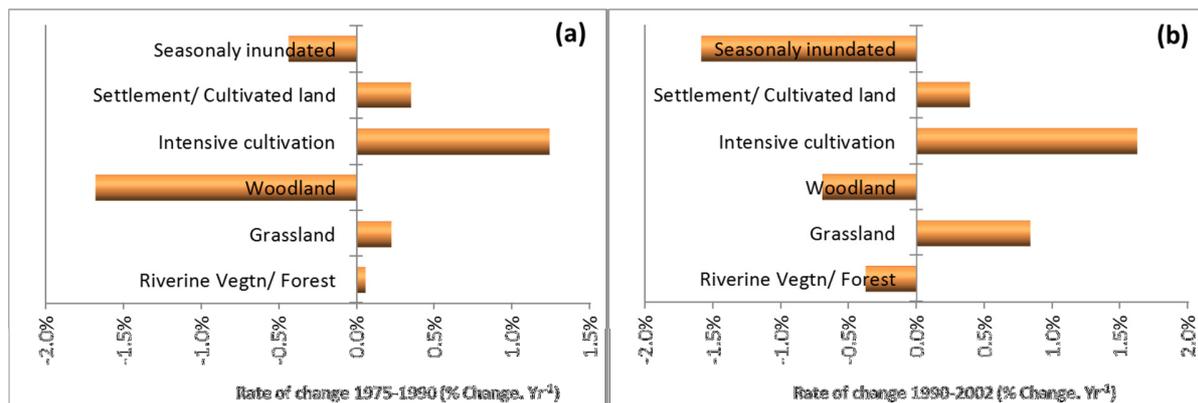
Figure 2.6 Percentage land cover distribution in the Kilombero Valley

The study shows that the Kilombero Valley has undergone close to absolute transformation from its near natural state to a highly exploited ecosystem over a span of 30 years.

The general trend of land cover change in the Valley is such that the cultivated land and settlement areas have continuously been replacing the Miombo woodland and the seasonal inundated land or wetland areas. By 2009 (the current state), the Miombo woodland, which used to be the dominant land cover, only covered 7% of the Valley compared to 42% in 1975. Cropland (cultivated land) is currently the dominant land cover in the Kilombero Valley, covering 36% of the Valley area (Figure 2.6). The area under grassland has also increased from 13% in 1975 to 21% in 2009. This is mainly as a result of the wanton destruction of the Miombo woodland by pastoralists, known to cut trees as a means of controlling Tse-tse flies in the area. This is in addition to the on-going charcoal burning by locals for income generation.

### 2.4.3 Change rates of land cover types

Clearly, woodlands and inundated areas have suffered considerable losses, particularly between 1975 and 2002. A summary of the net increase or decrease in areas of each land cover category is given in Figure 2.7.



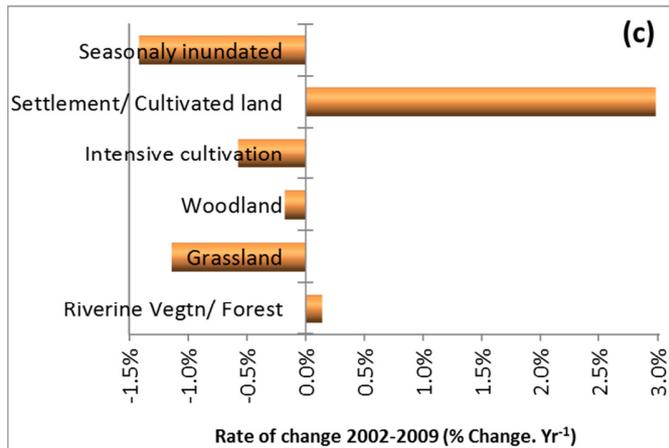


Figure 2.7 The annual rate of land cover conversion in the span of years indicated expressed as a percentage of the total area.

The fastest land cover transformation was observed with agricultural and settlement land uses. Figure 2.7 shows an agricultural land expansion rate of about 1.2% yr<sup>-1</sup> (1975-1990) and 1.6%.yr<sup>-1</sup> (1990- 2002). This is slightly higher than the annual increase of 1.05% that occurred between 1984 and 2001 in another wetlands-dominated river catchment in Tanzania (Kashaigili and Majaliwa, 2010). Estes *et al.* (2012) study of the Serengeti ecosystem, reported an annual increment in the agricultural areas of 2.3%.

Results show that the settlement/mixed cropping land covers have considerably changed the Valley's landscape, with the areas increasing at an annual rate of 2.97% between 2002 and 2009/10. Woodlands experienced a high loss rate, declining at annual rates of 1.68% in the first 15 years and continuing at a rate of 1.58% up to 2002. This is almost comparable to a national survey conducted on woodland deforestation which established annual decline rates of about - 1.02% for the period between 1990 and 2000, approximately -1.1% between 2000 and 2005; and -1.16% for the period between 2005 and 2010 (Devisscher, 2010). Slightly lower figures are reported in a study conducted by Masanja (2013) in other woodland areas in Tanzania which showed a decline of 46.7 ha per year (i.e. a rate of 0.3% per year) of woodland between 1984 and 2012 and a subsequent increase in farmland areas at annual rates of 0.8%.

Furthermore, Figure 2.7 shows that the Valley's wetlands (seasonally inundated land) declined at a rate ranging between 1.4% and 1.6% per year from 1990, amounting to total losses of about

2700 km<sup>2</sup> for the period under consideration i.e. 1975-2009/10. Other areas that experienced expansion are the agricultural and settlement areas, with annual rates ranging from 0.5% to 1.6% and 0.4% to 2.9%.

From the observations noted above, it can be deduced that 1990 was most likely the year in which the Valley started experiencing intensive human settlement and exploitation. However, this required confirmation by the Valley inhabitants, obtained through a questionnaire analysis.. Developments are evidently on the increase especially on agricultural fields, grassland and settlement areas, as earlier elaborated (Table 2.3). These developments significantly took place during the period of 2002 and 2009, accompanied by appreciable increase in settlement areas (built-up areas), which confirms that the observed changes are mainly associated with anthropogenic activities as highlighted in Section 2.2 of this document.

#### **2.4.4 Spatial distribution and progressive loss of Miombo woodland in the Kilombero Valley**

The significance of Miombo woodland in the Kilombero Valley ecosystem, as highlighted by other researchers, is linked to biodiversity and habitat provision of the game-controlled area (UNEP, 1998). Figure 2.8 shows the spatial extent of the progressive loss of woodland vegetation in the Valley. The entire Valley area appears to have suffered losses, with few exceptions where the woodland cover has persisted. These are the areas circled in red (i.e. the Kibasira Swamp around Mofu and on the foothills of the Mahenge Mountains). The high vulnerability of the woodland area to human intervention is probably due to its location in riparian areas (riparian woodland) and outside the government protected areas. The significant loss of Miombo woodland in the Valley has been a concern to many stakeholders, including the scientific community. However, less attention has been given to the obvious or possible impacts of such a large-scale human intervention on the sustenance of the hydrodynamics and biodiversity of the Valley ecosystem.

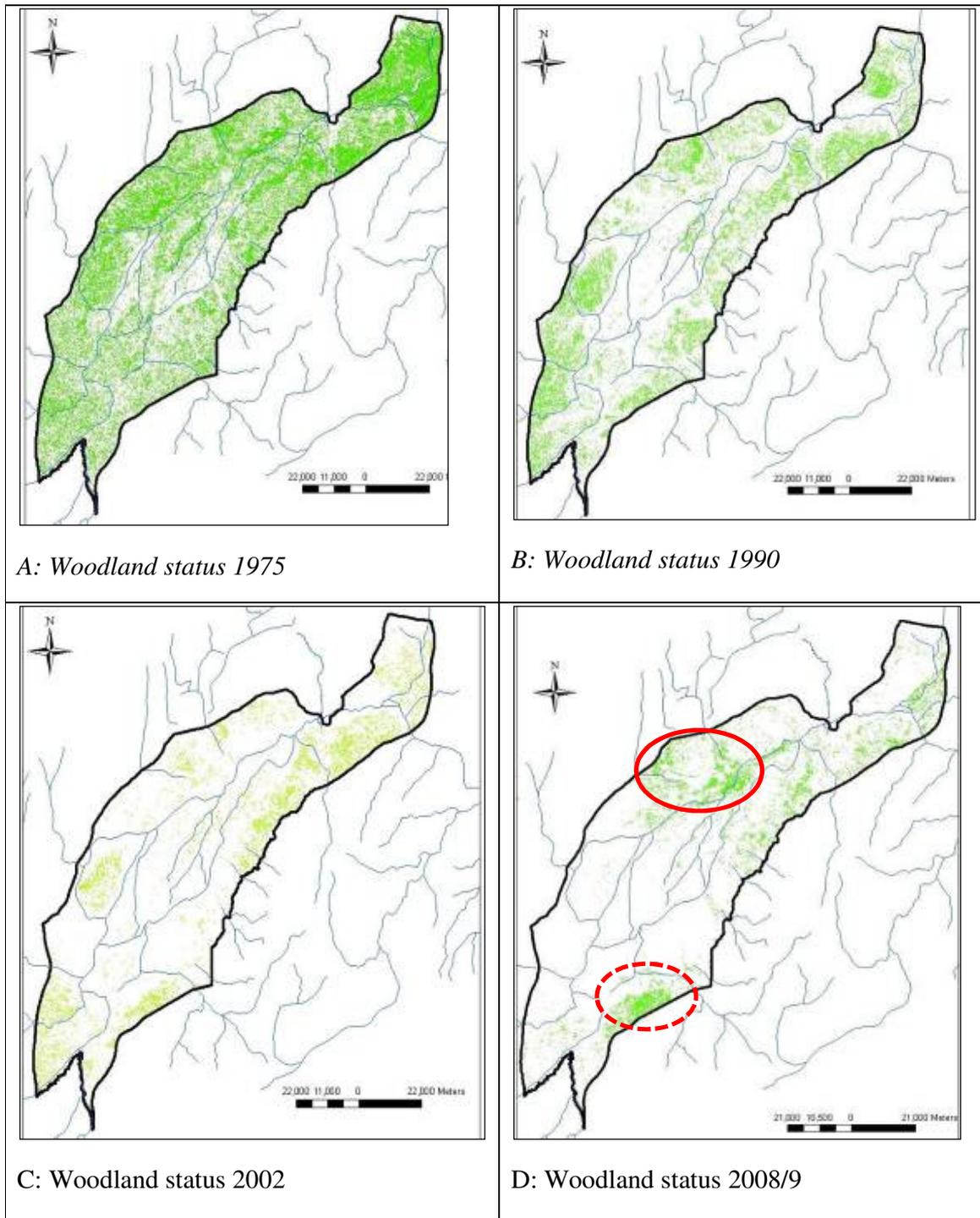


Figure 2.8 Spatial variability of the woodland in the Kilombero Valley, A – D show the progressive loss of woodland in time between 1975 and 2008/9. The solid and the dotted red circles indicate the location of the Kibasira swamp and the woodlands on the foothills of the Mahenge Mountains.

### 2.4.5 Commercial Teak forest plantations expansion

Commercial Teak plantations were highlighted in Chapter 1, section 1.3 as the largest commercial agricultural enterprise in the Valley, with the KVTC owning about 28,229 ha of the Miombo woodland for Teak forest plantation establishment.. The analysis established that by 2008 the company had replaced 8,400 ha of woodland (Table 2.5), approximately 30% of the total Miombo woodland area under their care. Figures 2.9 and 2.10 show the Miombo woodland areas that have been replaced by Teak forests.

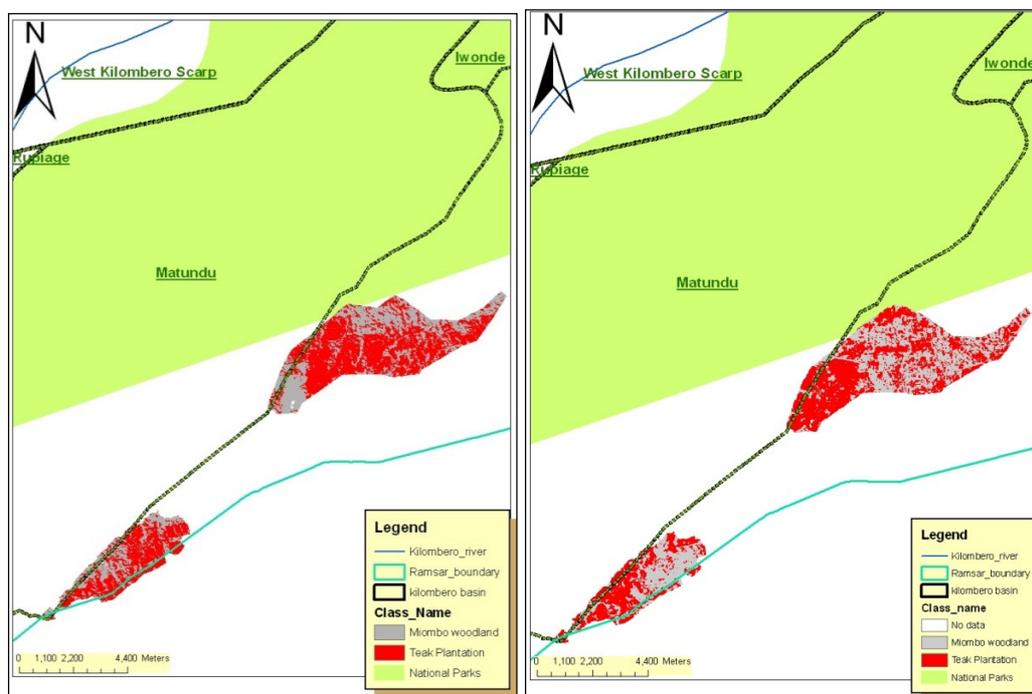


Figure 2.9 Teak forest plantations status in the year 2002 (LHS) and 2008 (RHS) at Ichima and Namawala wards of Kilombero District

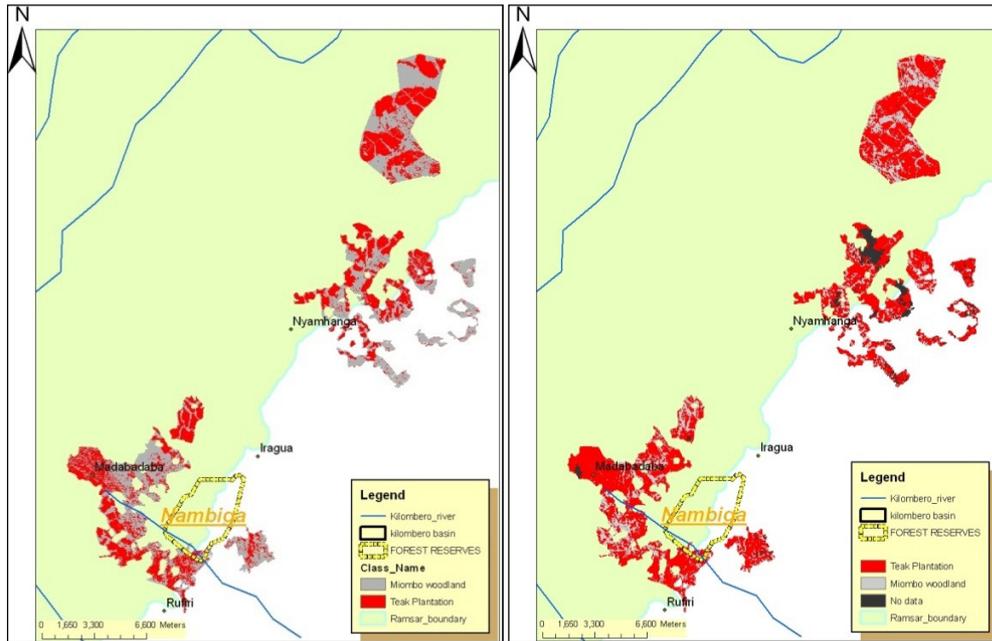


Figure 2.10 Teak forest plantations at Ulanga District in 2002 (LHS) and 2008 (RHS)

Table 2.5 Quantitative estimate of the Teak forests expansion in the Kilombero Basin

	2002	2008	net change
Teak area (ha)	6159.3	8433.4	2274.1
Miombo area (ha)	6414.4	3726.5	-2687.9
No data area (ha)		498	

*NB: the no data area is the area that is covered by clouds and was therefore not included in the analysis of the change in land cover.*

#### 2.4.6 Spatial patterns of the Kilombero Valley wetlands

Figure 2.12 indicates the progressive degradation and exploitation of the Kilombero wetland vegetation from 1975 to 2009, while figure 2.11 shows the emergence and expansion of farmland and settlement areas, almost throughout the Valley, in the first 15 years (from 1975).. These findings are in line with highlights from Kangalawe and Liwenga (2005) which attributed the community's preference of wetlands for agricultural production to the availability of perennial

soil moisture and the fertile soils in the Valley (factors which assure good crop yields to the smallholder farmer practicing traditional agriculture, regardless of rainfall patterns). Spatial analysis revealed that most of the seasonally inundated and woodland areas were converted to settlement or bare land.

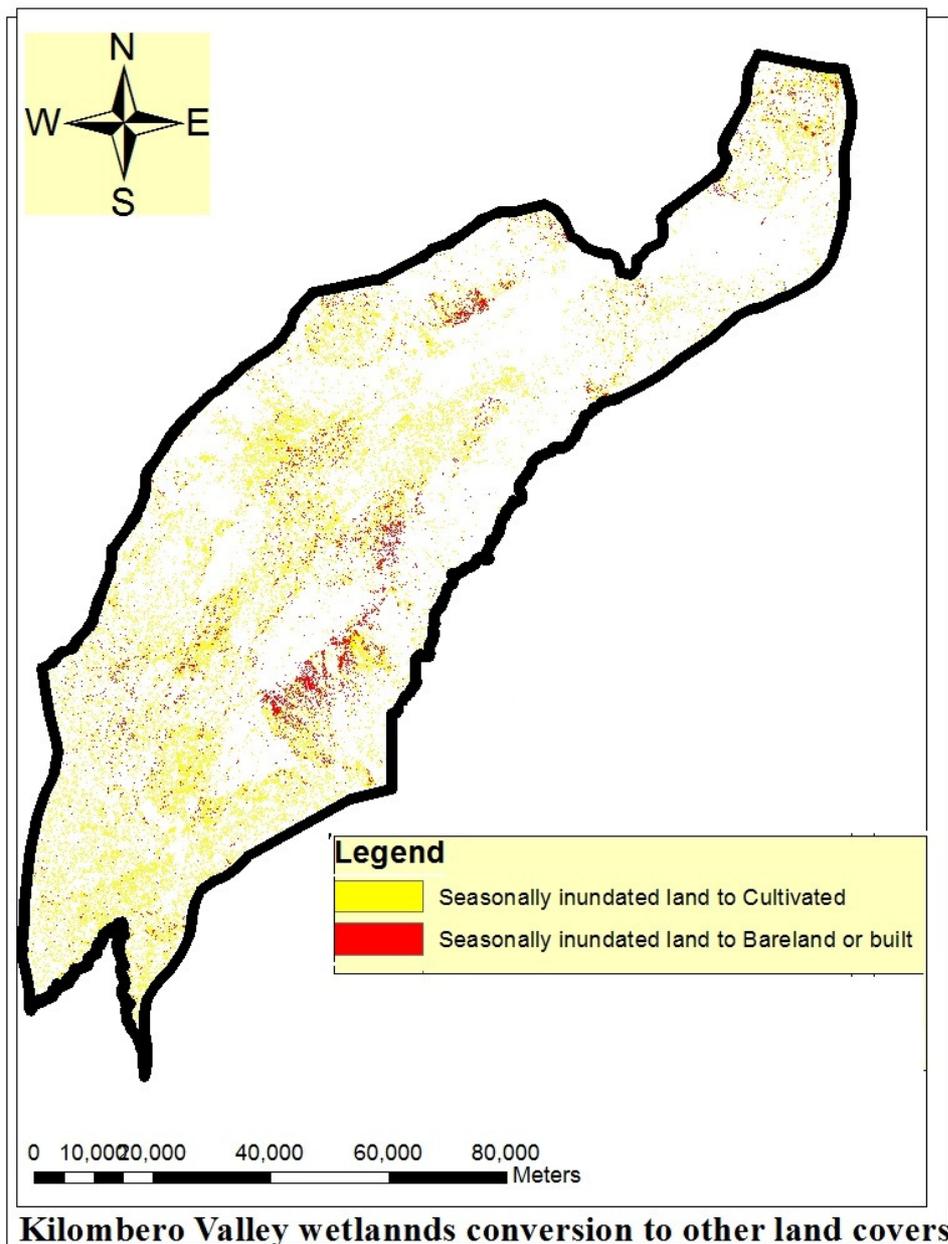


Figure 2.11 Spatial distribution of areas converted from seasonally inundated land to cropland and settlement areas between 1975 and 1990

### 2.4.7 Trends of human exploitation of the Valley

Figure 2.13 shows a progressive increase of agricultural activities and the expansion of settlement areas in the Valley. Table 2.6 indicates the quantitative estimates of human-altered land cover over time in the Valley for each year (i.e. the sum of agricultural land, settlement areas, barren land, idle cultivated land and other built-up areas, categories 4 and 5 of Table 2.5).

Table 2.6 Anthropogenic exploitation of the Valley area over the 30 year period

	1975	1990	2002	2008/9
Settlement and Cultivated area in Km <sup>2</sup>	Negligible	1899	3827	4974
% of the total valley area	Negligible	24%	48%	62%

From Figure 2.12 and Table 2.6, it can be noted that human exploitation of the Valley during the 1970s was insignificant. However, this progressively changed over time.. By 2008/9, a major part of the Valley (62%) was either under cultivation, built-up or bare land cover as a result of human interventions. This implies that by 2009 an even larger part of the Valley was under human exploitation due to the influx of commercial agriculture, smallholder farmers and pastoralists resulting in increased urban areas and barren grazing land. Literature concurs with this assessment, as elaborated in Section 2.2, citing an influx of pastoralists (immigrants) from nearby regions with large herds of cattle during this period.

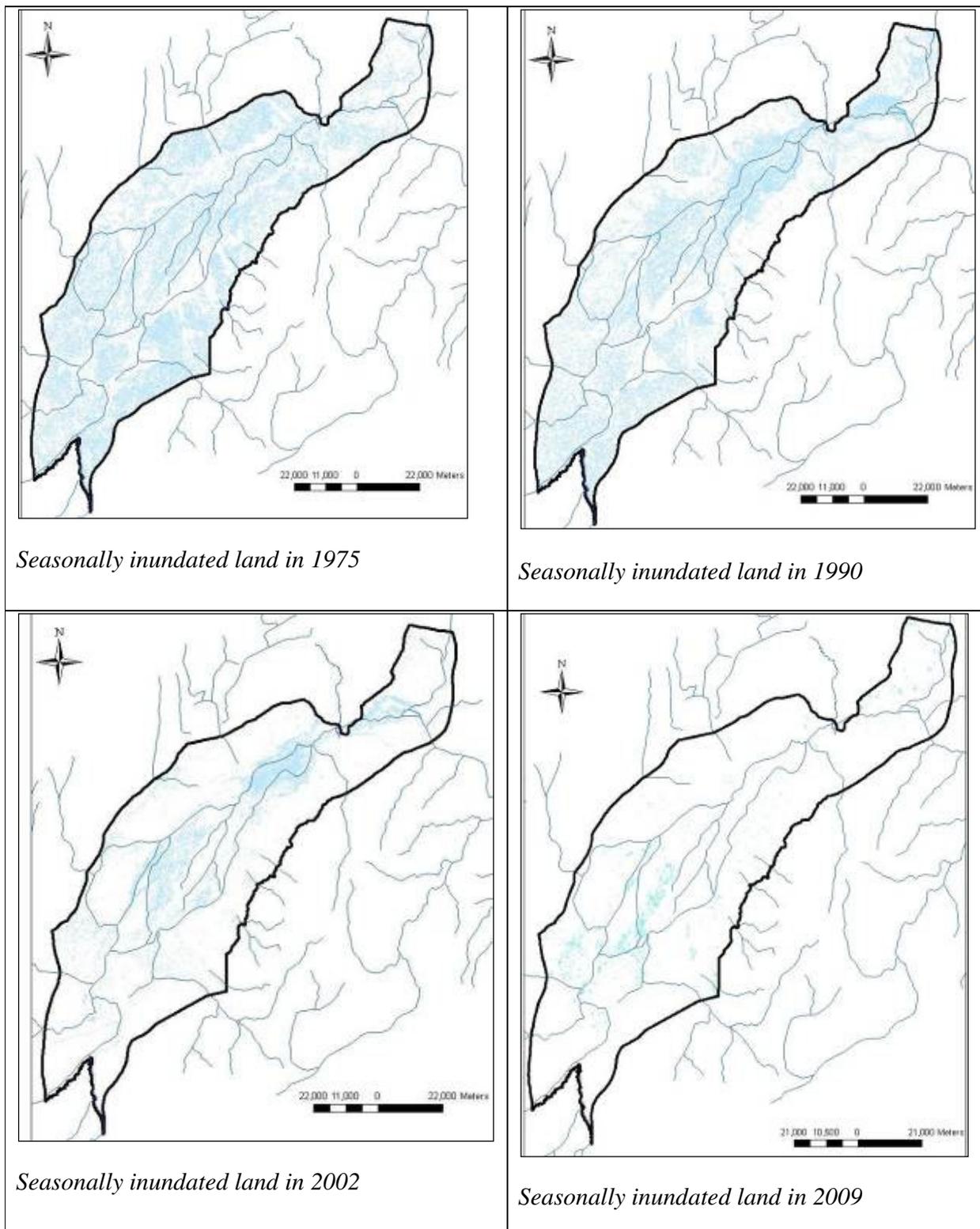


Figure 2.12 Progressive degradation of seasonally inundated lands in the Valley (1975 – 2009)

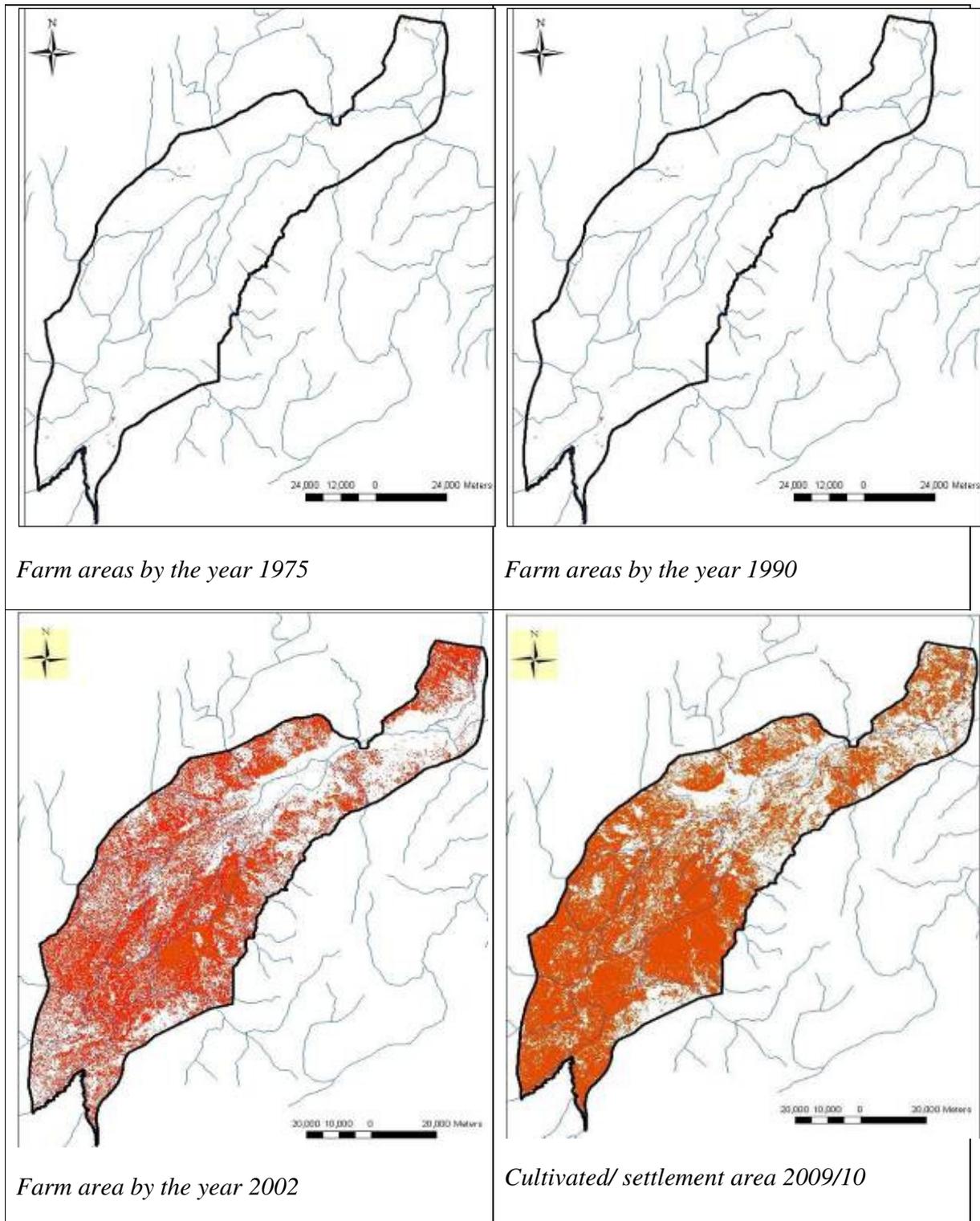


Figure 2.13 Progressive increase of farming activities and settlement in the Valley (1975-2009)

#### 2.4.8 Stability of the riverine forest in the Kilombero Valley (30-year situation analysis)

The existence of the riverine forest is relatively stable (Table 2.5), most likely due to its continuous natural pattern of regeneration and degeneration. There is little evidence of fragmentation of these forests in areas where cultivation is very close to the river, as indicated in Figures 2.14 and 2.15. It is noteworthy that the riverine forest is home to wild animals, especially crocodiles, an indirect discouragement to its exploitation.

A particular cause for concern in relation to the loss of natural forests in the Valley is the Nambiga Forest (currently a government reserve), whose area has evidently been reduced, as indicated by the red rectangle in Figure 2.15 and shown in Figure 2.14. The on-going encroachment into this reserve forest is mainly caused by the establishment of the commercial Teak plantations by the KVTC and illegal timber harvesting by the local community in the vicinity of the area.

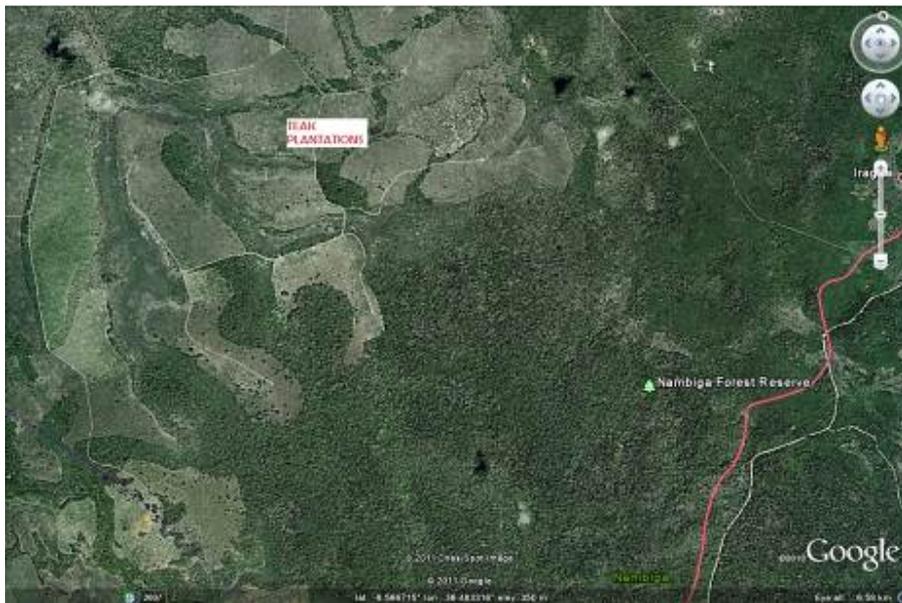


Figure 2.14 Google Earth image of KVTC plantations around Nambiga Forest Reserve

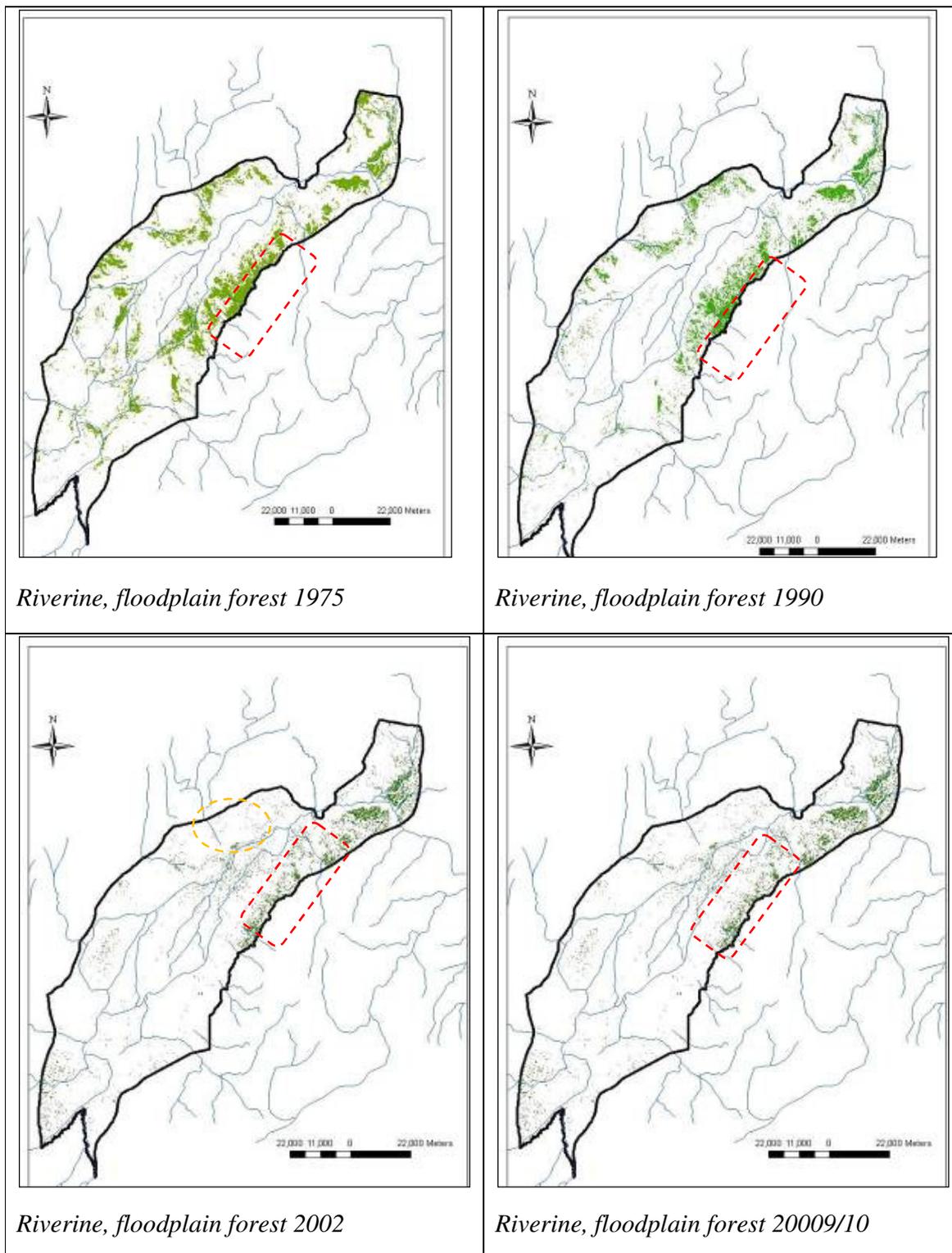


Figure 2.15 Riverine, floodplain forest cover in the Valley from 1975 – 2009 (red rectangle and a yellow circle indicates the location of Nambiga Forest and the Kibasira permanent swamp respectively).

It should, however, be noted that retrieving the forest signature was challenging due to cloud cover over the Udzungwa Mountains almost throughout the year, a challenge observed in 2002 too. To a large extent this also limited visibility around the foothills and the Kibasira swamp area as well (yellow circle in Figure 2.15). Efforts to mask out the cloud cover lacked success, leading to the under-representation of the forest in this particular location and explaining the dramatic forest reduction in 2002 indicated in Table 2.5. It is believed that the actual forest cover in that year was higher than 340 km<sup>2</sup> (Table 2.5).

## **2.5 Potential Hydrological Implications of Land Cover Change in the Kilombero Valley**

### **2.5.1 Alteration to catchment functioning due to land cover change**

A closer look at the geomorphology and terrain surrounding the Kilombero Valley suggests that these features have influenced the seasonal flow regimes of the river, including the inundation of the Valley. The surrounding hills on either side of the Valley confine the river to flow along a 200 km channel length on a flat plain of about 50 km to 60 km wide (see Figure 2.1 and 2.2). Upon approaching its mouth at Swero (within the Selous Game Reserve), the Valley narrows to a width of about 0.7 km as a result of the forested hills on each side of the Valley. This results in a backwater effect, especially during flood events, normally observed between Boma la Ulanga and Ifakara. Equally important is the existence of the conserved woodland vegetation at the Valley's mouth. This vegetative cover increases resistance to the river flow thus increasing the retention time of water which leads to increased deposition of sediments in the Valley.

This study revealed the significant conversion of woodland and grassland areas, on the floor of the Valley, to agricultural and settlement lands. These human activities have the potential to impact and alter the hydrodynamics of the Basin. Some of the human activities that have the potential to influence the quantity and quality of stream flows in the Valley include abstractions for irrigation needs and increased evapotranspiration from the floor of the Valley as a result of change in land use. The main input variables to the Kilombero River system are direct precipitation and inflow from upstream catchments. Groundwater contribution and interactions with surface water (recharge and discharge) of the Kilombero River system are not well known or documented in literature.

Unfortunately, little effort has been applied towards understanding this interaction which is of great importance in determining the water balance in the Valley. An importance further supported by the fact that the majority of the residents in the Kilombero Valley, including town centres and business facilities, rely entirely on groundwater supply. Of great concern to the water balance of the Valley is the fact that water abstractions for irrigated agriculture and evaporative water used by various land uses have never been quantified nor established. Yet, these two water uses contribute the highest percentage to the water balance of the Valley. It is, therefore, important that a better understanding on the occurrence and magnitude of these fluxes be acquired.

A common feature in the marginal areas along the Kilombero River is the abstraction of water from the River by the smallholder farmers for irrigation purposes. Unfortunately, these abstractions are not licensed and present a challenge to establishing withdrawal limits along the river based on the available water resources. Poorly-managed irrigation water abstractions have been shown, in some instances, to have detrimental effects on the available water resources. For example, the Colorado River underwent a similar process and currently has only 1% of its natural flow reaching the river's mouth, while the Senegal River's peak and low flows have been altered through water withdrawals causing the river to dry up in some instances (Tockner and Stanford, 2002).

### **2.5.2 Wetland and floodplain impacts**

The hydrology of a wetland is the most important determinant of its resilience and sustenance. Moreover, the manner in which the surrounding land is exploited, determines the wetland's hydrodynamics and sustainability. A number of studies have established that land cover alteration affects the behaviour of the hydrological cycle (see Section 2.1 of this document). A study in the Great Lakes reported an 8% loss of wetlands and rangelands due to agriculture and urbanisation (Nejadhashemi *et al.*, 2011). In some cases, depending on the level of exploitation, wetlands have been reported to dry up. According to Tockner and Stanford (2002), 11% of the riparian area of African rivers is intensively cultivated. Wetland agriculture and drainage causes drawdown of the water table and reduces the storage capacity of the soils, wetlands storage and regulation functions. The common hydrological behaviour that is observed after intensive cultivation of a

wetland is the lowering of the water table (Dixon and Wood 2003; Bruland *et al.*, 2003; Nejadhashemi *et al.*, 2011). The Rugezi Marsh in Rwanda is a good example where the drainage of the channels impacted negatively on the water table leading to increased peak flows and the drying up of swamp (Hategekimana and Twarabamenye, 2007). The soil storage function is mostly affected by the lowering of the soil's water storage capacity and infiltration capacity, due to oxidizing conditions (Dixon and Wood, 2003; Bruland *et al.*, 2003), while the tilling of soils, as a farming practice, results in compacted soils and reduced soil infiltration capacity. This is in line with observations made by Nejadhashemi *et al.* (2011), where the lowest water yield (sum of surface runoff, lateral flows and baseflow) was observed on agricultural farms, compared to other land cover categories, while urban areas showed an increased stormflow and reduced baseflow. Agricultural water use has been found to amount to 90% of the global consumptive water use and withdrawals (Gleick, 1998, 2003).

In this study, it was revealed that the major concern with regard to the hydrodynamics of the Valley is the seemingly over-exploitation of the wetlands for agricultural purposes. Notably, the seasonal inundation, and hence wetlands, of the Kilombero Valley floodplain has been sustained in the past by more than 15 seasonal and permanent rivers which originate from the surrounding highlands (the Udzungwa and Mahenge Mountains) and flow to aggregate on the Valley's floor. As previously noted in Chapter 1, section 1.4, some of the permanent swamps (e.g. Kibasira) have dramatically reduced in size while some of the seasonal swamps and streams have dried up. This is a good indication that there is cause for concern and more research is needed to establish the extent of such impacts on the larger Kilombero River Basin.

## **2.6 Summary and Conclusions**

The Kilombero Valley landscape pattern has dramatically changed over the past three decades, from its near natural habitat to a more human-managed landscape mostly covered by agricultural fields and settlement areas. The Valley's natural habitat supports wildlife and the tourism industry, while the current altered landscape supports local livelihoods and the food industry. The convergence of exploiting the natural resources in the Valley for food security and the

development and need to secure the sustainability and conservation of the Valley's ecosystem need to be addressed.

The study findings established that there has been a significant conversion of woodland and wetland areas to cultivated and settlement areas. Most significant is the landscape transformation that occurred between 2002 and 2008. The study has indicated that there is still potential for further exploitation by new commercial interests on the Valley's resources, with both the government and private sector becoming more aware of the production potential in the Valley. Further, the study has clearly highlighted the trends of human intervention in the Kilombero Valley, while noting the possible implications of the on-going extensive and intensive agricultural activities on the water resources in the Valley, the latter being the core of proper functioning of the Valley ecosystem and its resilience.

However, a conclusive quantitative hydrological impact analysis could not be carried out because of limited data availability and the lack of an operational streamflow and groundwater resources monitoring network. Any hydrological modelling of the hydrological processes at this stage would hardly represent the situation on the ground.

The study recommends that more emphasis should be given to understanding the hydrological functioning and processes controlling and sustaining the Valley. Attention should be given to the re-establishment of the catchment monitoring network, especially the outlet station at Swero (1Kb17). The management of the monitoring network in this area is highly challenged by its remoteness and bad road conditions, especially during rainy season, such that the only sustainable setup recommended is to embrace the emerging technologies that allow remote data access.

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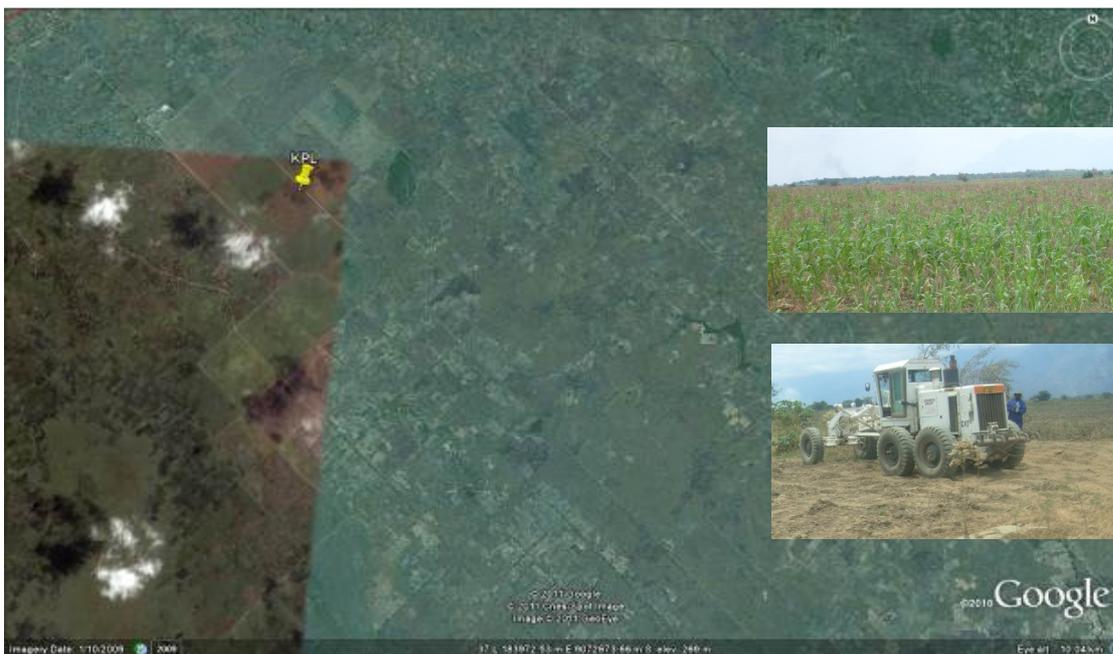
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## 2.8 APPENDIX

### 2.8.1 Google Earth images showing farming activities within the wetlands at Merera



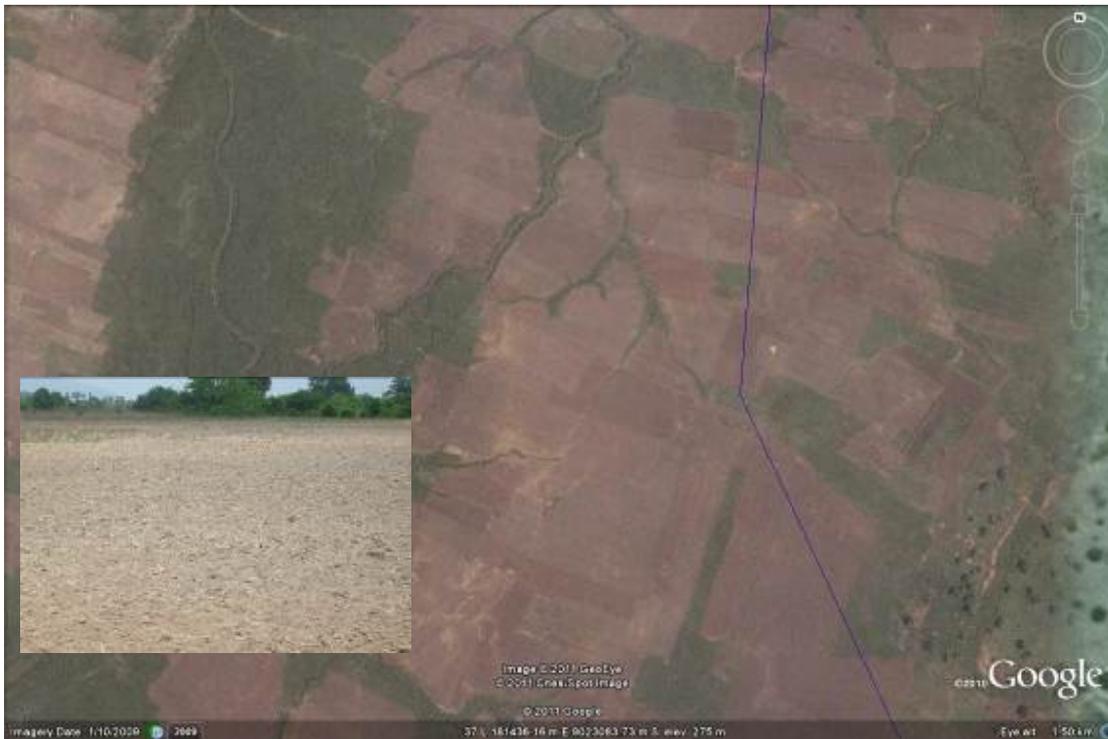
### 2.8.2 Google Earth map showing location of KPL farms on the valley (the photos were taken on the ground during the October 2009 field survey)



**2.8.3 Google Earth high resolution images of settlement encroachment in the Miombo woodland areas**



**2.8.4 Google Earth high resolution representation of harvested agricultural land, which on low resolution satellite would appear as bareland**



### **Lead into Chapter Three**

This thesis seeks to contribute to the understanding of the interaction between the land cover changes and the associated impacts in the catchment water resources. While Chapter Two established that the Kilombero Valley experienced dramatic land cover changes in the past two decades, the rest of the Chapters in this thesis are aimed at quantifying the impacts of the observed changes on the hydrological regime. Chapter Three addresses the gaps in the understanding of the evapotranspiration of the “replacing” as compared to the “replaced” vegetation in an attempt to improve the understanding of the impacts of the land cover changes quantified in Chapter Two. The focus of Chapter Three is on the implications of replacing the indigenous Miombo woodland with Teak forests.

The commercial Teak plantations studied in Chapter Three are managed by the Kilombero Valley Teak Company (KVTC), established in 1992. Through its operation, the company had already cleared more than 8000 ha of the Native Miombo woodland by 2008. The further spread of these plantations presents a continued threat to the Basin hydrodynamics, particularly since local communities are currently getting Teak seedlings free of charge from the company. Teak is a highly desirable, quality timber with competitive prices on the international market.

### 3. A COMPARATIVE ANALYSIS OF WATER USE CHARACTERISTICS OF MIOMBO AND TEAK FORESTS IN THE KILOMBERO VALLEY

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#### **Abstract**

Tanzania, through forestry landscape restoration initiatives and attempts to meet the timber market demands both locally and internationally, has engaged in commercial forestry afforestation. However, many of these undertakings involved the use of fast growing exotic tree species in place of former degraded grassland areas or open woodlands. This study is, therefore, geared towards assessing the hydrologic implications of replacing the native pristine Miombo forests with Teak forest plantations in the Kilombero River Basin, Tanzania.

In this study, a comparison of evaporative water use between the exotic tree species Teak (*Tectona grandis*) and native Miombo forests is highlighted. Teak trees are of high economic value with the potential to be widely adopted by the local community and replace the vast native, pristine Miombo forests. This calls for a more in-depth understanding of the potential impacts on water resources of the likely wider adoption and establishment of Teak forests in the area and the River Basin at large. There are no documented studies on the area, and Tanzania at large, on evaporative water use of Teak and Miombo forests. This article reports water use characteristics of exotic *Tectona grandis* trees and the indigenous Miombo trees, abundantly found within the Kilombero Basin. Ifakara is known to be the Miombo woodland strip.

The results of the study revealed a major difference in the water use of the two with Teak having higher total stand transpiration. The study further linked the difference in the relative transpiration rates with not only individual tree sapwood area, which was found to be higher in Teak trees even of younger age than Miombo, but also from the forest stand structure. It was also found out that Teak tree water use was strongly dependent on the rainfall pattern, implying that

the soil moisture availability was a much stronger driver while Miombo forest water use was mostly driven by atmospheric demand and had the highest transpiration rates immediately following rainfall cessation in the months of June and July. Forest evaporative water use for the entire dry season was significantly higher for Teak compared to Miombo, with total use amounting to 225.86 mm compared to 51.36 mm for Miombo. This suggests potential impacts in the alteration of the partitioning of rainfall and the water balance in general.

This study creates a unique platform for future and similar studies while contributing to the knowledge base through application of cutting-edge experimental studies on evaporative water use of Teak and Miombo trees. The information generated from this study is of great importance to the Rufiji River Basin Office, who have also been supportive of this study, for water and land resource management in the Basin.

**Key words:** *Miombo, Teak, transpiration, evaporative water use, Granier, sap flow.*

### **3.1 Introduction**

Large-scale forest conversion or clearance disrupts the hydrological cycle of a drainage basin by altering the partitioning of rainfall into evapotranspiration components and, consequently, the runoff response of the area (Fohrer *et al.*, 2001). It also affects the net rainfall amount reaching and infiltrating into the soils by interception through its canopy and floor litter. A review of experimental catchment studies by Bosch and Hewlett (1982) on vegetation cover changes effects on catchments water yield revealed that a 10% deciduous hardwood forest change results in significant change in evapotranspiration. According to Calder (1993), Calder *et al.* (1995) and Legesse *et al.* (2003), forests affect annual flows by increasing the interception storage during the wet season and increase transpiration during the dry seasons. The reason for this is that, during the wet season, the forest's rough surface increases the transport of water vapour to the atmosphere, specifically the intercepted water, while in the dry season they typically maintain a high evapotranspiration rate, owing to their great root depth. Legesse *et al.* (2003) highlighted that increased interception in forests may reduce floods, by removing a portion of storm rainfall and allowing soil moisture storage to build up. Forests also affect the seasonal flow by increasing the soil moisture deficit and decreasing dry seasonal flows. Coniferous forest, deciduous

hardwood, bush and grass cover have all been found to decrease annual runoff (Calder, 1993; Brooks *et al.*, 1997).

Forest structure and species diversity has been proven to be important with regard to forests' consumptive water use, since they determine the transpiration flux magnitude (Herbst *et al.*, 2008; McJannet *et al.*, 2007). The effect of stand age and stem sizes on stand-scale transpiration fluxes and water budget have also been highlighted in Delzon and Loustau (2005); Whitehead (1998) and Kostner *et al.* (2002). Delzon and Loustau (2005) established that forest transpiration declined with increasing age, owing to the reduction in leaf area index and stomatal activity, while Forrester *et al.* (2010) attributed the decrease to reduced sapwood area and sap velocity with tree age. The seasonal and daily patterns of transpiration are due to tree physiological controls, environmental conditions and soil water conditions (Calder, 1991).

Forest ecosystems make use of water resources, mainly through the transpiration process, where transpiration and canopy interception mark the largest contribution of the water balance (Jewitt, 2005; Komatsu *et al.*, 2010). Forest transpiration research has been studied and documented in different countries by various authors, including Komatsu *et al.* (2007); Wullschleger *et al.* (2006); Giambellua *et al.* (2003); Poyatos *et al.* (2007); Oishi *et al.* (2008) etc. However, there is no study in literature comparing Teak (*Tectona grandis*) and Miombo forest transpiration dynamics in Tanzania, as reported in this paper.

This comparative study was conducted in an area with both indigenous Miombo woodland forest and exotic commercial Teak forest, with the latter having been established recently (in 1990) following the clearing of the Miombo forest. A visual assessment of the Miombo canopy structure gives an indication that the slender and long leaves have lower canopy conductance, compared to the broad-leaved Teak forest plantations. Various authors including Komatsu, (2005); Herbst *et al.* (2008) and Komatsu *et al.* (2010) have highlighted concerns about the potential impact of broadleaved forests on water resources. This is due to their large leaf size, believed to create a thick surface boundary layer, resulting in a low aerodynamic conductance and high surface conductance (Grace *et al.*, 1982; Whitehead, 1998). Forests characterised by narrow cross-sectional foliage, or leaves, behave in a different manner because their rough aerodynamic surface results in a high aerodynamic conductance (Whitehead, 1998). Wullschleger *et al.* (1998) established that the decoupling of transpiration from stomatal control increases

significantly with increasing leaf size and they attributed this to the higher stomatal conductance in large-leaved, rather than in smaller-leaved, vegetation. Further, the same study reported that the stomatal conductance of *Tectona grandis* was as high as  $1250 \text{ mmol m}^{-2} \text{ s}^{-1} \text{ mm}$ , compared to a range of  $100 - 400 \text{ mmol m}^{-2} \text{ s}^{-1}$  for most trees species. Komatsu (2005) also noted that broad-leaved trees transpire at higher rates when they were compared to the conifers. Another cause for concern with regard to the broad-leaved forest is their relatively higher interception losses (Soulsby and Reynolds, 1995; Huber and Iroumé, 2001). For example, Staelens *et al.* (2008) reported forest interception losses of up to 21%. Bulcock and Jewitt (2012) linked canopy storage to leaf area index (LAI) and showed higher interception values with high LAI. Teak LAI ranges between 4 and  $5.3 \text{ m}^2 \text{ m}^{-2}$  (Imvitthaya and Honda, 2008; Kawamoto, 2003), which is higher than Miombo's LAI ranging between  $1 \text{ m}^2 \text{ m}^{-2}$  and  $2 \text{ m}^2 \text{ m}^{-2}$  (Huemmrich *et al.*, 2005). This implies that Teak canopy interception is likely to be higher than that of the Miombo.

The Miombo woodland is one of the main land covers in the Kilombero River Basin. It was established in this study that 42% of the Kilombero Valley bottom was covered by Miombo woodland forests during the 1970s. This has been reduced to about 7%, as was analysed from satellite images obtained in 2008 (Chapter 2). However, this research study (Chapter 2) has established that Teak forest plantations have continued to expand at the expense of Miombo woodland, increasing from 6,160 to 8,400 ha between 2002 and 2008. One of the objectives of this study was, therefore, to establish the consumptive water use of the indigenous Miombo woodland (*Brachystegia Stipula*), in comparison to the Teak forests, with an emphasis on understanding the hydrological implications of replacing the native Miombo woodland with exotic Teak forests in the Kilombero Valley. This study highlights the diurnal and seasonal variations of sap flow in both Miombo and Teak forests, while seeking to contribute to the understanding of the influence of environmental factors on measured sap flux density, with the specific objective of establishing empirical relationships relating meteorological parameters with the forest water uses. There is no documented literature on evaporative water use of Teak and Miombo forests in Tanzania, as highlighted in this study. Thus, this case study provides a unique platform for understanding the hydrological dynamics of the two land covers, of great importance in the management of water resources in the Kilombero River Basin.

Studies in other regions have indicated that Teak forests, being broad-leaved in nature, have a high evaporative demand, which Bruijnzeel (1997) attributed to the high interception losses, estimated to be approximately 20% of the annual rainfall. Another study by Kallarackal and Somen (2008) estimated the transpiration rates of a four-year old Teak plantation, using the Penman-Montheith method, and reported transpiration rates ranging from 2–13.4 mm.d<sup>-1</sup> during the post-monsoon season in the tropical areas of peninsular India.

There are a number of experimental methods available for vegetation water use estimation. Among these, plant physiological approaches like sap flow techniques estimate transpiration only, while both the water balance and micrometeorology methods provide estimates of local evapotranspiration entailing soil evaporation and plant water use (including interception loss). Sap flow methods are a useful in studies of the water or energy budgets of land surfaces as they can be used to partition evapotranspiration components between plant and soil evaporation and to divide estimates of transpiration among the component species of plant mixtures (Sakuratani, 1987; Kelliher *et al.*, 1992; Allen and Grime, 1995). Moreover, plant physiological approaches provide more insight into the processes involved in the forest water cycle. In this study, the transpiration rates of Teak plantations and Miombo woodlands were obtained using sap flow monitoring techniques, where measurements with Granier's thermal dissipation sensors are employed. This was complemented by measurements of soil water potential and an automatic weather station as further elaborated on in Section 3.3.

### **3.2 Study Area**

The experimental site is located at the Ichima Ward (S8.056, E36.505) on the north-eastern side of the Kilombero River Basin. Ichima is approximately 22 km from the town of Ifakara, the district headquarters of the Ifakara District. The Ward borders the Matundu Forest Reserve on the North-western side, Iwonde Forest Reserve on the North-eastern side and the Ihanga Forest Reserve on the east.

The area was originally a Miombo woodland zone, but is now under Teak plantations which are privately owned by the Kilombero Valley Teak Company (KVTC). The Company owns more than 1600 ha of forest land in the Ichima Ward alone, of which 890 ha has already been planted

with Teak, with corridors of Miombo forest being left between the Teak forest plantations (Figure 3.1) for ecosystem conservation purposes and migration pathways for wild animals (Frontier Tanzania, 2002). The Miombo forests in this area are semi-deciduous, open woodlands, pinnate-leaved trees of umbrella-like crown with undergrowth vegetation dominated by C4 grassland vegetation (Figure 3.4). Miombo woodland is mainly characterised by trees with 12-20 m canopy height. *Brachystegia* is the dominant species, but forests are also composed of *Dalbergia spp.* and *Diplorynchus spp.* (Hinde *et al.*, 2001). The density of the Teak trees in the KVTC-owned plantations is high, with 2,500 trees per ha organized in clusters, according to their planting date (Figures 3.2 and 3.4).

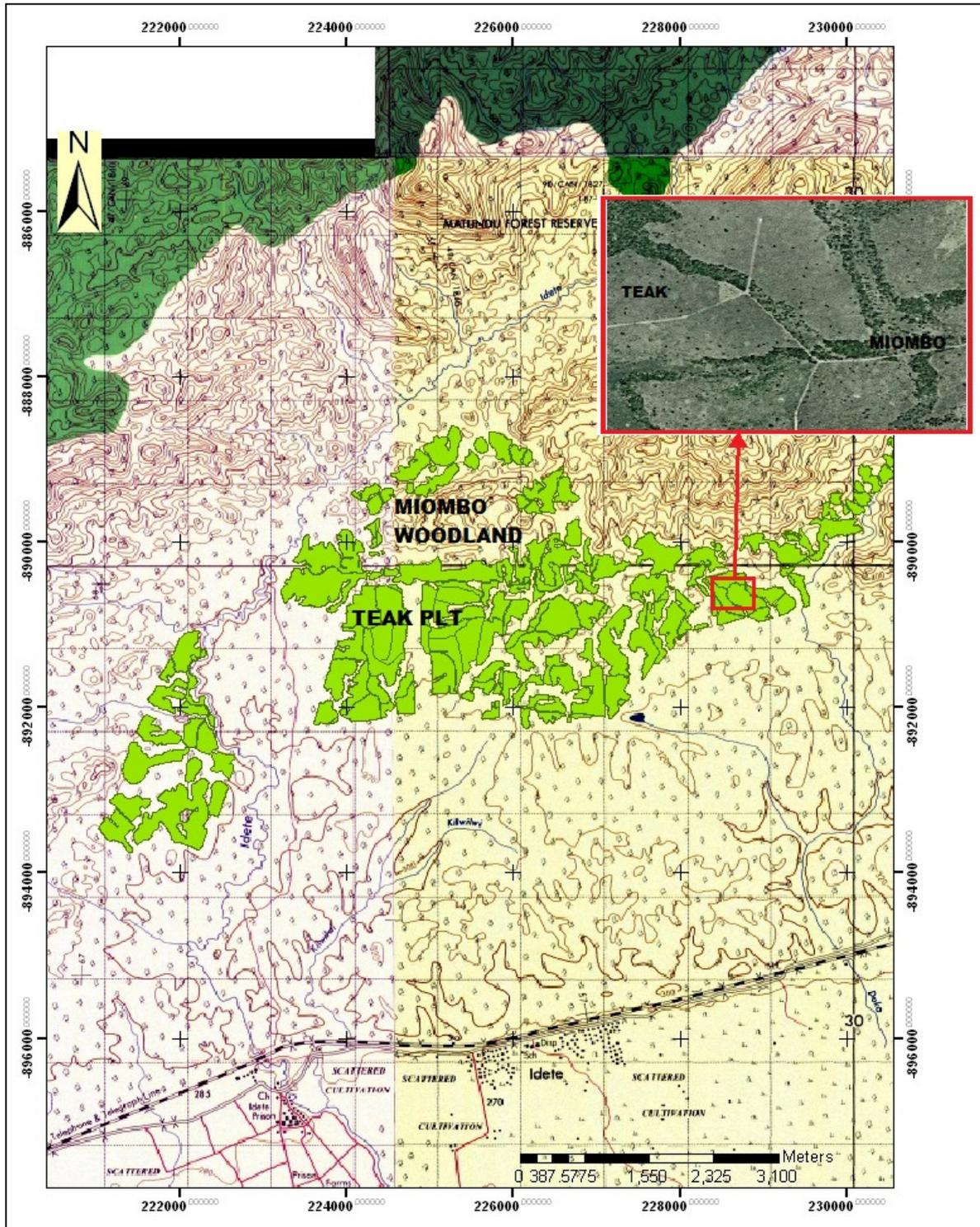


Figure 3.1 Study area representation on topo maps depicting the Teak forest plantations located at Ichima Ward (with Google Earth view of the plantation layout including Miombo corridors)

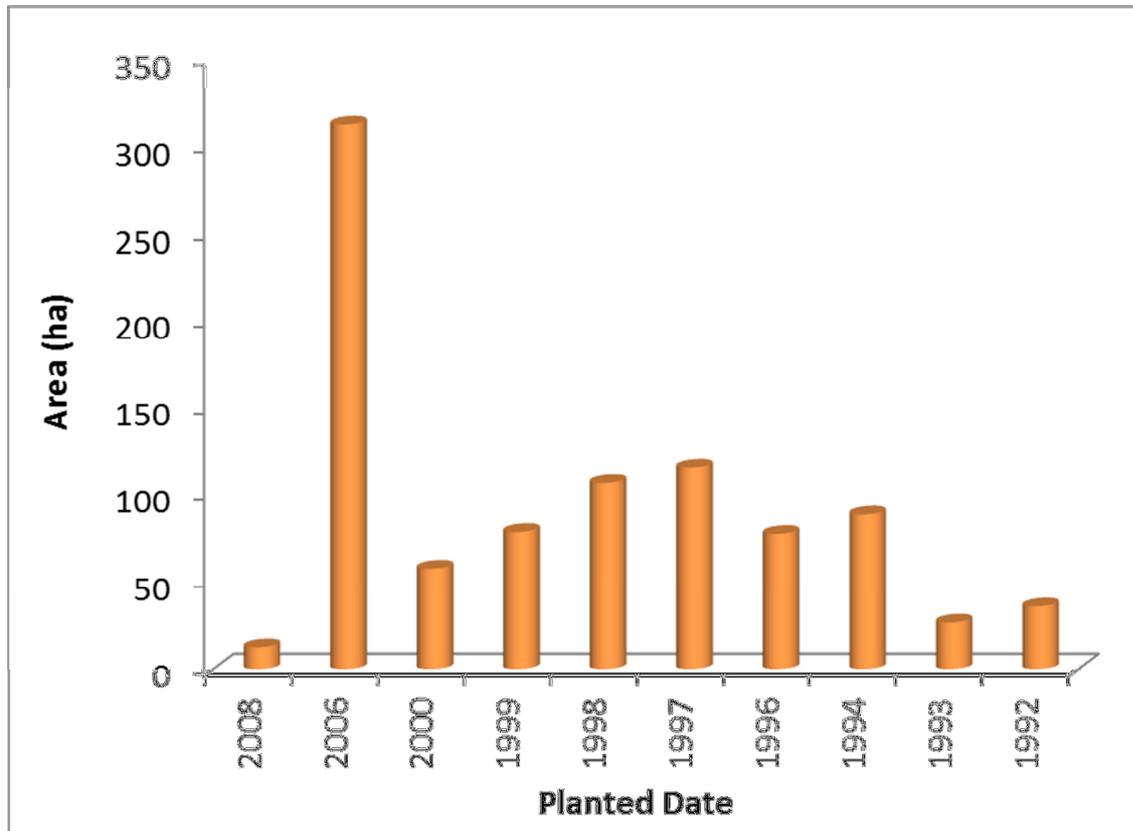


Figure 3.2 Teak tree age distribution at Ichima Block KVTC forest plantation

Information on Miombo woodland tree distribution in the area (Figure 3.3) was obtained from a study by Dirninger (2004), who conducted the analysis of the Miombo woodland forest composition. However, the study focused on the young regenerating Miombo tree stands with a small stem diameter, not of great use in the monitoring of transpiration rates but which provided a good indication of the distribution of the Miombo woodlands in the area, information which is relevant in the upscaling of the individual tree water use to stand level.

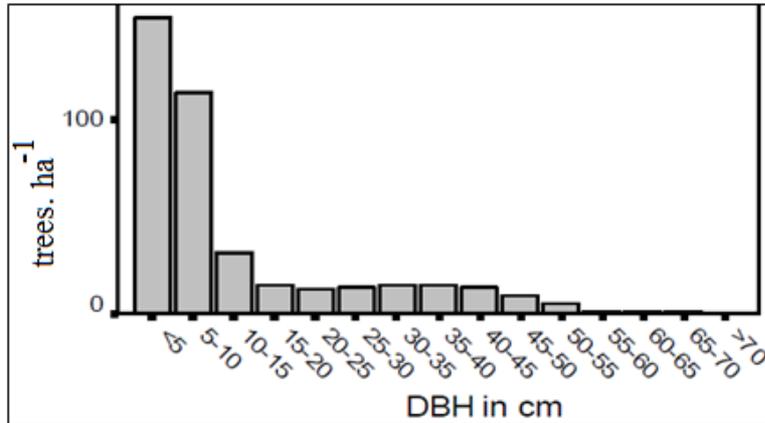


Figure 3.3 Open woodland Miombo diameter at breast height (DBH) distribution within KVTC plantations at Kilombero (after Dirninger, 2004).



Figure 3.4 Miombo tree corridor adjacent to Teak forest plantation during the dry season at KVTC-leased land, also displaying the differences in leaf development stages between the two forest stands (photo taken on 30th October 2008)



Figure 3.5 Teak trees leaf fall during dry season (LHS photo taken on 3rd November 2008) and Teak during wet season (RHS photo taken on 2nd January 2009) in the Ulanga District

The study area is characterised by mean annual rainfall amounts of 1300 mm per year, where the wet season starts in December and peaks in April, while June to November are the dry season months (Figure 3.6).

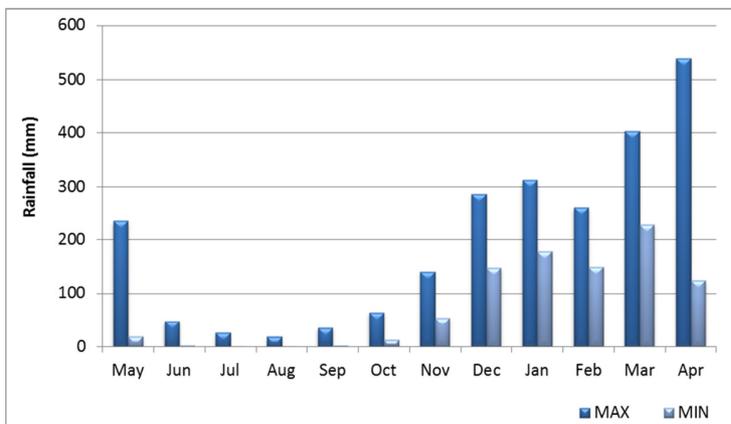


Figure 3.6 Long term annual rainfall characteristics (May – October represent the dry season; November - December the short rainy season and January – May represent the long rainy season)

### **3.3 Materials and Method**

This study employed xylem sap flow techniques to provide stand level transpiration of both Teak and Miombo trees. This was accompanied by simultaneous monitoring of meteorological conditions by an automatic weather station. Scaling techniques to extrapolate the sapflow rates to forest stand transpiration were employed as described in section 3.3.2. For the whole-tree and eventually stand-level transpiration to be derived, forest stand census and its characteristics had to be studied in a biometric survey, the details of which are described in section 3.3.2.

#### **3.3.1 Instrumentation, sampling and scaling of transpiration measurements**

Transpiration rates in both the Teak and Miombo forests were quantified using the Granier method of sap flow rate estimation (Granier, 1987). The Granier method of sap flow rate determination is based on measurements of the temperature difference between a heated and an unheated probe inserted radially into a tree stem. Heat is used as a tracer of xylem sap flow up the stem. A pair of Granier type thermal dissipation probes (Model FLDL-TDP XM1000, Dynamax, Inc., Houston, Tx, USA) of 30 mm (TDP30) and 50 mm (TDP50) length were inserted in sampled Teak and Miombo trees respectively. Each pair of probes was vertically aligned, with the vertical distance between two probes being 5 cm. The lower probe was set at a height of 1.5 m from the ground surface.

The tree samples (Miombo and Teak) were carefully chosen, taking into consideration a number of factors. Given the fact that the most dominant species in Miombo is the *Brachystegia* species, these were selected and instrumented for the purpose of representativeness. In this case, the trees were situated in a corridor left between the established Teak forest stand. In consideration of representativeness of the size distribution within the plantation, the trees in the 2006 Teak block (Figure 3.2) were instrumented. Their relative size distribution is indicated in Appendix 3.9.2.

The exercise of selecting the tree samples included locating an area with the same type of trees close to each other, a distance of less than 3 m. This was important so as to minimise the length of cables connecting them to a logger (Figure 3.7). Moreover, because the experimental site was within the premises of a forest company (KVTC), the selection was done in consultation with the company technical personnel for assurance that the selected trees and the forest stand in the

vicinity are not earmarked for harvesting or pruning for at least a year. Paramount to the sustainability of the experiment was the security of the equipment, which forced the research team to choose a site close to the 24 hr. guard office rather than deep in the forest plantation as desired. Lastly, given the limited budget, the research could only afford to instrument eight trees. Therefore, a total of four Teak (*Tectona grandis*) and four dominant Miombo (*Brachystegia stipula*) trees formed the sample for this experiment.

The temperature difference ( $\Delta T$ ) in the sap between the two vertically aligned probes was measured every five minutes and the values averaged over 30-minute intervals, with data being recorded with CR1000 data loggers (CR1000, Campbell Scientific Inc., Logan, UT). Each tree group was connected to its own data logging system. The probes were protected from exposure to direct sunlight and rainfall by covering the tree stems with a reflective foil material, as shown in Figure 3.7. Each data logging system was powered by a set of heavy duty 12V batteries that were secured in a metallic safe box for security reasons. Every second week, the batteries were taken for charging to the nearby town of Ifakara.

The Granier method has been well tested (Daley and Phillips, 2006; James *et al.*, 2002; McCulloh *et al.*, 2007; Sugiura *et al.*, 2009) and was chosen because of its simplicity, reliability and low energy requirements which suited the remoteness of our study site since no grid power supply was available. Moreover, as there was no prior information on the radial sap flow variations of these tree stems, this method was suitable because of its ability to integrate the sap flow along the length of a probe, making it more sensitive to radial sap flow variability than the heat pulse velocity point measurements (Lu and Chacko, 1998).

The experiment was setup towards the end of dry season (between 31<sup>st</sup> October and 16<sup>th</sup> November 2009), when the Teak trees had shed all their leaves, and the data collection continued until September 2010. The installation of the probes was done in four Teak trees chosen out of the dominant stand age in the Teak plantation forest (i.e. trees planted in 2006, as shown in Figure 3.1) as well as four Miombo trees. The timing of the installation was important because it is believed that during the time of leaf senescence, sap flow is at its minimum or zero, providing a basis of comparison with sap flow when the trees are actively growing during leafing).

The xylem sap velocity was estimated using the temperature difference equation (cf. Equation 3.1), recorded and scaled to whole-tree transpiration using a set of empirical equations after Granier's method (1987). Scaling up to the entire cross-section (whole-tree sap flow) was done by the integration of the sap flux density and area of the conductive tissue, i.e. the sapwood area ( $A_{sap}$ ) to obtain sap flow rate, as per the standard Granier calibration for thermal dissipation probe (TDP) methods (Granier, 1987; Chen *et al.*, 2011) as indicated in Equation 3.2.

$$v = 119k^{1.231} \quad (mm^3 \text{ mm}^{-2} s^{-1}) \quad (3.1)$$

$$F = vA_{sap} \quad (mm^3 s^{-1}) \quad (3.2)$$

Where  $v$  is the sap flux density,  $k$  a temperature gradient (dimensionless) that depend on  $\Delta T_{max}$  as elaborated in Equation (3.3),

$$k = \frac{\Delta T_{max} - \Delta T}{\Delta T} \quad (3.3)$$

Where  $F$  is the total sap flow rate and  $A_{sap}$  is the cross-section area of the sapwood,  $\Delta T$  is the temperature differences between the heated and non-heated probes and  $\Delta T_{max}$  is the maximum temperature difference between the two probes (at  $v=0$ )



Figure 3.7 Installation of TDP sensors within the Miombo forest, adjacent to the Teak forest plantation (lower photo shows: silicone covering the exposed part of the TDP probes: upper heated needle and lower reference needle)

In order to obtain the sap flux densities from the recorded temperature difference, it is assumed that the wood stem under study is homogeneous with a uniform temperature across the stem trunk and conductive tissue of the stem. The method also assumes that sap flow rates are zero to minimal at night and that the maximum temperature difference, or the minimum sap flow, occurs in pre-dawn hours. However, it is useful to note that other studies in literature such as Do and Rocheteau (2002) and Regalado and Ritter (2007) have highlighted the tendency of some trees to experience a non-zero night-time sap flow. Corrections were therefore made to the standard Granier approach so as to factor in the possibility of night-time non-zero sap flow as further elaborated under section 3.3.3.

The study recognises that the sources of uncertainties in the application of the Granier method include the assumption that the wood is thermally homogeneous, therefore allowing heat exchanges between water in the conducting elements and the tree matrix to occur simultaneously,

assuring uniformity in the temperature of the wood matrix. This assumption, however, has been proven to be invalid in some woody species (Do and Rocheteau, 2002; Hall *et al.*, 1998). Information on the internal stem structure and sap wood area is, therefore, important for the calculation of sap flux density or flow rates. This stem physical parameter cannot be measured directly from the stem surface, thus most studies have used destructive methods to get measurements involving cutting down the trees. Clearly, such an approach could only be applied at the end of an experiment. In this study, a slightly different approach was chosen making use of a biometric survey conducted to establish the physiological characteristics of the forest stand, as explained in Section 3.2. This information was further augmented by measurements of the internal stem structure and sap wood area of some of the trees that were being harvested by the KVTC as well as findings from previous studies.



Figure 3.8 KVTC Teak forest plantations in the Narubungo area, depicting high stand density (photo taken on 10th September 2008)

### 3.3.2 Biometric survey and upscaling to stand scale transpiration

The biometric survey was carried out in the Miombo and Teak forest plantations. Stem diameter at breast height (DBH) were measured with a diameter tape borrowed from the Forestry

Department of the Sokoine University. The sapwood areas and DBH of a representative sample trees were measured. For Teak, 75 trees from each age group were measured. For Miombo forest, a sample of 45 trees (30% of the population) with a DBH ranging between 10-15 cm and 45 ranging between 15 -20cm were selected. Five to seven trees for each one of the rest of the DBH classes were selected for the survey (cf. summarized data in Appendix 3.9.1 and 3.9.2). A relationship between sapwood area and DBH was established. The census data of DBH of all the trees within the surveyed plot is used to obtain the total stand sapwood area.

Tree crown height was measured by a hand-held clinometer borrowed from KVTC. The measured crown width was used to calculate the crown areas. Sapwood areas were calculated from sapwood depth determined through the extraction of wood cores by making use of an incremental borer (borrowed from the Forestry Department of Sokoine University), while observing the colour difference between the conducting and non-conducting tissues.

The Sapwood area, which is the fraction of the active conductive tissue in a tree, controls the transpiration quantity of a tree (see Equation 3.2). Lu *et al.* (2004) highlighted that errors in the quantification of transpiration rates of a tree stand mainly originate from the estimation of single tree sap flow, specifically, from the estimation of sapwood area, rather than the up-scaling methodologies. The accurate determination of the sapwood thickness of a tree is also important, as it determines the positioning of the sensor probes. In the event that the Granier probes penetrate beyond the sapwood into the heartwood, then the  $\Delta T$  values (cf. Equation 3.3) need to be corrected, as highlighted in Clearwater *et al.* (1999). If this is not taken into account, the original Granier calibration leads to underestimation of the sapflux density in ring-porous species such as Teak (Bush *et al.*, 2010). However, in the case of Teak, the sapwood depth was larger than the probe lengths used and, therefore, re-calibration was not necessary. Miombo trees, on the other hand, are diffuse-porous and, therefore, the standard Granier's assumption of thermal homogeneity and the calibration thereof becomes valid.

In this study, the upscaling of individual tree water use to stand level transpiration is done by selecting a measurable scalar that can easily be established and a relationship developed between the scalar and individual tree water use. The established relationship is then used to estimate the water use of the entire stand (Wullschleger *et al.*, 1998). Diameter at breast height (DBH) was selected as an easily measurable tree structural scalar quantity, to estimate the sap flux density for

all other trees in a stand that were not being monitored. Regression analysis was carried out to determine allometric equations, relating the measured diameter at breast height and the sapwood area for Teak and Miombo trees. This equation provides individual whole tree sap area depending on the DBH class. The total stand transpiration is computed by multiplying the total stand sapwood area by the average sap velocity of the trees measured. This approach has been applied successfully in other studies e.g. Vertessy *et al.* (1995), Wullschleger *et al.* (2001); Vertessy *et al.* (2005); Wullschleger and Hanson (2006); Zeppel *et al.* (2006); Zhang *et al.* (2008) and Lei *et al.* (2010). The same methodology was adopted in this study as well. Equation 3.4 shows the regression equation, relating sapwood area and Diameter at Breast Height (DBH) i.e.:

$$A_{sap} = B_o * DBH^{B^1} \quad (3.4)$$

Where  $B^o$  and  $B^1$  are a species specific coefficient determined through regression analysis,  $A_{sap}$  is sapwood area in  $cm^2$  and DBH is diameter at breast height (cm).

Leaf areas and crown area were not considered to be a good representative of the tree physiology, due to possible alterations from management practices (e.g. pruning in the Teak trees).

### 3.3.3 Maximum differential temperature ( $\Delta T_{max}$ ) determination and its implications

The Granier Equation for determining sap velocity requires the knowledge of maximum temperature difference between the two thermal dissipation probes (cf. Equation 3.1 and 3.3). In this study, as is the requirement of Granier method,  $\Delta T_{max}$  was thus determined separately for each pair of probes. The importance of the accurate determination of maximum differential temperatures has been emphasized by many scholars as it marks the time of zero sap flux. As discussed in Section 3.3.1, the Granier method (as well as some hydrological models) assumes that sap fluxes decrease to zero at night. This assumption has been found to introduce large errors in sap flux determination in the face of night-time sap flux occurrences which are then not factored into the calculations (Dawson *et al.*, 2007, Daley and Phillips, 2006, Regalado and Ritter, 2007). In this study, a careful observation of the sap flow trends in Miombo and Teak indicated the occurrence of night time fluxes and, hence, adjustments were made to the original

Granier approach to account for this flux dynamic. Thus,  $\Delta T_{max}$  was determined by assuming that the maximum differential temperature can occur at any time in a 24-hour period. This corrective approach has been applied successfully in recent studies by Oishi *et al.* (2008). Unique values of  $\Delta T_{max}$  were calculated for each set of probes, owing to its sensitivity to the thermal characteristic of the stem, as suggested by Clearwater *et al.* (1999) and Lu *et al.* (2004).  $\Delta T_{max}$  was analysed to check for trends and the possibility of external temperature interfering with the TDP signals. In principle, the Granier theory requires a stable and consistent  $\Delta T_{max}$  time series and any observed deviations are an indication of an anomaly in the instrumentation (Do and Rocheteau, 2002). Thus, following this principle, any probes that recorded unstable and inconsistent  $\Delta T_{max}$  were removed and re-installed afresh.

### 3.3.4 Stand level estimates of sapwood area

Allometric equations relating sapwood area and DBH were established separately for Miombo and Teak trees. A model after Vertessy *et al.* (1995), as elaborated in Equation 3.4, was successfully applied for Miombo and the following relationship was obtained, with an  $R^2 = 0.79$ .

$$A_{sap} = 7.015366 * DBH^{0.899882} \quad (3.5)$$

Miombo stand density and tree size distribution were adopted from a study undertaken by Dirninger (2004), and the total overstorey sapwood area per hectare was determined, as tabulated in Table 3.1. Field surveys revealed that the study site had Miombo trees of DBH ranging from 10 cm to 30 cm and few in the range of 40 cm to 45 cm.

Table 3.1 Stand sapwood area for Miombo

DBH	Average DBH (Appendix 3.9.1)	Area coverage (tree/ha)	Mean sapwood area pa tree in cm <sup>2</sup> (from equation 3.4)	Total sapwood area per ha (cm <sup>2</sup> ) pa class
10 - 15	12.50	31	68.10	2,111.1
15 - 20	17.80	26	93.60	2,433.6

20 – 25	22.43	< 26	115.25	2,996.5
25 – 30	27.15	25	136.86	3,421.5
30 – 35	32.45	25	160.68	4,017.0
35 – 40	38.90	25	189.15	4,728.8
40 – 45	43	25	207.00	5,175.0
<b>TOTAL</b>				<b>24, 883</b>

The total sapwood area in a hectare of Miombo forest was established to be 2,488 m<sup>2</sup>, with a stand density of 183 (stems.ha<sup>-1</sup>). These estimates may or may not be comparable to the findings from a study in the nearby Nyangaje Forest Reserve, which had a total basal area (i.e. a sum of heartwood, sapwood and bark area) of about 10.2 m<sup>2</sup> (Shirima *et al.*, 2011). This is due to the fact that their estimate is a total sum of heartwood, sapwood and bark area, while ours is strictly sapwood area only. Moreover, differences in the two estimates are anticipated due to the fact that the Nyangaje Forest Reserve has been protected since 1958 and is, thus, expected to have a much higher stand density and, therefore, higher basal area.

Using Equation 3.2, this study thus estimated the total sapflow per hectare for the Miombo forest as:

$$F_{ha} = 100 * V * A_{sap} \quad (3.6)$$

$$F_{ha} = 24883 * 10^2 * V \text{ (mm}^3 \cdot \text{s}^{-1} \cdot \text{ha)} \quad (3.7)$$

Where  $F_{ha}$  is total sap flow rate per hectare,  $A_{sap}$  is total sapwood area in an hectare (cm<sup>2</sup>) which is 24,883 (from Table 3.1),  $V$  is measured sap velocity (mm.s<sup>-1</sup>), 100 is the area conversion factor from cm<sup>2</sup> to mm<sup>2</sup>.

The range of tree diameters and ages existing at the site presented difficulties when generalizing Teak allometry in the whole stand as no suitable relationship could be found that explained the stand allometry. Therefore, groupings were established, based on age criteria, which presented a good relationship between the sapwood area and tree diameter (with an R<sup>2</sup> of 0.97) in older trees planted between 1993 and 1996, as indicated in Equation 3.8.:

$$A_{\text{Sap}} = 0.76944 * DBH^{1.5262} \quad (3.8)$$

A separate relationship (i.e. Equation 3.9) was developed for Teak trees planted in the year 2006 as this was the dominant group in the site area with a DBH of 13.7 cm (Appendix 3.9.2), as is indicated in Section 3.2 and Figure 3.1. The accuracy was in the order of  $R^2$  of 0.82

$$A_{\text{Sap}} = 3.247 * DBH^{1.281} \quad (3.9)$$

Similar Teak tree distributions and statistics were reported by Zyl (2004), who established that most of the Teak trees within KVTC plantations had a DBH ranging from 10-15 cm and very few were in the range of 15-20 cm. The study reported that the overall DBH was found to be 16.4 cm, with a mean height of 14.94 m for a sample of 100 Teak trees.

Tree sapwood area of 93.25 cm<sup>2</sup> (corresponding to DBH of 13.7 cm) was obtained from Equation 3.9 and the Teak stand sapwood area was obtained by making use of the teak tree density of 2500 trees per ha and subsequently applying Equation 3.9 i.e.:

$$A_{\text{Sap}} = 93.25 * 2500 = 233,126.6 \text{ cm}^2 \quad (3.10)$$

and the total Teak total sap flux rate in one hectare was subsequently computed, applying Equation 3.2 to obtain:

$$F_{\text{ha}} = 233,124.6 * 10^2 * V \quad (\text{mm}^3 \cdot \text{s}^{-1} \cdot \text{ha}) \quad (3.11)$$

NB: 1 lt. s<sup>-1</sup> ha<sup>-1</sup> = 8.640 mm day<sup>-1</sup>

### 3.3.5 Soil water potential and climate

Soil water potential along the soil profile in both the Miombo forest and the Teak plantation was monitored using Watermark sensors (Model 200 SS, Irrrometer Co. Riverside, CA) at depths of 30, 60, 90, 200 and 300 cm below the surface, from November 2008 to 2010. Each nest of Watermark sensors were linked to a 4 channel external HOBO data logger (Model U12-006,

OneSet Computer Corporation, Bourne, MA), which recorded and stored the soil moisture data and the latter was downloaded during each field visit.

A Davis Vantage Pro 2, with console automatic weather station (MC Systems, Steenberg, Cape Town) was installed at the Ichima experimental site where the main climatological parameters, including solar radiation, rainfall, humidity, air temperature wind speed and direction, were monitored at 15 minute intervals. The atmospheric water demand was represented by Vapour Pressure Deficit (VPD), which was computed using the equation after Goff and Gratch (1946) and cited by Lei *et al.* (2010) i.e.  $VPD = e^* \left(1 - \frac{RH}{100}\right)$  where  $e^* = \exp\left(\frac{17.27T_i}{T_i + 237.3}\right)$  where  $e^*$  is saturation air pressure (kPa),  $RH$  is relative humidity (%),  $T_i$  is air temperature ( $^{\circ}\text{C}$ ).

### 3.4 Results and Discussions

#### 3.4.1 Stand sapwood area

The power functions established through the regression analysis of DBH and the sapwood area indicated that the sapwood area increased with DBH and the relationship was age-specific for Teak trees. Equations 3.5, 3.8 and 3.9 gave satisfactory estimates of sapwood areas in Teak and Miombo. The stand sapwood area in one hectare of Teak was estimated to be 23.31 m<sup>2</sup>, while that of Miombo trees was only 2.49 m<sup>2</sup>, which is a remarkable difference in the volume of active conductive tissue in the two tree species. This was as a result of the difference in stand density, 2500 teak stems ha<sup>-1</sup> against 183 stems ha<sup>-1</sup>, and partly also due to the difference in their respective tree sapwood areas. It is obvious that, even if the sap flux density in the two forest types were the same, the total sap flow rate in a unit area would be much higher for Teak than Miombo owing to the differences in tree planting density (cf. Equation 3.7 and 3.11).

### 3.4.2 Evidence of night-time sap flux

Careful observations of the pattern of the differential temperatures data ( $\Delta T$ ), which is the signature recorded by thermal dissipation sensors, displayed consistent diurnal variation (Figures 3.9 and 3.10). This, as expected, indicates the role that the opening and closure of stomata plays in controlling the transpiration process in both Teak and Miombo forests. However, as was elaborated in Section 3.3.3, the information of the timing and occurrence of the maximum  $\Delta T$  is informative of the tree water use behaviour.

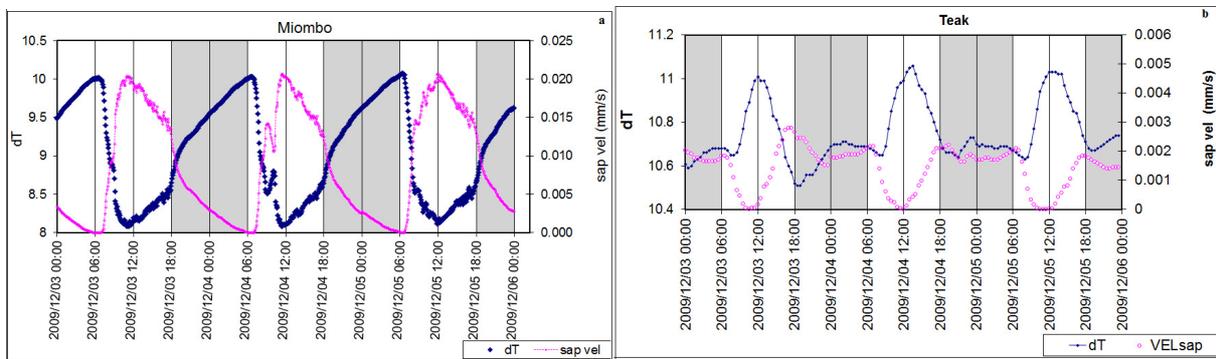


Figure 3.9 Diurnal course of TDP signal in Miombo and Teak following rainfall onset

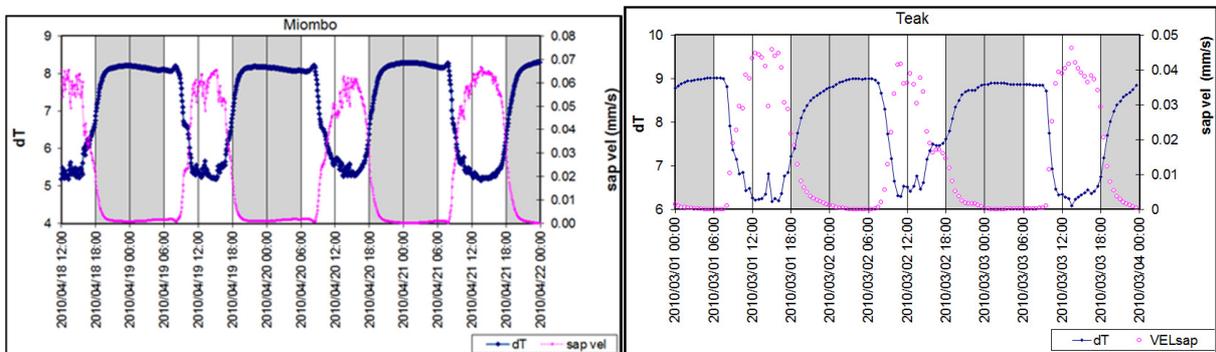
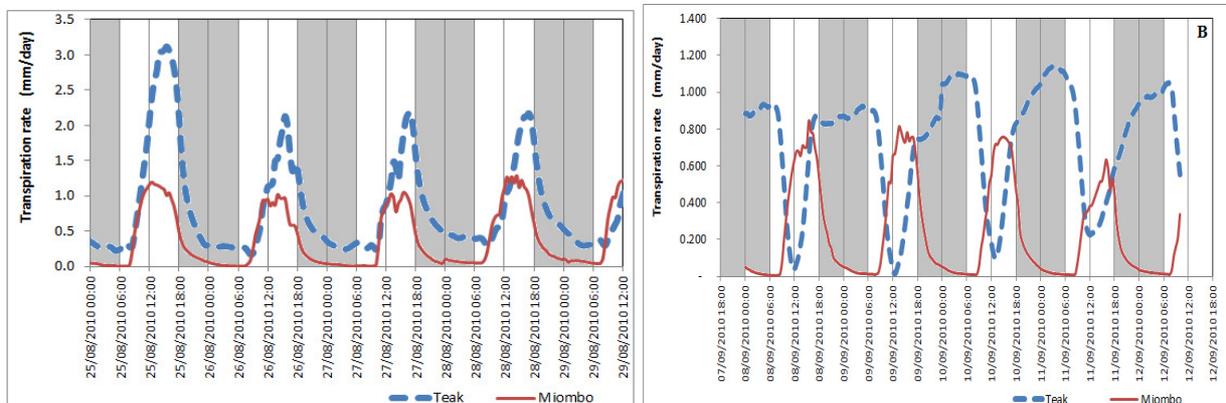


Figure 3.10 Daily course of TDP signals in Miombo and Teak in the wet period

Figure 3.9 depicts sample days of the characteristic diurnal  $\Delta T$  pattern observed immediately after rainfall onset in both Teak and Miombo forests. Contrary to normal expectations, where nocturnal transpiration is expected to be zero, during this period maximum  $\Delta T$  (a point of zero flux) was always observed after 0600 hrs. in Miombo and between 1000 and 1200 hrs. in Teak,

indicating that the sap flow velocity dropped to zero during this time (i.e. daytime zero flux) and therefore transpiration was non-zero during the night. The diurnal  $\Delta T$  pattern changed to flatter and broader  $\Delta T$  peaks in both Teak and Miombo forests during the rainfall season, as indicated in Figure 3.10, spanning the period between 2030 hrs and 0700 hrs everyday, thus eliminating the possibility of night-time fluxes. Sap flow velocity, on the other hand, was at maximum in the day and remained stable throughout the daytime (1100 - 1600 hrs), completely ceasing at night during the rainy season.

The evidence of night-time sap flux was observed in the Teak diurnal  $\Delta T$  cycle immediately following the rainfall onset, as Figure 3.9b depicts, and disappeared in the course of the rainfall season (December – April). Notably, Teak was also actively transpiring during the night, while transpiration fell to zero during the day-time for some days in the month of September (Figure 3.11b). During this time (September), not only was Teak experiencing transpiration decay, most probably as a result of the on-going shedding of its leaves, but it was also a time of maximum atmospheric water demand (Appendix 3.9.4).



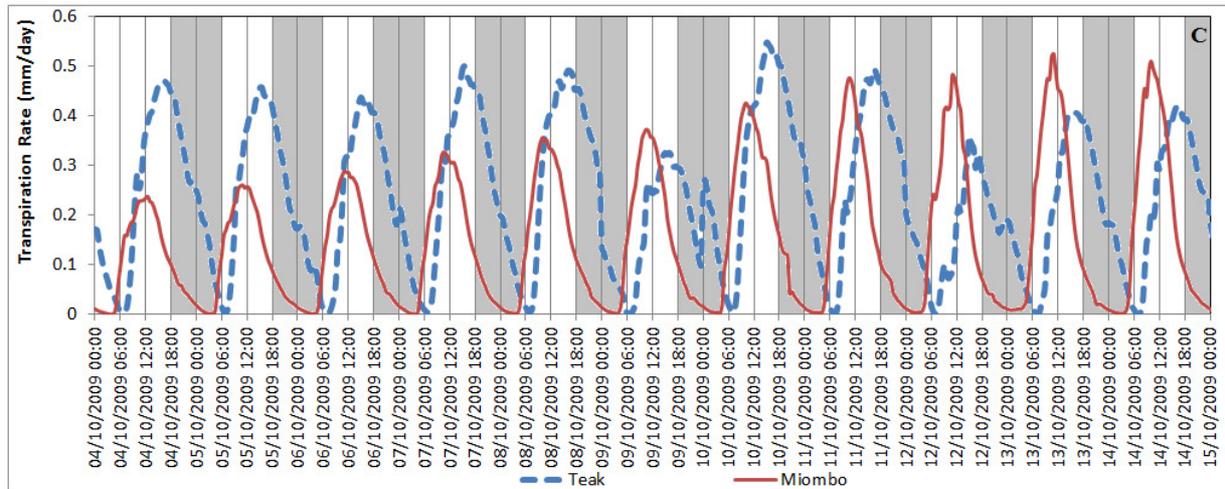


Figure 3.11 Characteristic diel-cycle of transpiration during the dry season (a) August (b) September (c) October in Teak and Miombo.

### 3.4.3 Variability in sap flux density as a basis for comparison of forest water use

A comparison was made between the variability of sap flux density of the native Miombo woodland and Teak plantation forest. The Teak forests were composed of different tree sizes and ages under careful management of KVTC. Sap flow velocity was chosen as one of the variables for comparing transpiration rates, and hence water use potential of the two forest stands as it is not affected by tree size or other biometric parameters. Sap flow velocity represents tree-specific xylem capacity to transfer root water to the canopy. Past studies such as Zeppel *et al.* (2006); Zhang *et al.* (2008); Lei *et al.* (2010) have established that tree structural parameters like stem diameter, crown area, leaf area or age of a tree highly influence the total sap flow quantities in a tree. For example, the xylem sap velocity presented in Figure 3.12 shows the transpiration rate per unit of conductive sapwood area for each forest type. This, therefore, represents results that have not yet been upscaled to whole-tree level.

It can be seen from Figure 3.12 that, with the exception of the dry period where Miombo shows a continued tendency to transpire, the sap velocity for Miombo and Teak appears to be more or less the same throughout the year. Both forest stands indicate a unimodal nature in their annual sap flux density response (cf. Figure 3.12), where minimum velocities occur in the dry season

(September) and increase gradually, attaining the maximum fluxes for Teak during the peak rainfall season (March-April). The Miombo attains the maximum flux rates after the rainfall season. Specifically, the maximum sap flow velocity for the Teak trees was recorded during the rainfall season between 26<sup>th</sup> to 29<sup>th</sup> March (cf. Figure 3.12) with a value of 0.06 mm/s. The maximum value for Miombo trees was recorded in July, with values ranging between 0.11 to 0.13 mm/s. Minimum sap flow velocity for Teak was observed during the dry season in September (cf. Figure 3.13), with a value of 0.003 mm.s<sup>-1</sup>, while the corresponding value for Miombo trees was between 0.01 – 0.025 mm.s<sup>-1</sup>.

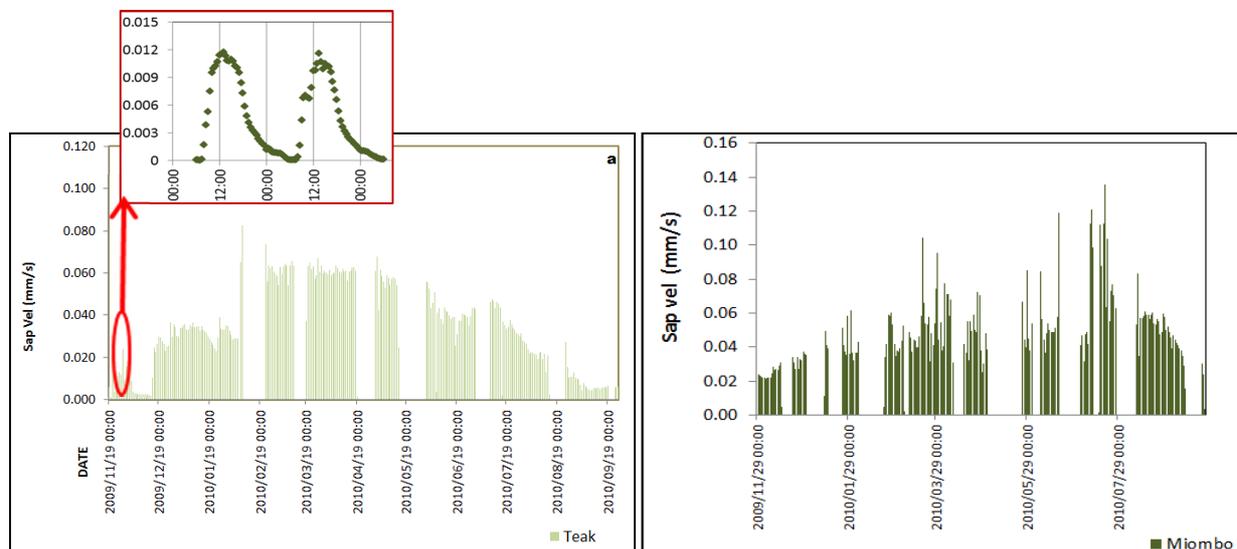


Figure 3.12 Seasonal variations in sap flow velocity of (a) Teak (b) Miombo (data gaps are due to equipment breakdown or power outages). Note that the Y-axes are not of the same scale due a large difference of the values presented.

The sap flow velocity characteristics established here are specific to Miombo and Teak forests and are independent of the tree structural parameters and forest stand structure. They can, therefore, serve as a guide to estimates of water use by other Teak or Miombo forest stands under similar climatic and soil conditions given the sapwood area and forest stand structure.

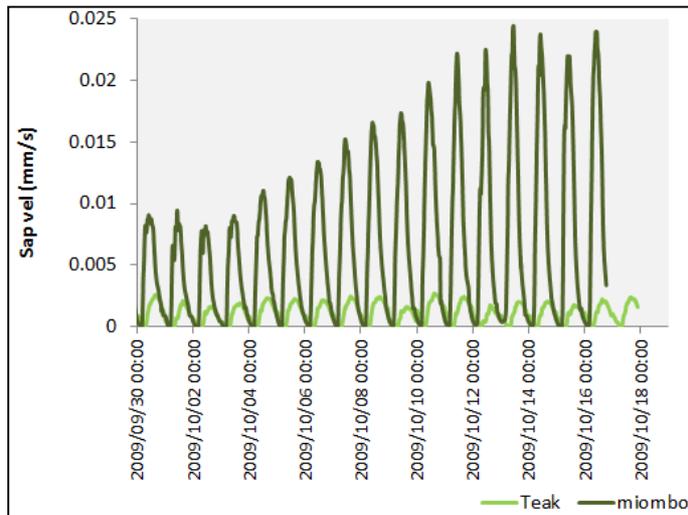


Figure 3.13 Comparison of dry season xylem sap velocity in Miombo and Teak (maximum water stress period)

Figure 3.13 depicts the sap flow velocities for both Teak and Miombo trees during the dry season period, three months after the rains stopped. As the figure shows, at the onset of transpiration for the Miombo trees, the Teak trees were still in the dormancy state of transpiration. At this particular time, the Teak trees had completely shed their leaves, while the Miombo trees had already started leaf growth by mid-October, even though the rainfall had not started. This indicates that their adaptation mechanism was different from that of Teak trees, a behaviour that has been observed in a number of studies conducted on Miombo, such as Frost (1996) and Ryan and Williams (2011), where pre-rain leafing was noted. Likewise, pre-leafing of up to 4-8 weeks before the first spring rains was observed in Zimbabwean Miombo woodlands (Chidumayo and Frost, 1996). Teak sap flux was triggered by the first rainfall event of November 14<sup>th</sup> 2009. It is important to note that the two forest stands were under the same climatic conditions and were subsequently subjected to similar atmospheric demands. The difference in the observed response (Figure 3.12 and 3.13) is, therefore, mainly attributed to either the tree-specific physiological controls or soil water limitations. However, the difference in the transpiration potential suggests that there could still be adequate reserves of soil moisture under the Miombo (even at this time when maximum water stress conditions are expected), enough to support the observed rates, while Teak trees were almost dormant in growth, with a sap flow velocity of  $0.003 \text{ mm}\cdot\text{s}^{-1}$ . On

the other hand, Miombo roots may have access to deeper soil moisture reserves, depending on their architecture. This will be further assessed in detail in Chapter 4 below, which focuses on soil water dynamics of the forest stands

#### **3.4.4 Total stand transpiration fluxes**

Tree stand transpiration, as presented in this study, is in mm per day of consumptive water used in the Miombo and the Teak forests. Data gaps represent times when the equipment was not operational, either due to power failure or technical reasons. It should be noted that tree to tree variability in canopy transpiration has been addressed through the inclusion of the spatial variability in DBH and sap wood areas, determined by biometric survey conducted. The total transpiration (water use) in both forests followed the diurnal pattern of sap velocity discussed in Section 3.4.2, where maximum transpiration was observed during the day whilst reducing to a minimum at night or pre-dawn most of the time (Figures 3.25 and 3.27).

The comparison between the consumptive water use of Miombo and Teak forest indicates that Teak forests have a much higher transpiration (sap flow) rate throughout the year, apart from when Teak is dormant, compared to Miombo forests (Figure 3.14). Differences of more than 100-fold were recorded during the rainfall season. Generally, stand transpiration is higher during the wet season than the dry season for both Teak and Miombo. It should be noted that the substantial variance observed between the water use in Teak and Miombo is attributed to the large differences in the respective stand sapwood areas ( $A_{sap}$ ), as discussed in Section 3.3.4 and 3.4.1.

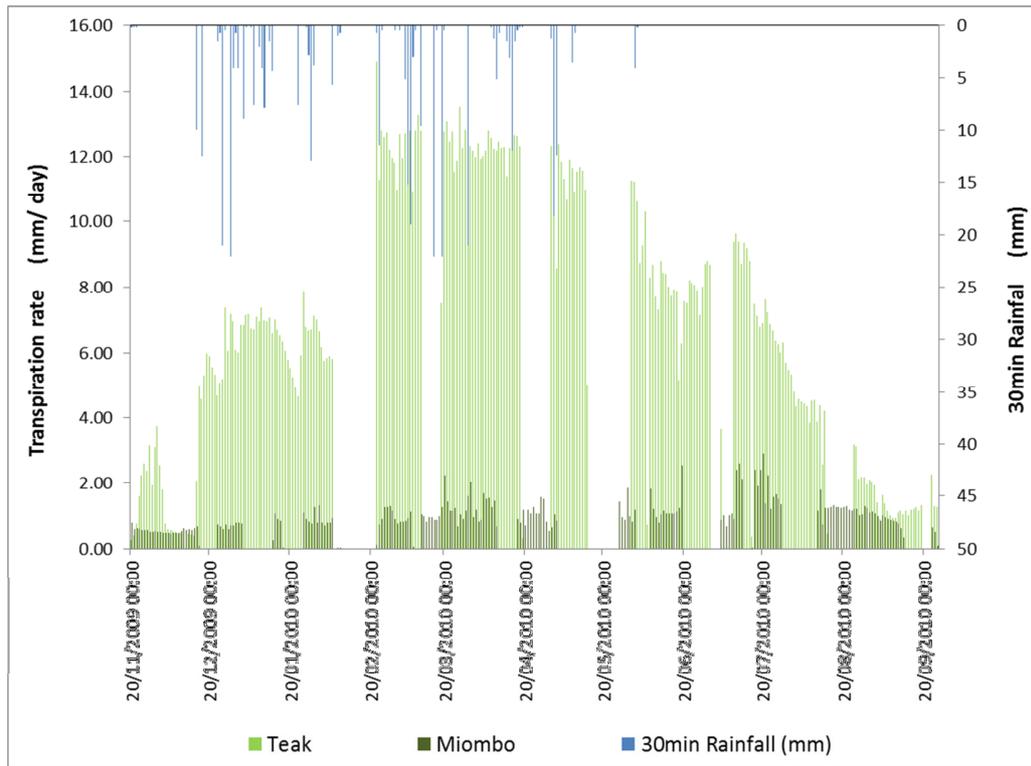


Figure 3.14 Comparison of transpiration rate in Miombo and Teak forests

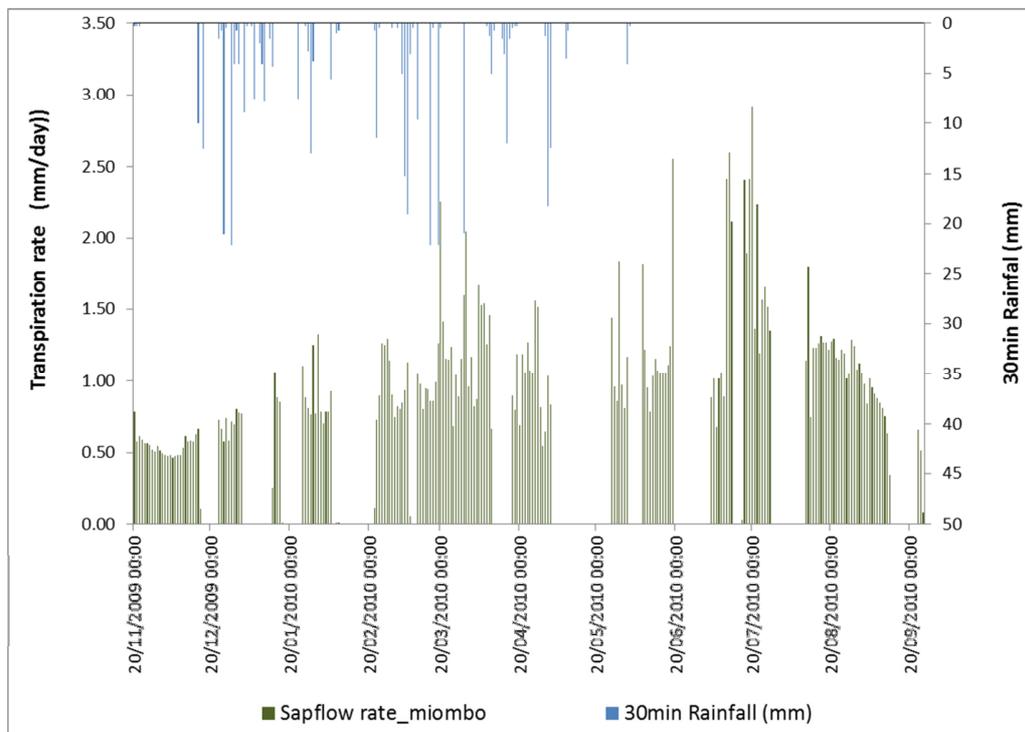


Figure 3.15 Seasonal pattern of transpiration rate in Miombo trees

Annual patterns the transpiration rates show unimodal behaviour for both forest stands. Maximum stand transpiration for Teak forests (about  $12 \text{ mm.day}^{-1}$ ) occurs in the months of February-April (Figure 3.14) , while the maximum transpiration rates of Miombo occur in July, with rates ranging between 2.3 to  $2.8 \text{ mm.day}^{-1}$  (Figure 3.15). Miombo forest transpiration gradually decreases late into the dry season due to its briefly deciduous nature, while a faster and immediate transpiration reduction is observed in Teak forests at the onset of the dry season.

It is obvious that transpiration (total sapflow) rates in Miombo trees did not entirely follow the rainfall pattern (Figure 3.15), since the transpiration rates kept on increasing even after the rainfall cessation. An increase in transpiration after the cessation of rainfall can only be triggered by an unmet, increasing atmospheric water demand (Appendix 3.9.4) resulting from the on-going depletion of the soil water reserves after rainfall cessation. The annual pattern of atmospheric water demand (Appendix 3.9.4) shows a systematic increase and reaching a maximum in October. Such behaviour as exhibited by the Miombo suggests a rooting system that is either tapping supplies of soil water deep in the soil profile during the dry season or has adapted to the prevailing soil water conditions over time. It may also imply that Miombo are more conservative in their water use allowing available soil water supplies to support growth even during dry periods.

### 3.4.5 Stand transpiration response to rainfall

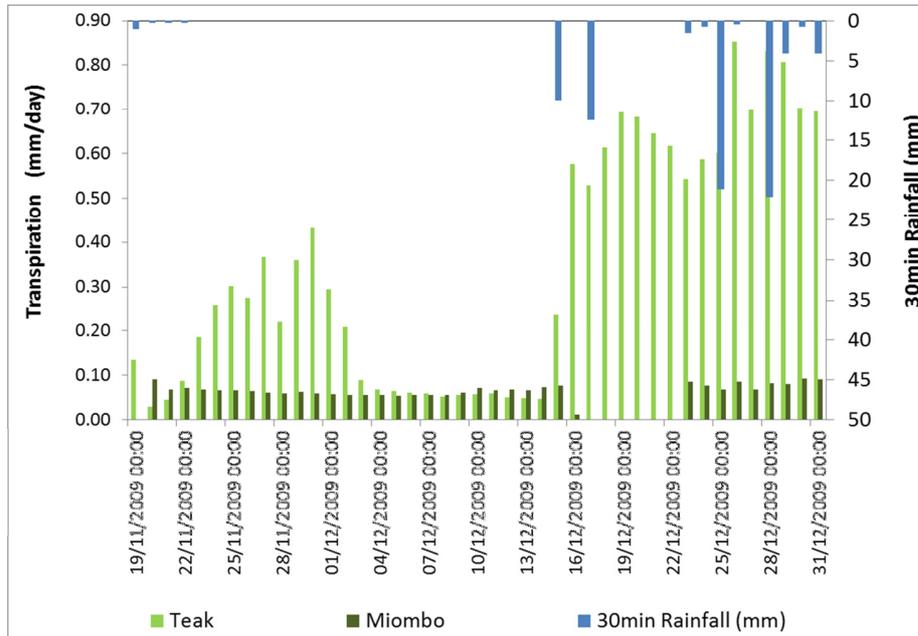


Figure 3.16 Stand transpiration response to the rainfall onset

Clearly, the availability of rainfall influenced the onset of Teak transpiration (Figure 3.16) and its cessation triggered the commencement of a decrease in Teak transpiration (cf. Figure 3.14). Teak shows greater sensitivity to the rainfall pattern than Miombo with transpiration decreasing immediately after rainfall cessation, regardless of the increasing evaporative demand (Appendix 3.9.4). A response which indicates that the physiological control of transpiration in Teak trees is much stronger than the climatic control as well as indicating strong stomatal control.

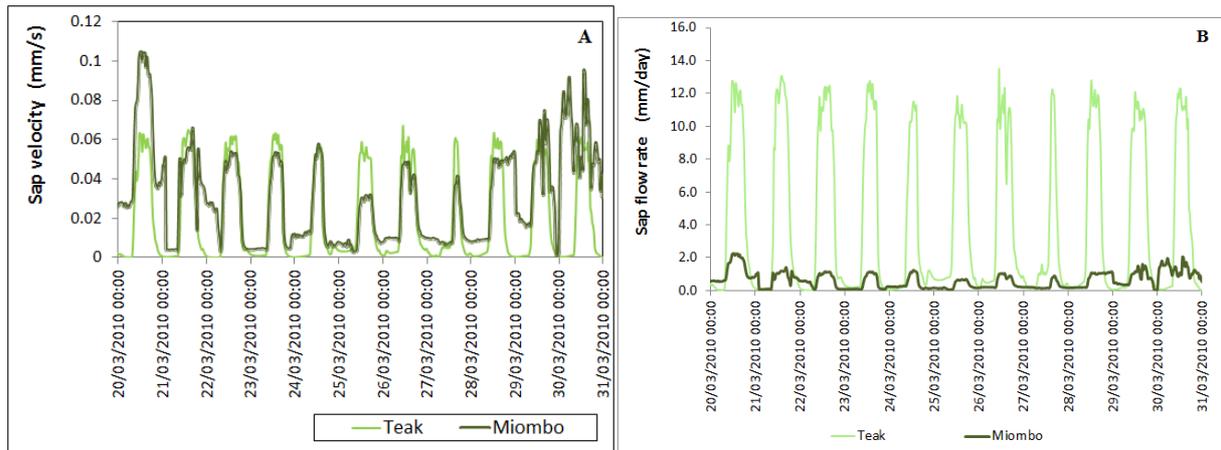


Figure 3.17 Comparison of (a) sap velocities and (b) sap flow rates (transpiration) in Miombo and Teak during peak rainfall season

During the rainfall season, when the soil conditions are not limiting, Teak trees had a stable flux pattern (Figure 3.17) and transpired at a maximum rate of about  $13 \text{ mm}\cdot\text{day}^{-1}$  (during the day). Teak trees continued to transpire at this maximum rate throughout the peak rainfall season (February–April), regardless of the changing atmospheric water demand exerted on them. Miombo trees, on the other hand, did not show much of a change during the rainy season, except for short periods of high transpiration rates lasting for the duration of or until after the rainfall event. This explains the spikes observed (quick response) after the rains started (Figure 3.17).

Evidently, the controlling transpiration mechanisms between the two forests differ. While Teak transpiration is significantly lowered following the reduction of soil moisture replenishment, a characteristic of forests with very high transpiration rates (Roberts, 2007), Miombo transpiration is not affected, indicating that soil moisture is not a significant limitation to transpiration in Miombo. Miombo water use appears to be more meteorologically demand-driven, though the tree physiological controls become effective towards the end of dry season when evaporative demand is at its peak. At this point, namely the month of September, Miombo starts to lose its leaves and its water use is reduced.

### 3.4.6 Soil moisture control on tree transpiration

The dependency of transpiration rates on soil water conditions was analysed, using the soil water potential measurements in both forest stand soils. A period of transition from the dry to the wet season (see Figure 3.18), highlights the impact of the soil water conditions on transpiration rates for both Miombo and Teak trees. There is a clear indication that Teak transpiration rates are sensitive to soil water potential. The two parameters have a more or less inverse relationship, where a decrease in soil water potential leads to higher transpiration rates (cf. Figure 3.18 after rains started on 15<sup>th</sup> December 2009). However, the Miombo forest transpiration rates showed more stability during high soil water potential. This observation is in line with other findings such as those of Roberts (2007) who found that old forests do not significantly get affected by a reduction in soil moisture levels. This may be due to the Miombo's adaptation to dry spells noted earlier.

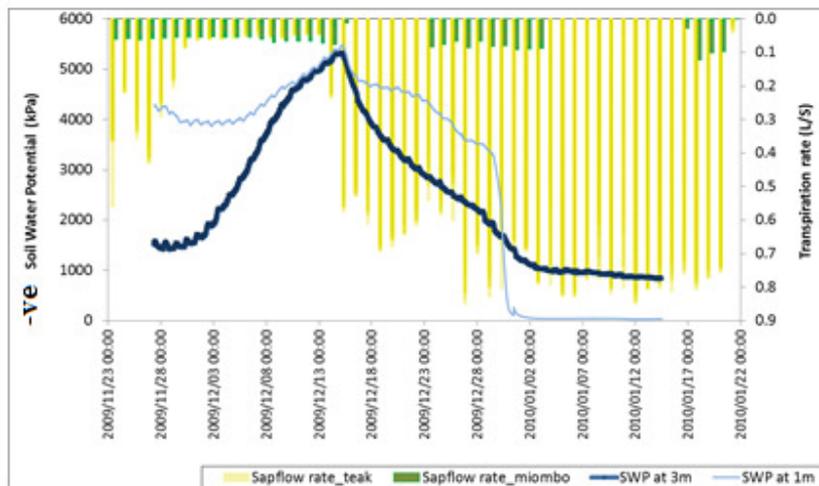


Figure 3.18 Teak tree transpiration response to soil water potential variations (dry to wet season transition)

Further analysis indicated that, almost throughout the year, the soils in the Teak forest site were drier than the soils at the Miombo forest site, as indicated in Figure 3.19. Towards the end of the dry season, soils in the Teak forest site had significantly dried all the way to 3 m (i.e. our deepest point of monitoring), with soil water potential values of reaching 4.5 MPa (Figure 3.19a);

whereas soils at a 3 m depth in Miombo, had potential values of 0.1 MPa at about the same time (Figure 3.19b). Consequently, growth could not be sustained due to limited soil water supplies and by mid-October, Teak had shed all its leaves. The rooting architecture of the Teak and Miombo forest stands, and the link to root water extraction, is thoroughly elaborated on in the paper to follow in Chapter 4.

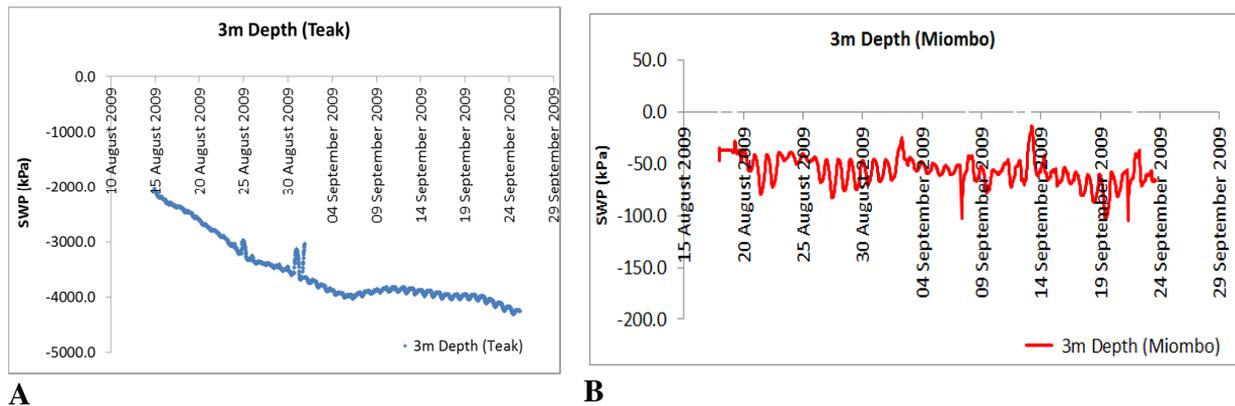


Figure 3.19 A comparison of soil potential values at a 3 m depth under Miombo and Teak forest (the Y-axes differ in scale due a large difference of the values presented)

### 3.5 Environmental Control of Forest Canopy Transpiration

The role of climatic variables, as drivers of transpiration, was assessed through a correlation analysis of sap flux density and vapour pressure deficit (VPD), air temperature (T), relative humidity (Rh) and solar radiation (SR). Table 3.2 summarises the analysis results which show that the meteorological variables tested significantly correlated with the sap flux density.

Table 3.2 Correlation analysis between climatic variables and transpiration fluxes

	VPD	T	SR	Dew Temp.	Humidity
Correlation coefficient Teak	0.836	0.811	0.874	0.797	-0.803
Correlation coefficient Miombo	0.813	0.756	0.792	0.674	-0.706

With the exception of solar radiation, all other variables presented in Table 3.2 were used to derive VPD, as elaborated on in Section 3.3.6. A detailed analysis of the relationship between sap velocities with VPD and solar radiation in Miombo and Teak forests is presented below.

### 3.5.1 Sap velocities and vapour pressure deficit (VPD)

The relationship between the sap flow velocity (Sapvel) and VPD showed a strong diurnal pattern (Figure 3.20), whereby highest values were observed during the day, with peak sap velocity being observed between 1100-1200 hrs and peak VPD at around 1600hrs.

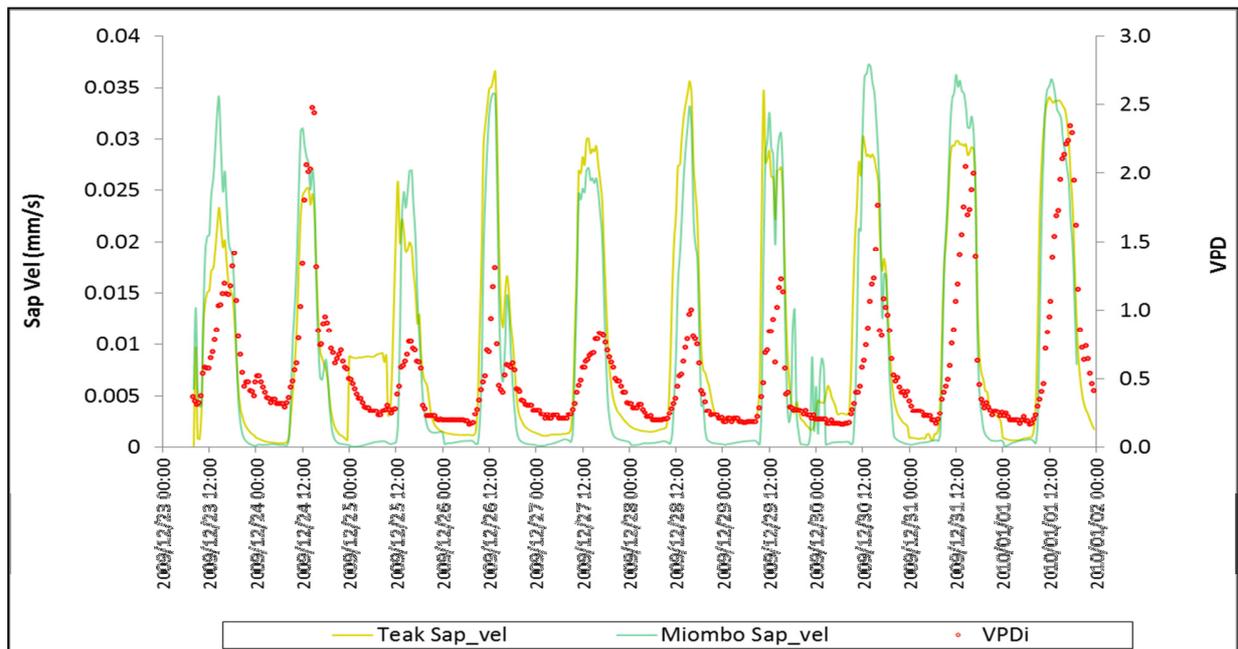


Figure 3.20 Response of sapflow velocity to climatic forcing

VPD was found to have a strong relationship with sap flow velocity in both Teak and Miombo forests. The least square regression analysis carried out in GraphPad Prism (GraphPad Software, Inc. La Jolee, CA) gave the following functional relationships:

i) Teak

$$Sap_{vel} = -0.00996 + 0.05704 * VPD - 0.01705 * VPD^2$$

with an  $R^2$  of 0.97 and sum squares of errors being 0.00007578

ii) Miombo

$$Sap_{vel} = -0.007605 + 0.044 * VPD - 0.01238 * VPD^2$$

with an  $R^2$  of 0.96 and sum squares of errors being 0.00006529

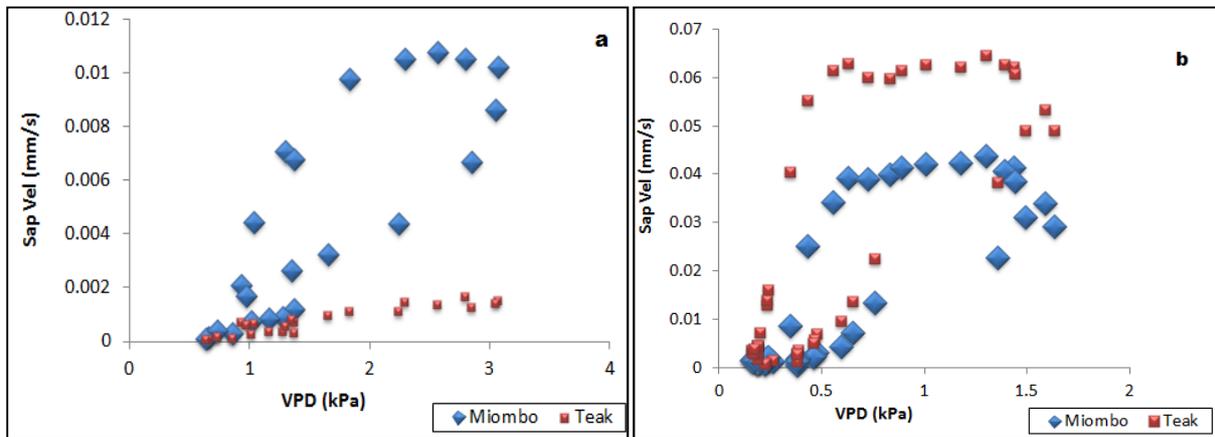


Figure 3.21 Diurnal pattern of hysteresis in Teak and Miombo in (a) dry (b) wet season

Further analysis of the diurnal pattern of relationship between vapour pressure deficit and sap velocity showed hysteresis behaviour (Figure 3.21), both during the dry and the wet season. This was because, for a given VPD, there were higher fluxes in the morning hours than in the evening hours. Similar observations have been reported in a number of studies, including Komatsu *et al.* (2010); Komatsu *et al.* (2006); Kostner *et al.* (2002); Grady *et al.* (1999) and Franks *et al.* (1997). Long-term analysis of the relationship between transpiration and VPD, completed by grouping VPD values at 0.1 intervals, confirmed the role of the physiological regulation of trees on the transpiration process, as indicated in Figure 3.22. A linear relationship is observed at low VPD values, while as VPD increases beyond 1.5kPa, transpiration fluxes seem to have reached a limit (levelled-off). This behaviour is attributed to partial stomatal closure.

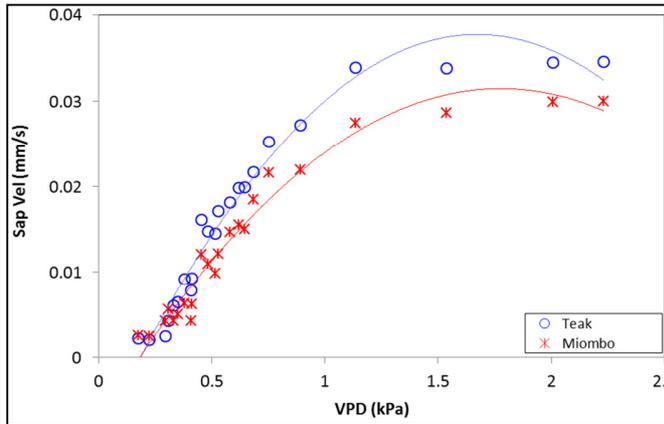


Figure 3.22 The relationship between VPD and sap flow per unit sapwood area (sapflow density)

### 3.5.2 Sap velocities and solar radiation

The environmental control on stand-forest transpiration rates was also analysed, based on the relationship between sap velocity and solar radiation (SR). The evident diurnal pattern in both SR and sap flow velocities (Figure 3.23) may be caused by different factors, such as the stomatal control of transpiration.

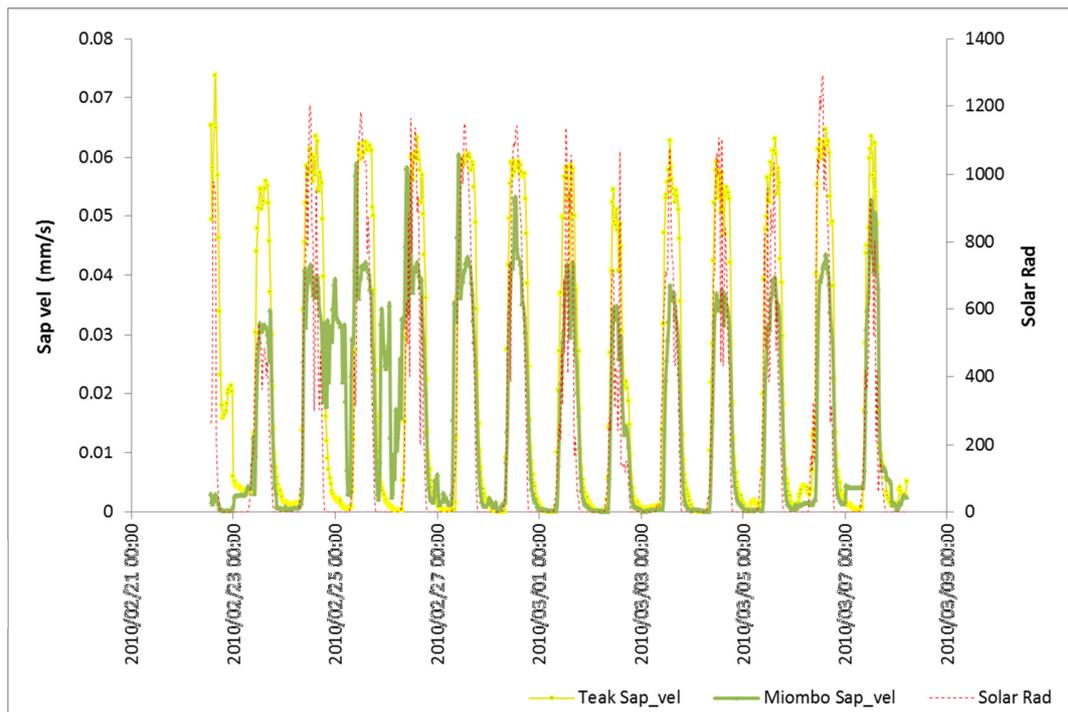


Figure 3.23 Diurnal pattern of solar radiation and sap velocity in Miombo and Teak

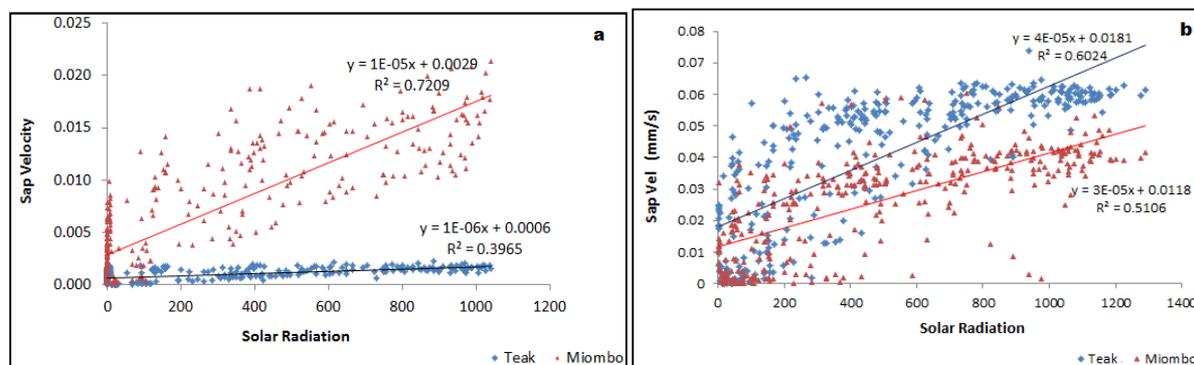


Figure 3.24 Relationship between solar radiation and sap flux density in (a) dry season (b) wet season

As Figure 3.24 shows, there is no significant and consistent relationship between transpiration and solar radiation in both dry and wet seasons in the Teak forest. However, the Miombo forest has a relatively consistent relationship compared to the Teak forest, with a better linear relationship during the dry season ( $R^2 = 0.72$ ). The Miombo-SR linear relationship is relatively

weaker during the wet season, with an  $R^2$  of 0.51. Reflecting on the above analysis, it can be concluded that VPD is a better variable for relating transpiration fluxes in both Miombo and Teak forests as compared to solar radiation.

### **3.6 Hydrologic Implication of Forest Conversion from Native Miombo to Exotic Teak**

The major concern regarding the replacement of native forest with the exotic species is the differences in their consumptive water use and their probable impact on water resources. This experimental study has established the validity of such concerns, where Teak and Miombo forests have shown a large difference in the quantity and timing of their consumptive water use. While Miombo forests have been shown to have more or less stable transpiration fluxes throughout the year, the transpiration fluxes in Teak forests are very high, but of shorter duration, which is likely to translate into water balance alterations in a catchment, or at least on a plot scale.

Quantification of maximum conductance rates indicates that the Teak forest stand's total transpiration (consumptive water use) occurred in the months of March and April, totalling 250.5 mm (about 125 mm per month), while in these months, Miombo had a total consumptive water use of only 23.6 mm. Contrary to the expectations, Miombo peak transpiration was during the months of June and July (dry season), with a total water consumption of 28.78 mm (i.e. 12.34 and 16.43mm, respectively). Due to the diurnal fluctuation in transpiration, the highest rate of water use in both Miombo and Teak forests occurs between 1200 hrs and 1800 hrs as indicated in Figure 3.25. With such relatively large transpiration rates from Teak forests, and given the fact that literature suggests 20% of all incoming rainfall is lost as canopy interception in these forests, the total evapotranspiration component of the water balance in Teak forests would increase more than in Miombo forests (expected to have less interception storage due to a smaller LAI). The hydrologic implication of converting the native Miombo forests to the exotic Teak forests points to a shift in the partitioning of rainfall (i.e. runoff, ET and deep water recharge) in the water balance, with the possibility of a reduction in deep water drainage beneath the Miombo resulting in reduced groundwater and subsequent reduced low flows.

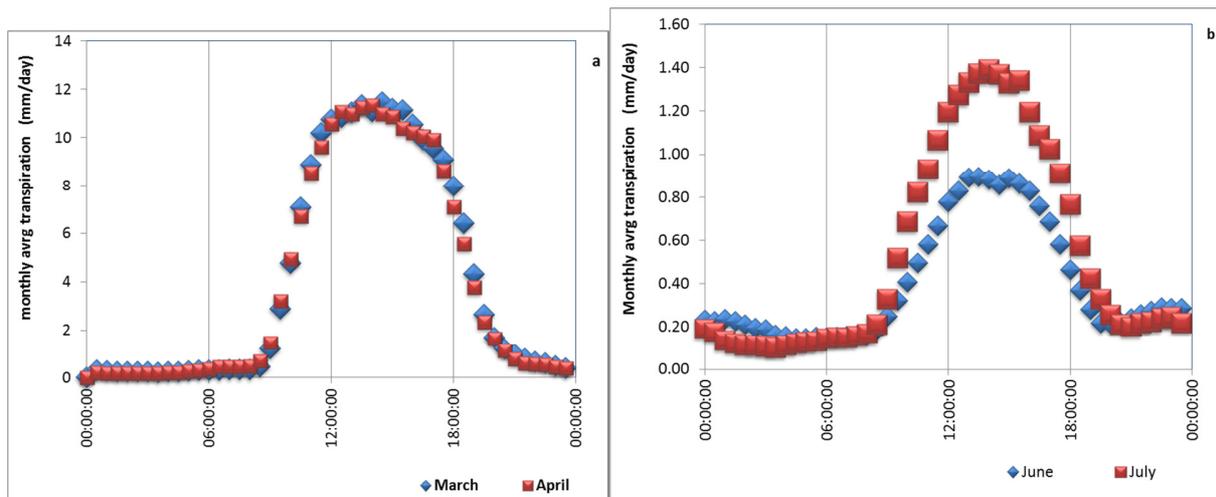


Figure 3.25 Maximum observed total transpiration (a) Teak (b) Miombo forest stand

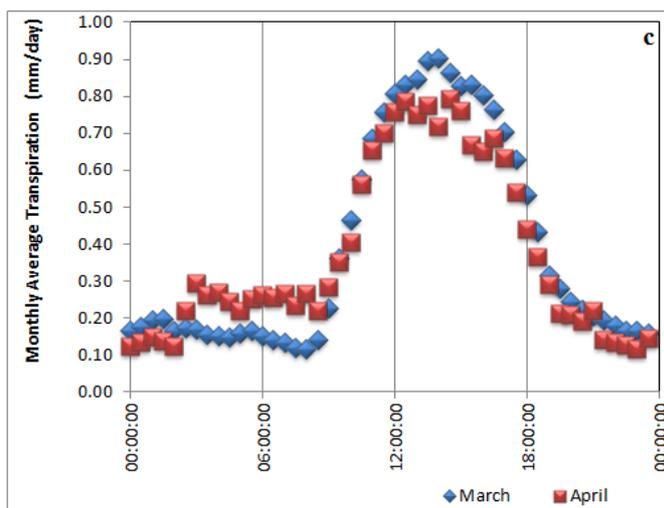


Figure 3.25c Peak wet season Miombo forest stand water use

Particularly important to water resource management is dry season transpiration (consumptive water use by the respective forests) as it has a direct impact on the hydrological cycle in general through the exploitation of deeper soil water reserves/deep ground water at a time when there is no replenishment (rainfall). Figure 3.26 summarises the dry season total transpiration losses from one hectare of Teak and Miombo forests in the experimental site.

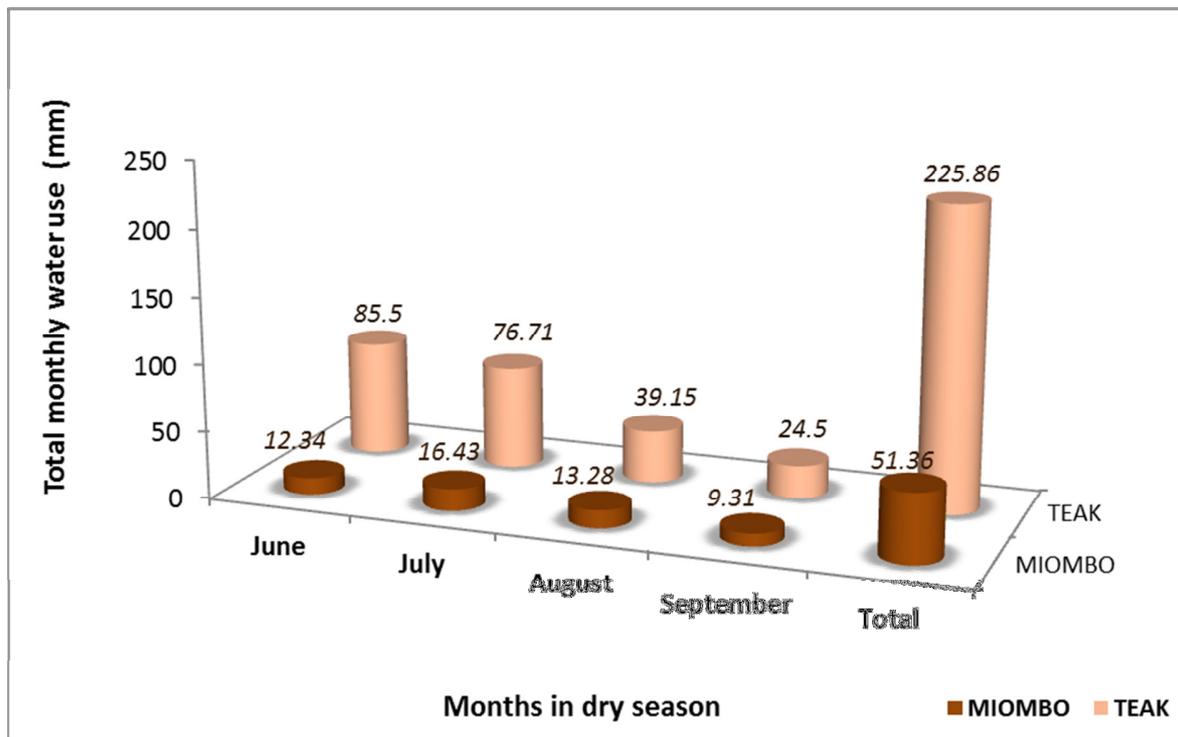


Figure 3.26 Dry season monthly total water use

The Teak forest stand shows a gradual decrease in the consumptive water use over the course of the dry season (June – September), as indicated in Figures 3.26 and 3.27, even though the total annual amount of forest stand water use was much higher compared to that of Miombo. However, the Miombo forest was found to have a higher transpiration rate during the dry season than the wet season in response to a higher evaporative demand, as indicated in Figure 3.27. This phenomenon has been observed in a number of natural forest ecosystems, as reported in Panama by Meinzer *et al.* (1999), who attributed the dry season transpiration to the rooting ability of the trees to extract deeper soil water. It should be noted, however, that this conclusion is limited to only one year of data.

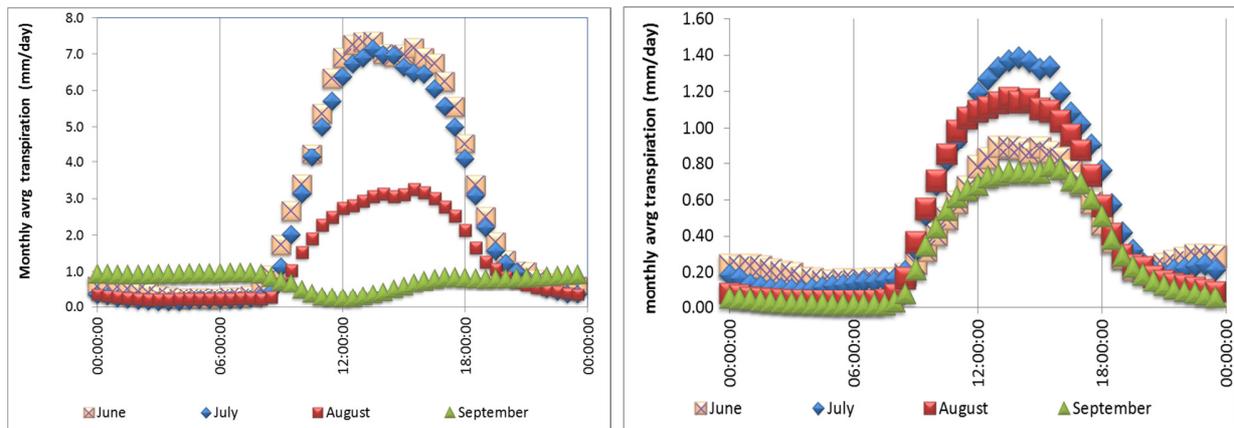


Figure 3.27 Diel-cycle of dry season monthly water use in (a) Teak (b) Miombo forest stand

Another important observation made in this study on the possible hydrological impact of the Teak forests, is their location within the catchment. Figure 3.1 shows that the forests are located just downstream of the Matundu Forest Reserve (part of the Udzungwa Mountain Forest), where the Ruipa and Idete Rivers originate. Downstream of these plantations, and at a lower elevation, are the headwaters for Doko and Kilwilwi (seasonal Rivers), while the Narubungo and Namwawala Rivers drain through these plantations. All these rivers and streams discharge into the Kilombero Valley floodplains. It is likely, therefore, that these forests are located on ground water recharge areas of the catchment since the location of headwaters is normally associated with the location of high recharge zones (Haigha *et al.*, 2004). Unfortunately, all of these rivers are ungauged, yet they provide an important source of water for the community's domestic water supply, agricultural use and fishing, an aspect which will be assessed further through hydrological modelling.

### 3.7 Conclusion and Recommendations

Generally, the monitored transpiration rates indicated both diurnal and seasonal variations. The tree physiological controls are responsible for the diurnal patterns observed from the study side,

while seasonal transpiration patterns followed soil moisture availability (especially in Teak) and/or environmental forcing, which was more evident in Miombo forests.

The Teak plantations, owing to their high stand density, were found to transpire at an average daily value of about  $12 \text{ mm}\cdot\text{day}^{-1}$  during the non-limiting soil moisture conditions, while Miombo was using about  $1 \text{ mm}\cdot\text{day}^{-1}$  during this same time. However, there was not much of a difference in the sap flow velocity between the two forest types, with velocities of about  $0.1 \text{ mm}\cdot\text{s}^{-1}$ , clearly indicating that the remarkably high stand transpiration variance between the two originates from differing stand structure and individual tree structural parameters. It is established here that total stand transpiration is strongly influenced by forest structure (in addition to tree size) which, for plantation forest (like Teak), is highly dependent on management strategies, while a natural forest ecosystem (like the Miombo woodland) depends on natural patterns and influences, such as fires, but more importantly on the level of fragmentation or human exploitation.

It should be noted that both the Teak and the Miombo forests, at a certain time, experience nocturnal transpiration, though this needs further and more thorough investigation, probably through tracer studies monitoring root water uptake in connection with this night-time flow. This study recommends further research on the canopy and litter interception of the two forests for a conclusive analysis of the hydrological impacts of the conversion, since canopy interception can be as high as 45% of incoming rainfall, while litter interception can be as much as 12% (Bulcock and Jewitt, 2010).

Interestingly, the maximum transpiration potential of Miombo is expressed during periods of maximum atmospheric demand i.e. during the dry season months of June and July, implying that even at this time, there was still enough available soil water to cater for the increasing atmospheric water deficit. Miombo transpiration, therefore, is more atmospheric demand driven than soil water supply limited.

This study demonstrates the impacts of converting native forests to exotic forests, providing quantitative estimates of transpiration water uses throughout the year. It is evident that management decisions on the forest structure cannot be ignored with regard to water resource management. Moreover, sap flow velocity is species-specific and is regarded, here, as a stronger basis for the comparison of consumptive water use potential among forest stands, than sap flow

rate which is dependent on the forest stand structure. This study, therefore, recommends its use for future comparative studies on tree water use and also for the results to be easily transferable to other similar catchments.

Furthermore, based on the results, it is possible that the conversion of the native Miombo forest to Teak forest plantations in this area is likely to impact negatively on the baseflow component and the groundwater recharge during the rainfall season because of the high transpiration and interception losses of teak forests. Likewise, the observed high dry season transpiration losses may cause a reduction in the dry season flows.

Tanzania has never considered forestry as a water user, nor is it considered as an activity that can impact on water resources in catchments. This study has demonstrated, through field monitoring, that trees have the potential to become significant water users. Such potential places importance on the need for Basin Water Offices to consider the issuing of water rights to forest plantations, currently being established all over Tanzania, at the expense of the already highly adaptive native forests community. Practical advice to water basin management authorities is to become involved in the establishment phase of such undertakings and to advise the local and private initiatives accordingly.

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### 3.9 Appendix

#### Appendix 3.9.1 Biometric survey field data (Ichima)

NATIVE MIOMBO TREES BIOMETRIC CHARACTERISTICS			
	MEAN	MINIMUM	MAXIMUM
<b>DBH range '10 - 15'</b>			
DBH (cm)	12.2	11.1	14.6
Crown Diameter (cm)	294.64	185	400
Crown Depth (cm)	3.6	2.3	4.7
Sapwood area (cm <sup>2</sup> )	58.60	48.96	79.12
<b>DBH range '15 - 20'</b>			
DBH (cm)	17.18	15.9	18.5
Crown Diameter (cm)	699.4	330	890
Crown Depth (cm)	6.12	4.7	9.5

Sapwood area (cm <sup>2</sup> )	84.64	74.85	92.93
<b>DBH range '20 - 25'</b>			
DBH (cm)	22.43	21	24.8
Crown Diameter (cm)	724.25	450	847.5
Crown Depth (cm)	8.45	5.6	11.8
Sapwood area (cm <sup>2</sup> )	123.7	91.84	145.89
<b>DBH range '25 - 30'</b>			
DBH (cm)	27.15	25.8	29.6
Crown Diameter (cm)	871.3	751	967
Crown Depth (cm)	7.4	4.9	10.8
Sapwood area (cm <sup>2</sup> )	138.11	104.99	160.23
<b>DBH range '30 - 35'</b>			
DBH (cm)	32.45	30.8	33.4
Crown Diameter (cm)	605.375	370.5	891
Crown Depth (cm)	8.225	5	13.9
Sapwood area (cm <sup>2</sup> )	183.7375	105.7	224.6
<b>DBH range '35 - 40'</b>			
DBH (cm)	38.9	36.9	39.8
Crown Diameter (cm)	890.7	500	1072.5
Crown Depth (cm)	12.6	9.8	15
Sapwood area (cm <sup>2</sup> )	192.7	166.73	290.44
<b>DBH range '40 - 45'</b>			
DBH (cm)	43.0	40.7	46.2
Crown Diameter (cm)	995.7	882.5	1179.5
Crown depth (cm)	14.0	12.9	14.8
Sapwood area (cm <sup>2</sup> )	206.18	166.13	244.25

**Appendix 3.9.2 Teak plantation forest biometric characteristics (field data)**

	MEAN	MINIMUM	MAXIMUM
<b>12 YRS AGE (1999)</b>			
DBH (cm)	17.9	14.0	20.1
Crown Diameter (cm)	673.9	540.5	834.0
Crown Depth (cm)	7.3	5.2	10.1
Sapwood area (cm <sup>2</sup> )	100.8	75.4	135.4
<b>5 YRS AGE (2006)</b>			
DBH (cm)	13.8	8.8	17.3
Crown Diameter (cm)	470.1	330.0	571.5
Crown Depth (cm)	7.7	4.9	11.3
Sapwood area (cm <sup>2</sup> )	93.8	41.4	134.6
<b>16 YRS AGE (1995)</b>			
DBH (cm)	15.0	13.1	19.1
Crown Diameter (cm)	407.3	340.0	15.1
Crown Depth (cm)	12.9	10.8	15.1
Sapwood area (cm <sup>2</sup> )	47.0	19.7	77.8
<b>18 YRS AGE (1993)</b>			
DBH (cm)	27.3	20.1	33.4

Crown Diameter (cm)	828.3	592.5	1049.0
Crown Depth (cm)	16.3	10.8	19.8
Sapwood area (cm <sup>2</sup> )	111.9	75.5	141.4

*Crown depth is the length along the main axis from the tree tip to the base of the crown.*

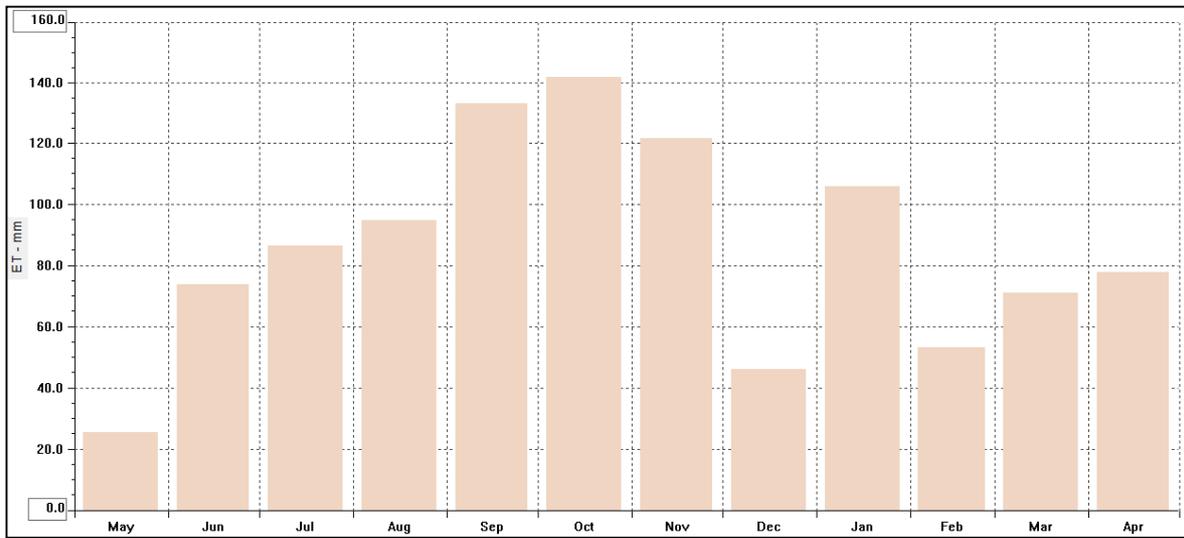
*Crown surface area (Ca) is calculated assuming the crown is a solid geometric shape with a measured crown depth (L) and crown width (D); assuming hemispherical shape  $Ca = \pi D^2 / 2$*

**Appendix 3.9.3 Annual climatic data summary at Ichima weather station (2009/10)**

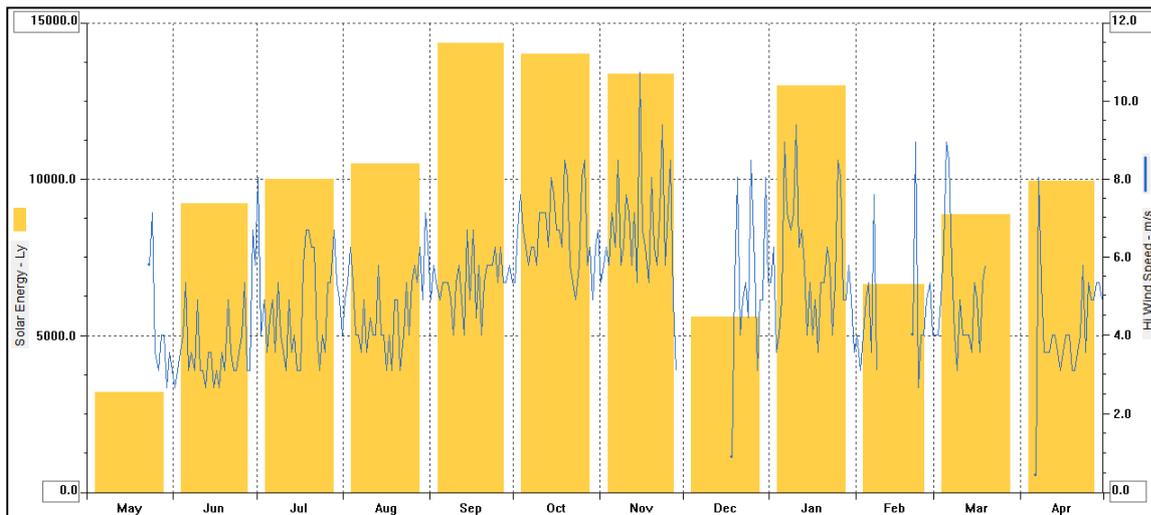


*Measurement units are; Humidity (%), wind speed (m/s), Temperature (°C), solar radiation (watts/m<sup>2</sup>) and 15 minutes rainfall totals (mm)*

### Appendix 3.9.4 Atmospheric water demand (2009/10)

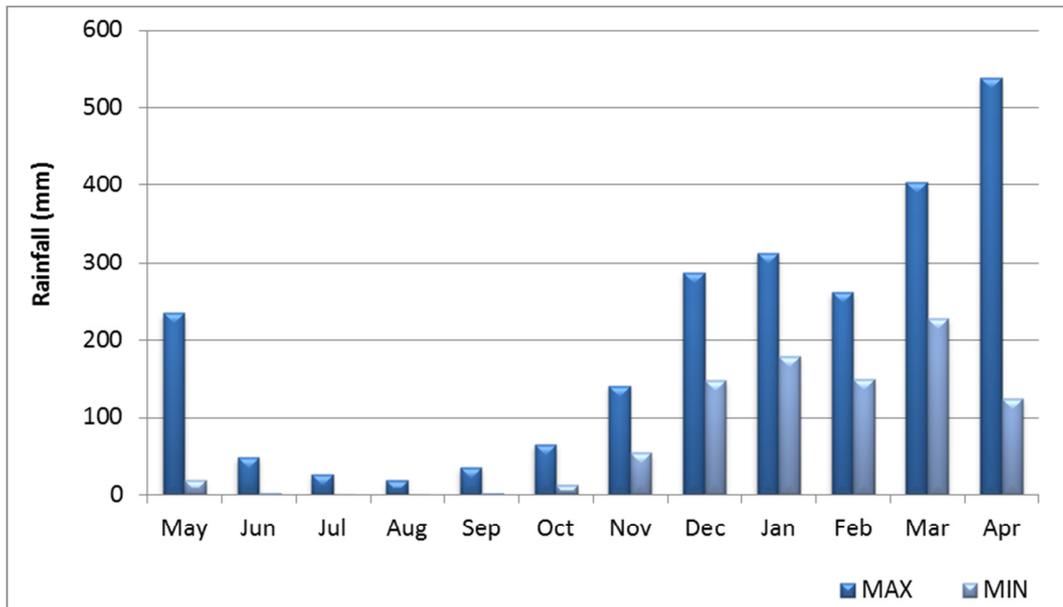


Hourly potential ET (mm)



Solar energy in Langleys

**Appendix 3.9.5 Long-term annual rainfall characteristics**



**Appendix 3.9.6 Seasonal leafing behaviour in Teak and Miombo forest at Ichima**  
(all photos taken by the research team during site visits)



Leaf-fall within Teak in 2008 dry season



Miombo woodland still leaved no evidence of leaf-fall in September 2008



Teak forest completely leafless during installation (29<sup>th</sup> September 2009)



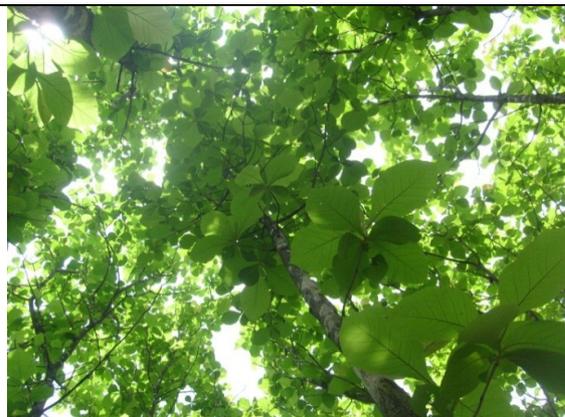
TDP installation in dry season (29<sup>th</sup> September 2009)



Leafing onset Teak (photo taken on 5<sup>th</sup> October 2009)



Initial stages of Teak leafing (photo taken 5<sup>th</sup> October 2009)



Teak leaved 2<sup>nd</sup> January 2010



Teak fully leaved during peak of wet season April 2010

#### **4. IMPACT OF FOREST CONVERSION ON DYNAMICS OF SOIL WATER FLUXES IN FORESTED CATCHMENTS: A COMPARATIVE STUDY OF TEAK AND MIOMBO FORESTS IN THE KILOMBERO RIVER BASIN**

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##### **Abstract**

Any land use change has the potential to induce an additional dynamic in the biophysical processes, especially in the soil water continuum. In particular, the conversion of natural Miombo forest to exotic Teak forest in the Kilombero Basin in Tanzania has the potential to change the soil water characteristics in the area. In this study, a comparative analysis was carried out on the vertical soil water profile beneath the indigenous Miombo forest (representing the situation prior to forest disturbance) and the exotic Teak forest (marking the forests' post conversion situation) in an attempt to characterise the potential impacts of this conversion on soil water regime. Each forest has a unique structure which is known to alter, to varying degrees, interception, infiltration amount, soil water redistribution and deep water drainage.

In this study, nested Granular Matrix Sensors, commonly referred to as Watermark sensors (Model 200 SS, Irrrometer Co. Riverside, CA), were installed at different sites in both the Teak forest and the Miombo woodland at depths of 30 cm, 60 cm, 90 cm and 200 cm. In each nest of Watermark sensors, the data were recorded using a HOBO data logger at a time interval of one hour. The sensors also provided soil temperatures at the various depths similarly recorded in HOBO data logger.

The study established that the upper 30 cm of the soil is subjected to diel fluctuations, following temperature and transpiration gradients. Soil water is extracted from various depths, depending on the location of maximum root activity. Maximum root activity in Miombo was observed at 2

m depth while this was greater than 3 m in Teak forest. Modelling with WAVES (Water, Vegetation, Energy and Solutes) revealed significant soil water extraction to a depth of 4 m beneath Teak, implying that the maximum root activity was at such depths. Moreover, Miombo root water uptake operates on the compensation principle, such that root water uptake begins on upper soils and progressively moves deeper during the course of the dry season. The stability of Miombo root water uptake and its ability to maintain its transpiration rate, regardless of the season, is attributed to this dynamic root behaviour.

Compared to Miombo, the Teak water use was higher throughout the year, which significantly reduced drainage to the soil. Field measurements indicated that, in the Teak forest, drainage only occurred late in the wet season while the same was observed to occur early during the rainy season in the Miombo forest. Simulations with the WAVES model further confirmed that, during the wet active growing season, Teak forests partition more than 50% of the incoming rainfall for consumptive water use and 8% as interception loss, while Miombo consumptive water use was only 11% of incoming rainfall, with negligible interception. Furthermore, the study highlighted the difference in consumptive water use in Teak and Miombo forests during the transition from wet to dry season - prior to leaf fall between the months of May and June. In this period, the consumptive water use of Teak was noted to be 2.6-folds more than the total rainfall received. This observation indicates the relatively higher consumptive water use by Teak, during this season, of which most of the soil water is mainly drawn from deep soil water reserves. Another difference relates to deep drainage, which amounted to about 20% of the soil water reserves beneath the Teak forests and 70% beneath the Miombo forests. Notably, there is a greater potential for contribution to groundwater recharge under the Miombo forests. This study has clearly established the difference and contrast in the consumptive water use, with focus on soil water balance, of Teak and Miombo forests. Such information is useful to water resource managers in the advent of upscaling or intensification of Teak forests in the Kilombero Basin.

**Keywords;** *soil moisture potential, watermarks, zero flux plane, Kilombero*

## 4.1 Introduction

Teak (*Tectona grandis*) is one of the most resilient wood trees in the world, broad-leaved in nature and exotic to Tanzania. The tree species was introduced to Tanzania following assessment at several trial plots in various parts of the country in 1905 and 1936. Its adoption mainly started with government plantation establishments in the 1960s in Mtibwa, in the Morogoro Province, with 430 ha, and Longuza in the Tanga region, with 240 ha (Malende and Temu, 1990). According to Kraenzel *et al.* (2003), Teak forest plantations rank third (in terms of area) among the tropical hardwood plantations world-wide. Teak timber is a highly valued product worldwide and the establishment of Teak plantations and tree stands for timber production is rapidly gaining popularity in Tanzania, both by local and foreign enterprises. This is of concern, given that the potential eco-hydrological impacts of such large-scale establishment of fast-wood, commercial plantation forests is not well understood in Tanzania and little effort has been made to advance research towards gaining understanding.

This study was carried out in the Kilombero River Basin, in the Ifakara District, (cf. Figure 4.1), where there is on-going expansion of Teak plantations at the expense of native Miombo woodland. The Kilombero River Basin is known for its Miombo woodland and is hence commonly known as a Miombo woodland zone. The woodland, however, is currently highly fragmented due to deforestation by the local community, as they expand and establish new farmlands, as well as tree logging activities for the charcoal trade and domestic fuel wood supply (cf. Chapter 2). Despite the on-going threats to the Miombo woodland, prior to this study no information has been gathered or efforts made towards investigating the hydrological implications of the on-going expansion and intensification of Teak forest plantations at the expense of the indigenous Miombo woodlands in the Kilombero River Basin, or in Tanzania as a whole.

Chapter 3 established that Teak forest stands had higher consumptive water use compared to Miombo forest stands. Moreover, Miombo trees had a very stable transpiration pattern which was atmospheric demand driven rather than soil moisture limited. Notably, the atmospheric evaporative demand increases further into the dry season, causing Miombo transpiration to increase, even after cessation of rainfall. This interesting phenomenon prompted the research

team to further investigate the effects of the observed surface fluxes on the unsaturated soil water regime and to evaluate the differences in the vertical stratification of a soil water profile beneath Teak and Miombo forest stands.

In particular, this paper highlights the vertical soil water distribution patterns during the dry and wet season beneath the native Miombo woodlands and exotic Teak forests at the study site, with the objective of investigating the impact of the forest conversion on soil water dynamics. Feedback effects of changes in forest transpiration on soil water are analysed through a modelling platform, as elaborated in Section 4.3.2. This paper forms part of a comprehensive monitoring and assessment study conducted in the Miombo woodland area of the Kilombero River Basin in Tanzania, with a broader objective of determining the potential hydrological impacts of land use changes in the Basin.

One of the major concerns to the scientific community and water resource managers is the increasing rate of establishment of fast-growing, commercial forest plantations that have been shown to have relatively high water use rates (Jewitt, 2002; Jewitt, 2005) and to impact negatively on streamflows, baseflows or ground water resources (Keenan *et al.*, 2004; Dye and Versfeld, 2007). Concerns regarding ground water resources exploitation by forests in general have been highlighted in a number of studies throughout the world, including Calder *et al.* (1997); Leduc *et al.* (2001); Chandler (2006); Price and Jackson (2007) amongst others. Forests change the soil water regime through the alteration of the hydrologic cycle and, depending on the canopy structure, changes in the partitioning of incoming rainfall to infiltration, overland flow and evapotranspiration (Fohrer *et al.*, 2001; Jewitt, 2005; Dietz *et al.*, 2006; Santoni *et al.*, 2010). Forest conversion, through changes in transpiration and interception, may lead to a decline in ground water recharge or deep percolation (i.e. the flux of water moving beyond the root zone of vegetation) which largely depends on the soil moisture storage reservoir (Walker *et al.*, 2002; Chandler, 2006; Štekauerová *et al.*, 2006; Santoni *et al.*, 2010). It therefore follows that forest stand structure and the associated changes have a significant influence on the soil water regime, particularly processes like infiltration, soil water redistribution and deep water drainage that determine vertical soil water stratification and profile characteristics that are likely to be altered.

This study is built upon, and takes advantage of, the monitoring of soil water potential conducted in the study area, to characterise the differences in the soil water regime beneath the indigenous

Miombo woodlands and the newly-established exotic Teak forests. A modelling exercise, using a soil-vegetation-atmospheric model, Water, Vegetation, Energy and Solutes (WAVES) model (Zhang and Dawes, 1998), was carried out to integrate the soil water dynamics and the associated consumptive water use of the vegetation, in order to establish the implications of the forest conversion on the soil water balance. Special attention was given to deep water drainage flux and root water extraction, as important contributors to soil water withdrawals from the soil matrix.

According to Walvoord *et al.* (2002), soil water movement is controlled by the hydraulic potential gradient between soil layers which, in this case, would be inferred from soil water potential ( $\psi$ ). Total soil water potential is a sum of gravitational potential (i.e. elevation of measurement point above a reference level), matric potential (absorptive and capillary forces) and osmotic potential (Izbicki *et al.*, 2000). Soil water potential ( $\psi$ ), as used in this document, refers to the soil matric potential, since osmotic potentials are commonly of negligible quantities and therefore soil water flux is regarded, in most cases, to be predominantly controlled by matric potential gradient (Stephens, 1996; Tindall and Kunkel, 1998; Hillel, 1998; Izbicki *et al.*, 2000). Consequently, as is the case with this study, most other studies on soil water flux estimation and direction determination have preferred to use soil water potential over soil water content, since soil water content is much more affected by the soil texture (Hosty and Mulqueen, 1996; Scanlon *et al.*, 2002). In unsaturated zones, matric potentials become increasingly negative with decreasing soil water content and, therefore, the drier the soils, the lower (more negative) the soil water potential ( $\psi$ ).

A comparative analysis of the vertical soil water profile beneath the Miombo and Teak forests in the study area determined, from observed  $\psi$  data, the location of the zero potential gradient and therefore zero water flux i.e. zero flux plane (ZFP), as defined by McGowan and Williams (1980). ZFP is the hypothetical plane separating the zone of upward movement of water and downward water movement in a thoroughly wetted soil (Cooper *et al.*, 1990; Khalil *et al.*, 2003). This plane is known to be dynamic in nature, moving upward or downward, depending on the hydrological processes occurring in the root zone and surface. This provides a quick and simple way of determining the maximum zone of root influence and direction of soil water fluxes.

The ZFP approach has become popular, following attempts by Stammers *et al.* (1973) as cited in Khalil *et al.* (2003), to develop equations for estimating evaporation and drainage from ZFP. This

method has been recommended to be most useful where there is limited information on soil hydraulic properties of the entire profile (Khalil *et al.*, 2003, Zhou *et al.*, 2004). Moreover, due to the high variability of hydraulic conductivity of soils and soil heterogeneity, the direct application of Darcy's Equation becomes impractical (Hosty and Mulqueen 1996; Walker *et al.*, 2002; Zhou *et al.*, 2004), hence the preference of the ZFP approach for water fluxes estimation through the soil profile.

The determination and use of ZFP location has been successfully used in the past to quantify evapotranspiration (Schwarzel *et al.*, 2009), in partitioning of evapotranspiration from drainage (Fernandez *et al.*, 2007); in separation of forest floor evaporation and transpiration (Shimada *et al.*, 1999), while Robert and Rosier (2005) used the ZFP method to study the soil water fluxes, the drainage depth and root water extraction depth. Cooper *et al.* (1990) used a similar ZFP approach to quantify the groundwater recharge. Others, such as Dreiss and Anderson (1985), used the soil water flux information inferred from ZFP determination to estimate contaminate levels in soils of a land treatment site in their study. The WAVES model, which uses and integrates ZFP in its computations, was used to integrate the various field observations to determine the interaction of the climatic forcings and vegetation water use on the soil water dynamics.

This study in the Kilombero River Basin contributes to the scientific knowledge base. Firstly, it targets the national and local communities, where hardly any efforts have previously been made towards understanding the hydrodynamics of forest conversions, and secondly it targets the global community, with regard to hydrological model uncertainty in soil moisture accounting and root water uptake profiles of forested ecosystems. This study provides insight into the seasonality of the vertical soil moisture regime of forested vegetation which, in most models, (e.g. SWAT, Arnold *et al.*, 1998) is assumed to be of a fixed pattern, regardless of the vegetation type, while in others (e.g. HSPF, Bicknell *et al.*, 2001), it is handled as a sink term.

## 4.2 Study Area

The study site is located in the Ichima Ward (S8.056°, E36.505°) in the Kilombero District, on the north-eastern side of the Kilombero River Basin in Tanzania. At the study site, two forest stands, indigenous Miombo woodland (*Brachystegia*) and Teak (*Tectona grandis*), were instrumented and closely monitored. Figures 4.1 and 4.2 show the research site and the experimental layout respectively. The Miombo woodland is mainly characterised by trees with the 12-20 m canopy height of the *Brachystegia* as the dominant species, but also composed of *Dalbergia spp.* and *Diplorhynchus spp.* (Hinde *et al.*, 2001).

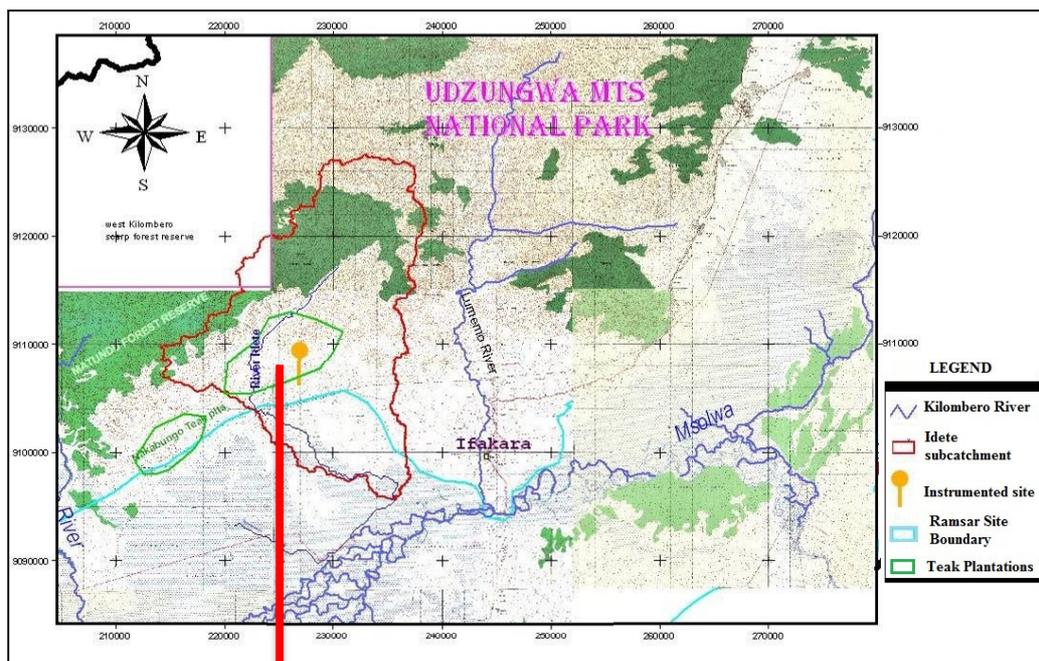


Figure 4.1 Location of the Study site (See detail below)

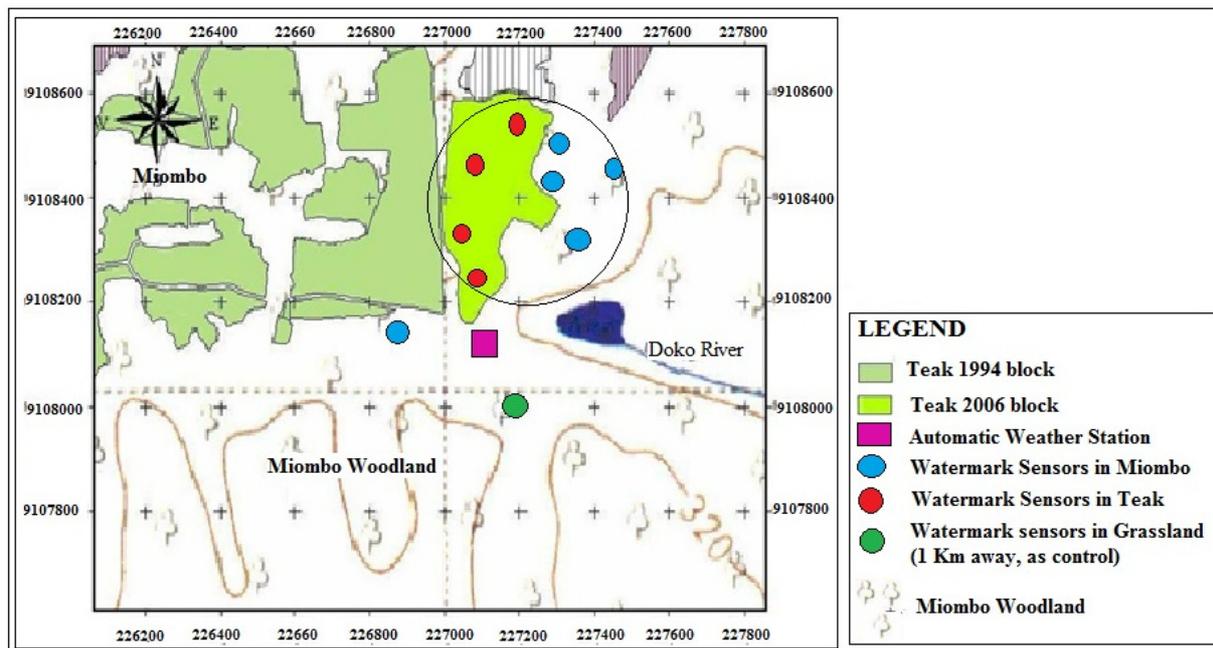


Figure 4.2 Instrumentation layout within the research site (the circled areas indicate location of sensors used in measuring soil water dynamics in this analysis)

The Ichima Ward was selected as a study site because the area was originally a Miombo woodland zone and is now gradually being replaced by Teak forest plantations by the privately-owned Kilombero Valley Teak Company (KVTC) and other smallholder forest plantation owners. The KVTC owns more than 1600 ha of forest land in the Ichima area alone, of which 890 ha of native Miombo woodland has already been replaced with Teak plantations with narrow corridors (less than 20 m wide) of remnant Miombo forest being left in the Teak forest plantations for ecosystem conservation purposes and migration pathways for wild animals (Frontier Tanzania, 2002). The Miombo Forest in this area forms open woodlands with understory vegetation, dominated mainly by grassland and a few shrubs.

#### 4.2.1 Rainfall

The Kilombero District is characterized by hot-dry and cool-rainy seasons. The relatively low-lying Kilombero Valley receives a mean annual rainfall ranging between 1100 to 1400 mm p.a,

while the surrounding mountainous area of Udzungwa receives higher rainfall ranging from 1500 – 2100 mm p.a (URT, 2009). The annual rainfall pattern in Kilombero is unimodal, with the wet season starting towards the end of November and continuing to April, occasionally extending to the month of May, as indicated in Figure 4.3. March to April is the peak rainfall season, the dry season spans the months of June to October.



Figure 4.3 long-term mean, monthly rainfalls in Kilombero Basin: 1960 – 1995 (after URT, 2009)

The long-term rainfall data (1960 – 1995) were obtained from the Ifakara weather station (-8.088, 36.676) located 25 km from the Ichima site. Other climatic data used in this study were obtained from an automatic weather station installed at the study site in 2009, which recorded data at a time-step of 15 minutes.

#### 4.2.2 Soils

The soils around Ichima are developed from the metamorphosed upper-Precambrian gneiss and schist formations (Geological Map, Sheet 235). According to a KVTC laboratory analysis report (2007) and personal communication with the KVTC management (2010), the soil horizon is characterised by a thick surface layer of dark-brown humus, sandy, loam soils, of about 15 – 20 cm depth, which overlays a deep well-drained reddish, sandy, clay loam to sandy, clay soils. The Soil and Terrain database (SOTER) map (Figure 4.4) indicates that the study site is situated on deep, well-drained, red soils that are freely draining (i.e. Nitisols).

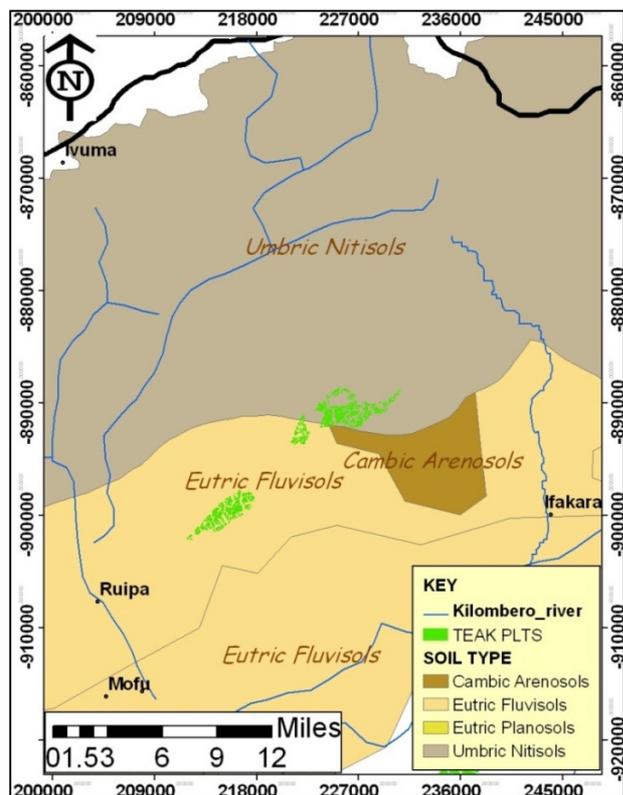


Figure 4.4 Map showing the predominant soils of the study area (Source: SOTER FAO, Land and Water Digital Media Series)

#### 4.2.3 Vegetation characteristics

The experimental site is a woodland-dominated catchment, with highly fragmented deciduous Miombo trees, indigenous to the area, and extensive Teak forest plantations, exotic to the area. Miombo woodland is mainly composed of understory shrubs and grassland vegetation, while Teak has hardly any understory vegetation, but is composed of substantial amounts of forest floor litter. Only remnant corridors of Miombo woodland remain.

A detailed description of the evolution of Teak plantations over the course of time and quantitative estimates of the cleared Miombo woodland is given in a separate paper of this thesis (Chapter 3).

### **4.3 Materials and Methodology**

#### **4.3.1 Site instrumentation**

##### *Soil Water Potential*

Soil water potential at the study site was monitored using Granular Matrix Sensors (Model 200 SS, Irrometer Co. Riverside, CA), commonly referred to as Watermark sensors that were linked to a 4 channel external HOBO data logger (Model U12-006, OneSet Computer Corporation, Bourne, MA). Four sets were installed in the Miombo woodland and the other four sets in Teak forest (cf. Figure 4.2). Two sets in Miombo and a further two in Teak were installed at 1 m, 2 m and 3 m depths from the surface. The other four set of sensors, two in each forest stand, were placed at depths of 30 cm, 60 cm, 90 cm, 200 cm and 300c m respectively. The watermark sensors recorded the level of soil water tension, which is indicative of the force that the plant roots would use to extract water from the soil. The installations were done close to each other in similar soil profile (identification of similar soil zones was carried out with the help of the soil expertise and extensive soil database of KVTC). The description of the soil profile is given under section 4.3.4, as it formed part of the WAVES model parameterisation process. In each nest of Watermark sensors, the data were recorded using a HOBO data logger at a time interval of one hour, starting from November 2008 to August 2010. The sensors also provided soil temperatures at the various depths similarly logged by the HOBO data logger.

##### *Meteorological parameters*

A Davis Vantage Pro 2, with console automatic weather station (MC Systems, Steenberg, Cape Town) was installed at Ichima in November 2009. This recorded all the main climatic variables i.e. rainfall, solar radiation, air temperature and relative humidity data at a time-step of 15 minutes.

##### *Forest transpiration measurements*

Forest consumptive water use in the study site was monitored using Granier thermal dissipation probes (Model FLDL-TDP XM1000, Dynamax, Inc., Houston, Tx, USA), which were installed in both the Miombo and Teak forest stands from November 2009 to August 2010. A detailed

analysis of the installation and analytical procedures for the transpiration measurements is outlined in a separate paper (Chapter 3) of this thesis. Figure 4.5 highlights the findings in which Teak trees were observed to have higher consumptive water use than the Miombo throughout the whole year, including the dry season.

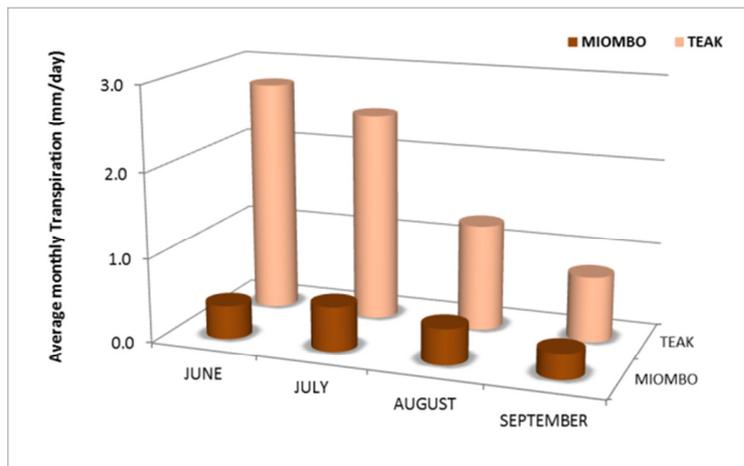


Figure 4.5 Observed Teak and Miombo transpiration during the dry season

#### 4.3.2 The zero flux plane method for the characterisation of the vertical soil moisture flux

Vertical soil water flux through the soil profile in the Teak and Miombo woodland is inferred in this paper, using the zero flux plane (ZFP) approach. The ZFP is a determinant in the resultant soil water fluxes and redistribution, as highlighted in the introduction to this paper. Soil water flux is determined by examining the location of ZFP and the hydraulic soil water potential gradient in a soil profile. Specifically, dZFP (i.e. a divergent zero flux plane) is formed whenever the soil water gradient results into an upward soil water flux above this plane and water percolation downward to the saturated zone below it. The assumption is that the upward flux of water is a result of root water extraction and evaporation. Moreover, it is commonly assumed that there are no roots below the ZFP and that any downward movement of water contributes to groundwater recharge (Zhou *et al.*, 2004). Another phenomenon can occur whenever there is downward movement of soil water above the ZFP and upward movement below the plane; this is what is referred to as convergent zero flux plane, cZFP (Zhou *et al.*, 2004). cZFP location was useful in deducing the maximum root zone of influence beneath both the Teak and Miombo

forests. A comparison of the soil water potential profile and seasonal changes beneath the two forest types is made in this study, with particular focus on the drying and wetting cycle fluxes. Attention was paid to the onset of infiltration and the progressive rate of the wetting front movement beneath both the indigenous woodland and the exotic Teak forest.

The measured soil water potentials were useful in determining the soil water potential profile at each sensor location. ZFP locations were then visually identified from the soil water potential profiles, while the vertical soil water fluxes and direction were deduced from the hydraulic gradient as elaborated above. Studies, such as that of Rutter *et al.* (2012), have demonstrated the reliability of this method in determining the soil water movement in the unsaturated zone. More recent applications of this approach include studies by Wang *et al.* (2012) and Schwärzel *et al.* (2009) who used ZFP in the soil water balance for evaporation determination. Krishnaswamy *et al.* (2013) used the approach in determining the land-cover-specific evapotranspiration and recharge in an attempt to report the hydrological effects of forest conversion.

#### **4.3.3 Soil water modelling with WAVES**

A link between forest consumptive water use i.e. forest root water uptake (Chapter 3) and the soil water profile characteristics was established through a modelling exercise using the WAVES model (a one dimension Soil-Vegetation-Atmosphere transfer model). WAVES was found useful in the integration of the various field observations and to determine the interaction of the climatic forcing, vegetation water use and soil water dynamics in both Miombo and Teak forests.

The WAVES model, developed by the Land and Water CRC of the CSIRO in Canberra, Australia (Zhang *et al.*, 1996; Zhang and Dawes 1998), was applied in this study to analyse the implications of forest conversion (Miombo to Teak forest). The model integrates the surface and subsurface hydrological processes in response to changes in the canopy and the atmosphere. WAVES consists of four modules i.e. energy balance, water balance, carbon (plant growth) and solute balance. The soil water balance module deals with rainfall infiltration, overland flow, soil and root water uptake, moisture redistribution and drainage (recharge), while evapotranspiration is estimated using the Penman-Monteith equation (Monteith, 1981) from the calculated available

energy under the energy balance module. Therefore, WAVES determines evapotranspiration from understory and overstorey vegetation, soil evaporation, soil water redistribution, drainage (recharge) and the soil water storage (Slavich *et al.*, 1998). The model derives interception loss through an empirical equation linking gross rainfall and LAI after Hoyningnen-Huene (1983). The model uses Richard's Equation to simulate the vertical soil water redistribution through a profile. The soil moisture characteristic and conductivity curves required for solving Richard's equation are generated by the Broadbridge and White model (1988). WAVES has successfully been applied in a number of studies in different regions, including South Africa (Dye *et al.*, 2008), Australia (Xu *et al.*, 2008, Crosbie *et al.*, 2008, Barron *et al.*, 2012) and other parts of the world like Brazil (Soares and Almeida, 2001) and elsewhere (Yang *et al.*, 2003). The model has been shown to reproduce the water balances of a number of watersheds, for example in Australia (Crosbie *et al.*, 2008; Barron *et al.*, 2012). Few studies have looked into uncertainties associated with the WAVES model, although some exists such as a study on recharge estimation that reported projection uncertainty of 24% of the observed historical recharge (Crosbie *et al.*, 2011).

WAVES was selected for use in this study to assess the influence of vegetation changes and, therefore, plant water use changes on the soil water balance after it had been successfully used for similar purposes in a number of other watersheds as highlighted above.

Soares and Almeida (2001) describe WAVES as one of the most complete Soil-Vegetation-Atmosphere coupling models available. When compared with other models like HYDRUS 2D (Simunek *et al.*, 1998), whose code is not freely accessible, it was found more useful as it models the interaction between plant and soil, unlike HYDRUS 2D and SWIMv2 (Soil Water Infiltration and Movement version 2). Moreover, WAVES is a generic model and not designed for specific climates or land covers, and has been demonstrated to satisfactorily predict soil moisture balance in changing climate and vegetation (Yang *et al.*, 2003). Further, WAVES represents vegetation canopy in layers and derives the aerodynamic resistances with considerations of climatic conditions, unlike models such as UAPE (Uso de Água em Plantações de Eucalipto or Water Use by Eucalyptus Plantations) that uses constant aerodynamic conductance. More importantly, WAVES, in contrast to HYDRUS and many other models, is able to model plant root water uptake with compensation mechanism, where it is assumed that, in times of partial wetting or soil

water depletion, preferential uptake can shift to zones of higher soil moisture regardless of the root distribution.

#### **4.3.4 Parameterisation of the WAVES model**

The WAVES model is a parameter driven tool which needs to be constrained with the right data. The model requires information on forest stand structure characterisation for establishing forest growth dynamics, rainfall partitioning and water use characteristics.

In this study, the WAVES model was set up such that the Miombo forest stand was defined by the overstorey wooded trees of an average canopy height of 20 m with uneven, discontinuous understory C4 grassland and shrub vegetation (Figure 4.6). Teak forest population was represented in the model by only the overstorey Teak trees and forest floor litter layer that was observed at the field to be very thick, despite the frequent fires.

WAVES assumes that canopy leaf area growth is linearly related to specific leaf area and the leaf carbon (Lambers and Porter, 1992). Difficulties were encountered with LAI seasonality as it is reduced during the dry season, drops to zero during leaf-fall and increases again to a full bloom at the peak of the rainfall season. This limitation was also noted by Green *et al.* (2007) and Zhang *et al.* (1999) who commented on the inability of WAVES to simulate the dormancy stage. To work around this challenge, the model was run separately for dry and wet seasons, adjusting parameters like leaf areas and aerodynamic resistance accordingly. Thus, modelling was carried out in two seasons, the period representing the dry season from 1<sup>st</sup> May 2010 and 29<sup>th</sup> June 2010 (60 days) and a wet season with a period of 180 days, starting on 1<sup>st</sup> Nov 2009 to 29<sup>th</sup> April 2010. The simulation period, as elaborated earlier, was selected taking into consideration in-situ transpiration data gaps due to instrument failure. The model was initialised at the maximum observed soil water potential value in the field at the time just before the rains stopped, where the whole soil profile was assumed to be thoroughly wetted to field capacity. The bottom (3 m depth) boundary condition was assumed to be a free drainage boundary. Soil heterogeneity was represented in the model by defining and adding soil layers, the hydraulic properties of which were obtained from literature, according to the Broadridge-White Model (1988). The model was

calibrated, with the objective of reproducing the measured overstorey transpiration observations and subsequent soil water potentials along a 3 m soil profile, for each forest stand instrumented with Watermark sensors.

The textural class representative of the upper 20 cm horizon is sandy, loam soils and the rest of the depth to 3 m and 4 m of soil is sand, clay, loamy. In the absence of soil water retention data, the parameters were estimated by iteratively fitting the measured transpiration and soil water potential profiles to the simulated ones. The table below represents the parameters used in the Broadbridge and White (1988) model using the BWSOIL module of WAVES.

	<b>Ks</b> <b>Sat hydraulic conductivity</b> <b>(m day<sup>-1</sup>)</b>	$\Theta_s$ Sat moisture content <b>(m<sup>3</sup> m<sup>-3</sup>)</b>	$\Theta_d$ Air dry moisture content <b>(m<sup>3</sup> m<sup>-3</sup>)</b>	$\lambda_c$ (length scale) (m)	C (shape parameter)
Sandy Clay Loam	0.3	<b>0.4</b>	0.1	0.1	1.4
Sandy Loam	0.4	<b>0.4</b>	0.09	0.8	1

The biophysical parameters used in the WAVES model were obtained from a biometric survey conducted at the study site while other parameters were sought from literature, as explained below.



Figure 4.6 Watermark sensors in the Miombo woodland of the KVTC site at Ichima (a) before a bush fire and (b) after a bush fire in October 2009



Figure 4.7 Teak forest plantations at the research site showing significant forest floor litter

This section details the various approaches that were used to obtain the forest structure characteristics, as well as the phenological characteristics of both Miombo and Teak forests necessary for the parameterization of the WAVES model.

#### 4.3.4.1 Tree root architecture and root density distribution

The soil water dynamics of a vegetative system are governed by the root water uptake strategy of the plants which, to a large extent, depends on the root geometry and root density distribution down a soil profile. This then controls the pattern of soil water depletion of that profile.

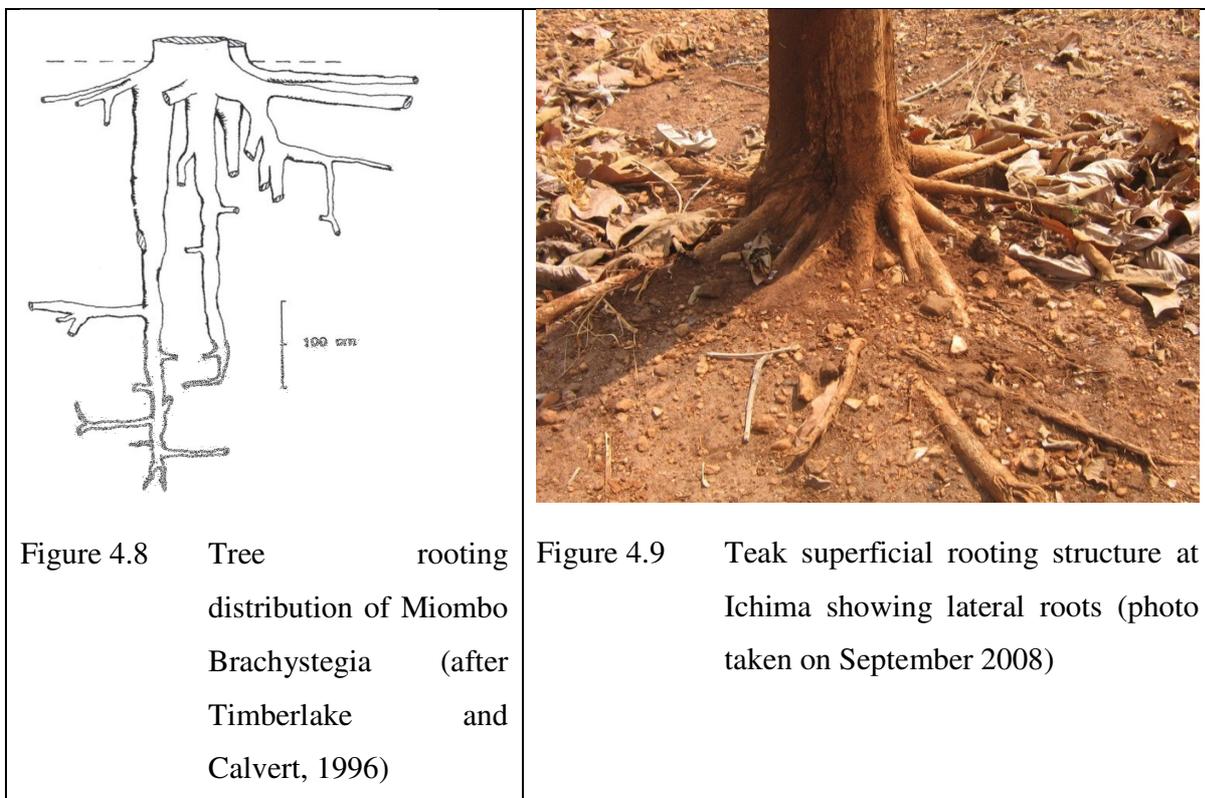
Jackson *et al.* (1996) undertook a comprehensive study of the root distribution of global plants and derived a function that defines the distribution with depth. The study defined the vertical root distribution of global biomes on the basis of a function Gale and Grigal (1987) i.e.

$$Y = 1 - \beta^d \quad (4.1)$$

Where  $d$  is depth and  $Y$  is cumulative root fraction from the soil surface to depth  $d$ . High values of  $\beta$  signify deeper root profiles and low values indicate a greater proportion of roots at the surface. The study suggested  $\beta$  value of 0.961 for tropical deciduous forest, which allocates 70% of the root biomass in the upper 30 cm with a total biomass of 4.1 kg/m<sup>2</sup>. Important to note is that this conclusion was inferred from the observation of a range of biomes, but with only three forest studies that monitored roots to at least a 2m depth. However, in many instances, the rooting structure in forest ecosystems has been shown to vary with stand density (Landsberg and RIRDC, 1999), making the determination of the lower boundary of a forest root system challenging. Binkley *et al.* (1997) elaborated that rooting density and depth increase with planting density because of the competition between trees which causes soil water extraction to occur mostly from deeper soils. Thus, due to these limitations, this study sought specific information and data from literature on the rooting characteristics of Miombo and Teak forests.

A good description of the tree rooting structure of Miombo woodland is provided by Timberlake and Chidumayo (2011) who described a deep taproot reaching a depth of up to 5 m, in some instances (Figure 4.4) and accompanied by large lateral roots (Timberlake and Calvert, 1993). Teak root information was not readily available since most studies concentrated on the fine root dynamics which, according to Takahashi *et al.* (2002), contribute only a very small percentage of total root biomass. Takahashi *et al.* (2002) further report fine root biomass of about 0.219 kg/m<sup>2</sup> in the upper 30 cm soils and 2.250 kg/m<sup>2</sup> between 30-120 cm down the soil profile. Another study by Tanaka *et al.* (2009), carrying out a soil strength analysis using a penetration test, suggested a maximum rooting depth of one metre, while a study by Garcia-Saqui (2007) reported Teak root depth of about 6 m down a soil profile. Weaver (1993) describes Teak roots as

comprising of a long and thick taproot with strong lateral roots and fine roots on the upper 30 cm of soil. It should be noted that, in some instances, Teak roots have been used to fabricate expensive and unique furniture. Following such inconsistent reporting, this study determined the most likely maximum rooting depth for Teak trees, through a model calibration (parameter optimisation) process. The implications of changing maximum rooting depth (in an attempt to constrain the WAVES model) are reported in Section 4.5.5 of this paper. Despite the fact that Teak roots have been found in the past to reach depths of 2 m in other areas, this study adopted a rooting depth of 1 m based on field observations in the study area.



#### 4.3.4.2 Leaf phenology

The leaf periodicity of any deciduous forest, determined by the timing of defoliation and leaf-out of a tree, is crucial for vegetation water use studies as it is a determinant of the onset and cessation of tree transpiration or the active period of root water uptake and soil water reduction.

Vegetation canopy structure directly affects the interception and transpiration processes of the water balance (Yoshifuji *et al.*, 2006; Bulcock and Jewitt, 2010).

The Miombo woodland site was observed during field visits to be in a state of dormancy (leafless) for a very short period of time in the dry season, mainly in the month of September. It was also observed that for the years 2008 and 2009, the Miombo started leafing consistently prior to the onset of rainfall, towards the end of October (i.e. the last dry month). Similar observations have been reported by Frost (1996) and Ryan (2009), where the latter highlighted that this phenomenon occurs about 37 days before the onset of rainfall. The Miombo woodland seasonality in this area may also be affected at times by frequent bush fires commonly started by local farmers practicing traditional burning methods as a means of clearing and preparing farmlands during the planting season (cf. Figure 4.6).

The Teak forest, on the other hand, was observed to remain leafless for most of the dry season with the leafing-out triggered by the first rainfall event. Thereafter, it attained complete leaf regrowth a month after the first rainfall (between November and December). A study on a Teak plantation at the Mae Moh site in Thailand by Imvitthaya and Honda (2008) reported that peak leaf area index measurements (i.e. 4 – 4.5  $\text{m}^2\text{m}^{-2}$ ) coincided with peak rainfall months, while Kawamoto (2003) noted that Teak plantation LAI varies from 0.5 to 5.3  $\text{m}^2\text{m}^{-2}$ , depending on the season.

Miombo woodland is normally characterised by very low LAI values, ranging from 1  $\text{m}^2\text{m}^{-2}$  at the peak of the dry season to 2  $\text{m}^2\text{m}^{-2}$  at the peak of the wet season (Huemmrich *et al.*, 2005). Since the Miombo at the Ichima research site were open woodlands, the LAI was expected to be lower. The actual value of LAI for Miombo used in the WAVES model was obtained by a calibration process, while considering the above information from literature.

Other parameters on leaf phenology used in the WAVES model e.g. specific leaf area and radiation coefficient were also obtained from literature. The specific leaf area and radiation coefficient for Teak used in the study was 12.13  $\text{m}^2\text{.kg}^{-1}$  (121.3  $\text{cm}^2\text{.g}^{-1}$ ) and 0.37  $\text{m}^2\text{m}^{-2}$ , respectively, as suggested by Yoshifuji *et al.* (2011).

#### 4.3.4.3 Vegetation carbon pools

Important parameters in the plant growth module of the WAVES model are the forest carbon stocks above- and below-ground, including the assimilation rate. This is a sensitive model parameter that controls both transpiration and plant growth rate. However, most of the studies in literature have indicated a high variability of this parameter, as shown in Table 4.1. Research studies of Miombo woodland suggest that the woodland above-ground biomass is around 55 t dry matter ha<sup>-1</sup> (Frost, 1996), while its root biomass is around 20% of the total woody biomass (Malimbwi *et al.*, 1994). The Miombo above-ground biomass is approximately 19.2 t.ha<sup>-1</sup> (1.92 kg.m<sup>-2</sup>) in the Miombo forest reserves in Tanzania (Munishi *et al.*, 2010).

Table 4.1 Maximum carbon-dioxide assimilation rate

Parameter	Value	Reference
Miombo maximum carboxylation rate	20 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$	Kutsch <i>et al.</i> (2011)
Miombo maximum photosynthetic rate	11.95 $\pm$ 1.69 $\mu\text{mol m}^{-2} \text{ s}^{-1}$	Choinski and Johnson (1993)
Teak maximum carboxylation rate	50 $\mu\text{mol m}^{-2} \text{ s}^{-1}$	Tanaka <i>et al.</i> (2009)
Teak maximum carboxylation rate	65 $\mu\text{mol m}^{-2} \text{ s}^{-1}$	Gopalakrishnan <i>et al.</i> (2010)
Teak maximum carboxylation rate	20 $\mu\text{mol m}^{-2} \text{ s}^{-1}$	Obtained through model calibration Tanaka <i>et al.</i> (2003)

It is clear from Table 4.1 that there are a range of suggested maximum carboxylation rates. This study used the minimum allowed value in the model, which is 0.01 kgm<sup>-2</sup>day<sup>-1</sup> (kg of carbon per day per square meter of ground) for Miombo and 0.04 kg m<sup>-2</sup>day<sup>-1</sup> for Teak, obtained through a calibration process.

Other data necessary for model operation, including the above- and below-ground carbon stocks distribution, are sought from a number of research findings elaborated in Tables 4.2 to 4.5.

Table 4.2 Above-ground carbon stock

Parameter	value	Reference
Teak leaf: stem C ratio	0.94	Derived from data collected by Jana <i>et al.</i> (2009)
Teak leaf: stem C ratio	0.96	Derived from data collected by Meunpong <i>et al.</i> (2010)
Teak leaf carbon	0.093 – 0.456 kg m <sup>-2</sup>	Pande (2005)
Teak leaf carbon	0.238 kg m <sup>-2</sup>	Meunpong <i>et al.</i> (2010)
Miombo leaf carbon per leaf area	0.050 kg C m <sup>-2</sup>	Ryan and Williams (2011)

Table 4.3 Below-ground biomass and carbon stock

Parameter	Value	Reference
Teak root biomass	5.05 kg m <sup>-2</sup> 0-30cm depth	Takahashi <i>et al.</i> (2009)
	11.74 kg m <sup>-2</sup> 0-120cm depth	
Teak root carbon	3.40 kg m <sup>-2</sup> 0-30cm depth	Takahashi <i>et al.</i> (2002)
	1.65 kg m <sup>-2</sup> 30-120cm depth	
Teak litter carbon	0.27 kg m <sup>-2</sup>	Kraenzel <i>et al.</i> (2003)
Miombo root carbon	0.85 ±0.05 kg C m <sup>-2</sup>	Ryan <i>et al.</i> (2011)

Table 4.4 Miombo soil carbon stocks distribution (after Ryan *et al.*, 2011)

Soil depth	Carbon stock (tCha <sup>-1</sup> ) (quoted)	Calculated carbon stock (kg.m <sup>-2</sup> )

0 – 2.5 cm	8 ± 0.4	0.84 ± 0.04
2.5 – 10 cm	17.7 ± 2.0	1.77 ± 0.2
10 – 20 cm	16.0 ± 2.4	1.60 ± 0.24
20 – 50 cm	34.5 ± 5.4	3.45 ± 0.54
Soil total	76.3 ± 9.9	7.63 ± 0.99

Table 4.5 Teak soil carbon stocks (after Meunpong *et al.*, 2010)

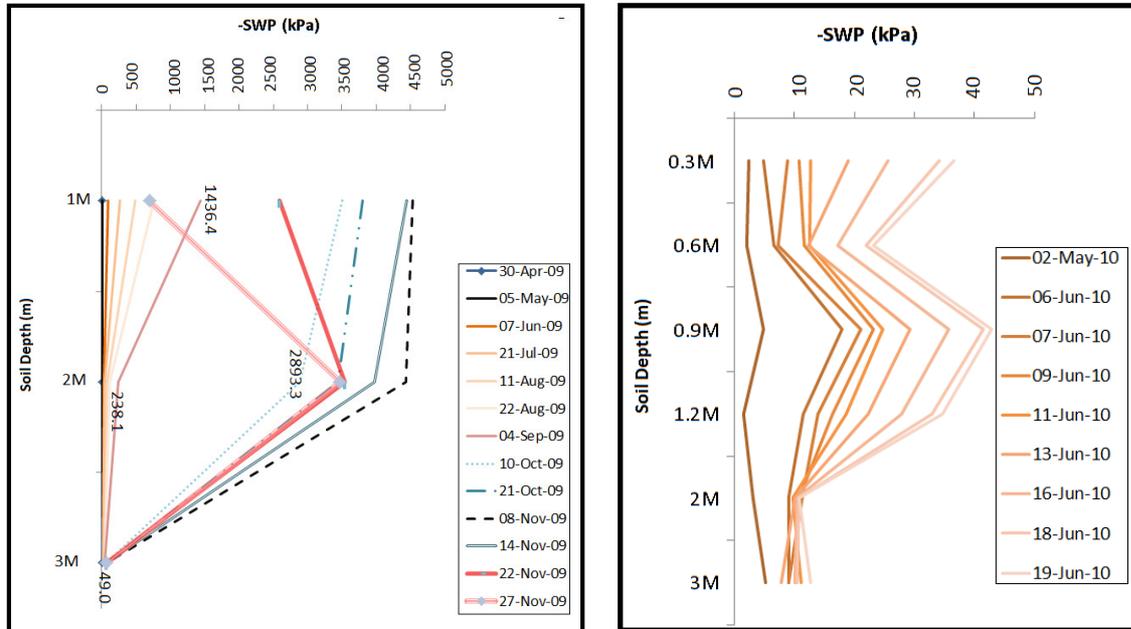
Soil depth	Carbon stock (tC ha <sup>-1</sup> ) (quoted)	Calculated carbon stock (kg m <sup>-2</sup> )
0 -10 cm	17.81	1.781
10 – 20 cm	14.48	1.448
20 – 30 cm	11.26	1.126
30 – 40 cm	9.93	0.993
40 – 50 cm	3.30	0.33

## 4.4 Results and Discussion

### 4.4.1 Observed temporal variability of soil water potential under Miombo during periods with no rainfall

The soil drying phase in the Miombo woodlands is characterised by a progressive reduction in soil water potential, with more pronounced effects in the upper 1 m soils (Figures 4.10). During the course of the dry season, gradual development of ZFPs is observed. These occur at three locations, the divergent flux plane (dZFP) at 0.6 m, the convergent cZFP at around 1-1.2 m and dZFP at a 2 m depth (Figure 4.10). This implies that there is localised soil water depletion at 0.3 m and 1-1.2 m depths resulting in lower water potential developing at this depth than the

surrounding soil layers. It was also noted that cZFP (at 1-1.2 m) was not static, but was observed to gradually move downwards during the course of the dry season to a maximum depth of 2 m by the end of the dry season, as indicated in Figure 4.10a.



(a) Soil profile for the transition from wet to dry season of the year 2009

(b) Soil profile for the early stages of dry season of the year 2010

Figure 4.10 Temporal changes in soil water potential profile during the dry season for the Miombo woodland

Multiple ZFP occurrences in a vertical soil profile, as observed in Miombo, have been reported in past studies like that of Shimada *et al.* (1999) who reported ZFP locations at 20 and 70 cm and used them to partition the pine forest floor evaporation from the tree transpiration. Similarly, Zhou *et al.* (2004) obtained multiple ZFPs at 0.5 m and 3 m depths and concluded that the convergent ZFP always occurred at the plant root zone, while Krishnaswamy *et al.* (2013) noted ZFPs at 0.5 m and at depths greater than 1.2 m and attributed this to active root water uptake in these locations for meeting the transpiration demand.

Zones of low soil water potential (cZFPs) develop in areas of high root density resulting in higher soil water depletion by root water uptake (Sachez-Perez *et al.*, 2008). The hydraulic gradient

formed in the soil profile as a result of the low water potential zone, determines the soil water flux. Water transport in the dry vadose zone is more sensitive and more accurately described by the hydraulic potential gradient, due to discontinuities in the soil water content gradient at the interface of soil layers (Kalinka and Ahren, 2011; Evett *et al.*, 2012). Thus, many have suggested that soil water movement should rather be determined from measured soil water potential than water content values (Zhou *et al.*, 2004; Hurtado and Van Lier, 2005).

The observed vertical pressure head distribution and the ZFP locations indicate that soils at 0.6 m (Figure 4.10b) lose their moisture to both the layers above and beneath it, while all the net infiltrating water beneath 0.6 m fluxes towards the 1-1.2 m depth to replenish the moisture that is used from there by the rooting system. Moreover, an upward flux of soil water below this point to a 2 m depth is evidently an attempt to replenish and balance the soil water potential gradient.

In an effort to link the vertical soil water flux direction with the Miombo woodland vegetation structure, it can be deduced that soil water depletion in the superficial soils above 0.3 m, and an upward soil water flux from 0.6 m, is driven by either understory vegetation or forest floor evaporation, or both. The development of cZFP at 1-1.2 m depths is likely to be the result of overstorey root water extraction.

Further, the dynamicity of the zero flux plane indicates the ability of vegetation roots to adapt to the gradual drying of superficial soil layers resulting in a transition in the effective root water uptake from shallow to deeper, wetter layers in the course of the dry season. This phenomenon is consistent with observations from other studies such as Lai and Katul (2000); Schwarzel *et al.* (2009) and Wang *et al.* (2012). According to Lai and Katul (2000), this phenomenon (stress compensation) occurs when soil moisture in superficial soil layers approaches a wilting point. Other studies e.g. Adiku *et al.* (2000), highlighted an exponential increased root activity with depth whenever superficial soils begin to dry. Teuling *et al.* (2006) observed the same, attributing this to a plant adaptive capacity in an attempt to achieve unstressed transpiration during a soil drying phase and recommended a stress compensation mechanism as a better representation of root water uptake in water-limited scenarios than a non-compensation one.

The ability of Miombo to shift its zone of maximum root influence downwards during the dry season is an indication of an adaptive mechanism of the roots to reduce stress. According to the

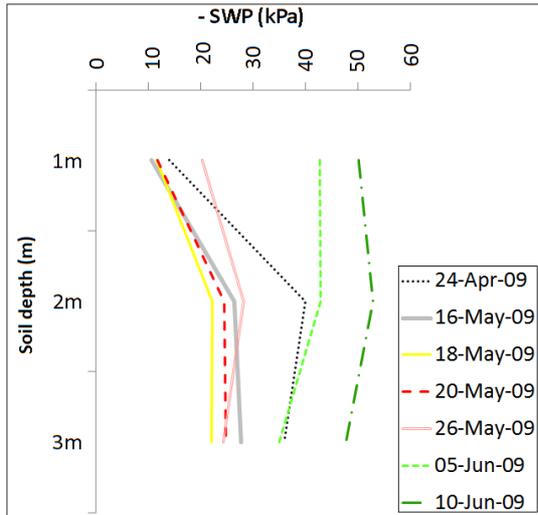
findings in Chapter 3, transpiration rates of the Miombo woodland remain stable throughout the wet season. However, a delay in the cessation of transpiration after the rains had stopped was apparent indicating that the Miombo have an efficient coping mechanism for soil moisture deficiency.

The above observations serve as a guide for future soil water balance and root water uptake modelling within Miombo woodland. Clearly, attempts to model the root water extraction of the Miombo woodland have to consider the compensation mechanism of the roots to allow for increased soil water uptake from deeper layers as soil moisture in the superficial soil layers is depleted. The water uptake by the Miombo roots is dynamic and, therefore, a soil moisture compensation mechanism needs to be incorporated in the model, as is the case with the WAVES model. Soil water extraction in the WAVES model has been described by Feddes and Raats (2004) as increasing exponentially down the soil profile to a certain maximum, decreasing again to zero at the bottom of a root zone.

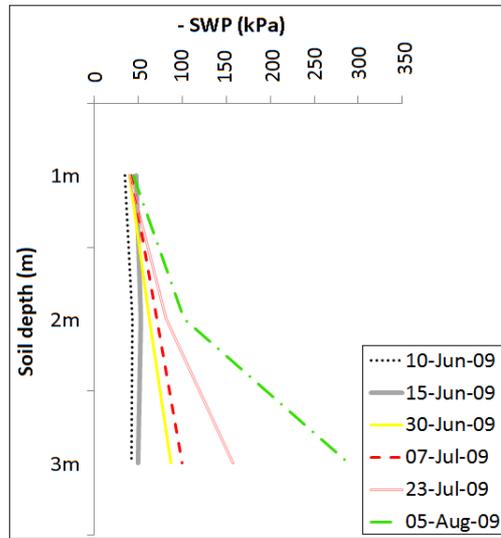
#### **4.4.2 Observed temporal variability of soil water potential in Teak during periods with no rainfall**

Variations in soil water potential versus depth over the course of the dry season are shown in Figures 4.11 a-d. The soil water potentials of the upper 3 m soils are observed to gradually reduce, with the development of one cZFP at a depth of 2 m that eventually migrates to a depth of 3 m. This pattern was consistently observed in 2009 and 2010, as indicated in Figures 4.11.

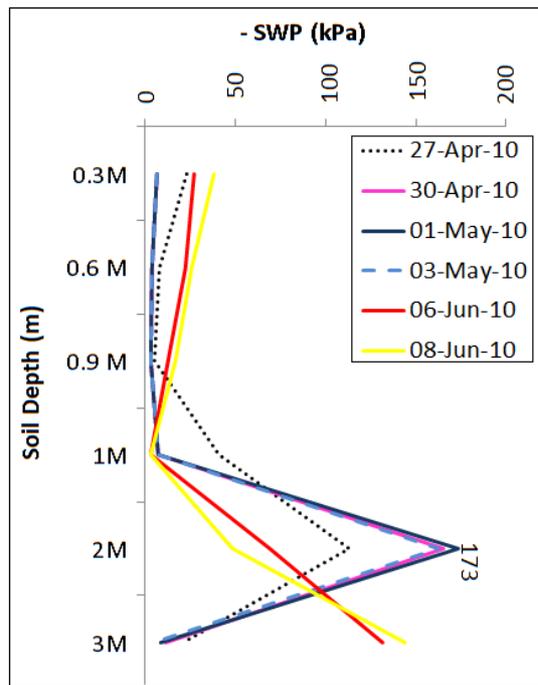
From this observation, the maximum zone of root influence in Teak was noted to lie between a depth of 2 and 3 m. However, it should be noted that 3 m was the maximum observation depth during the experiment and hence there is a high possibility that this zone could occur at deeper depths. The observations indicate that the soil water moves towards the cZFP from both below and above this depth to replenish the root water extracted.



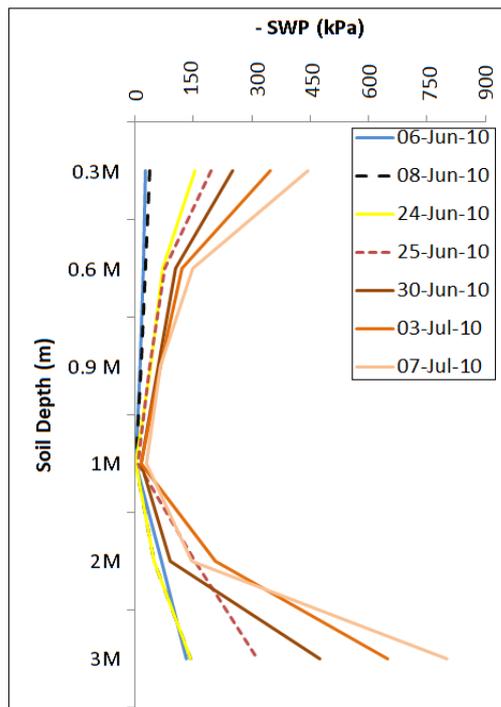
a: Profile at the onset of the dry season in 2009



b: Soil profile in dry season in 2009



c: Soil profile at the onset of dry season in 2010

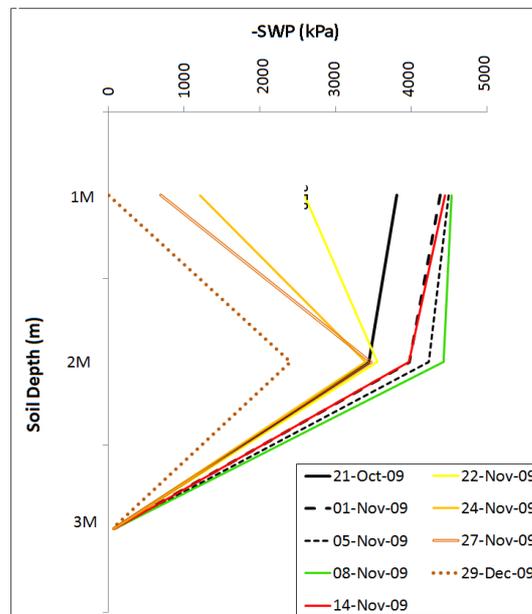
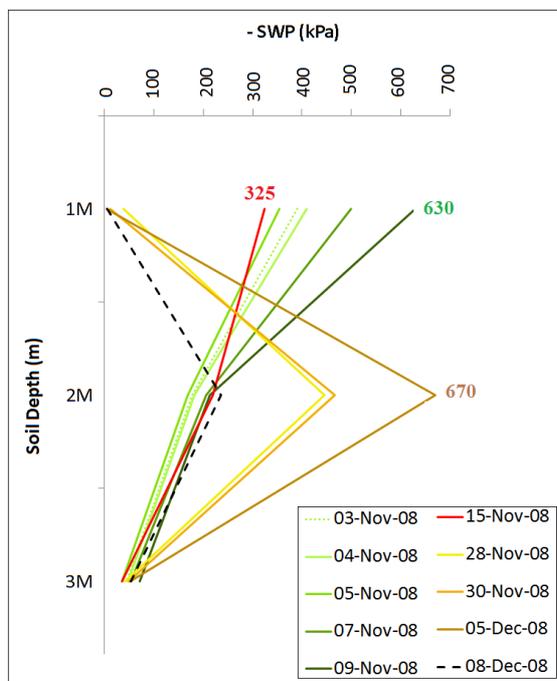


d: Soil profile in dry season in 2010

Figure 4.11 Temporal changes in soil water potential profile at selected dates during the dry season in the Teak forest

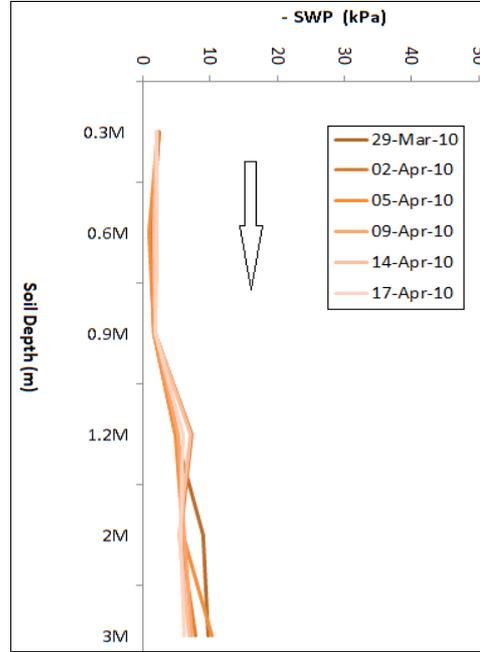
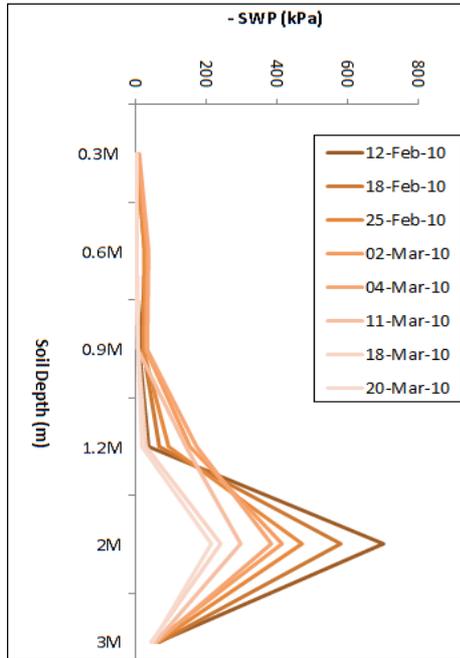
#### 4.4.3 Observed temporal variability of soil water potential in Miombo during the rainy season

The graphs depicting vertical soil water potential profiles for the rainy season in the Miombo woodland are shown in Figures 4.12 a-d. Three important observations are made; the first being that soil water potential increases throughout the soil profile, starting from the top soil and gradually increasing down the soil profile in response to the wetting front progression. Soil water potential sensors at depths up to 1 m depth respond immediately to the start of rainfall. This happened consistently for the years 2008 and 2009. Secondly, the disappearance of both ZFPs in the course of the rainy season (Figure 4.12d) was noted; and thirdly soils at 3 m depth remain stable and wet throughout the seasonal changes. A delay of close to one month is noticed in the wetting of soils at a 2 m depth compared to the upper soils of less than 1 m depth that are observed to wet immediately after the rains start. This partial wetting of the soil profile results in a reversal of the potential gradient between the two depths and, hence, the reversal of soil water movement in the profile. Prior to the rainfall onset, soils at a 2 m depth were losing water to the 1 m depth. This is the same region where the lowest potentials were noted, due to the extraction of soil water by roots. After the rains start, the flux is directed downwards to 2 m depth.

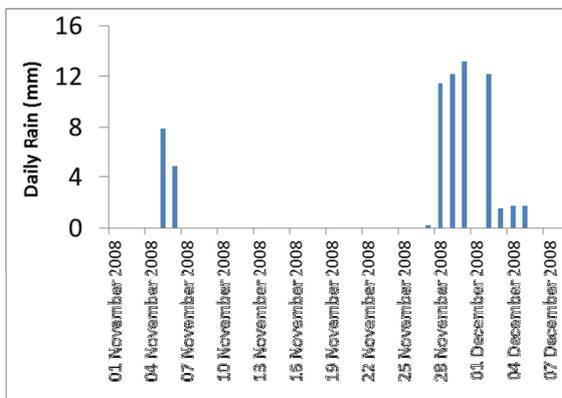


b: Response at the onset of the 2009 rains

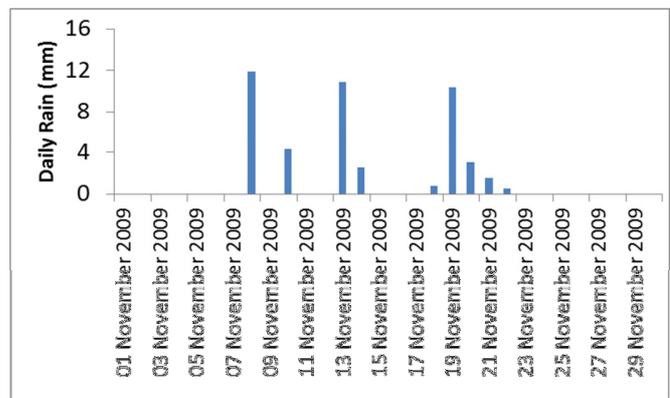
a: Response at the onset of the 2008 rains



c. Response during the 2010 rainfall season



d: Response at the peak 2010 rainfall



Rainfall time series for the month of November 2008 (mm. hr<sup>-1</sup>)

Rainfall time series for the month of November 2009 (mm. hr<sup>-1</sup>)

Figure 4.12 Total soil water potential profile during the rainy season in Miombo woodland

Soil water replenishment continues with  $\psi$  of values less than -10 kPa (Figure 4.12d) recorded during peak rainfall times such as April, implying that the soil field capacity was attained. It is

acknowledged that, at this point, soil water redistribution is suspended and any incoming net rainfall in the form of infiltration contributes directly to percolation (i.e. deep drainage) flowing past the root zone under gravitational pressure. Additionally modelling with WAVES gives more clarity on the timing of the onset of drainage, as discussed in Section 4.5 of this paper.

#### **4.4.4 Observed temporal variability of soil water potential in Teak during the rainy season**

Figure 4.13 depicts the vertical soil water potential profile beneath Teak forest plantations as it changes during the course of the rainy season. The following observations were made:

- Soil water potential increases throughout the monitored soil profile, starting from the top soils and gradually proceeding to lower depths;
- The top 1 m soils respond to the rainfall with immediate effect, while soils below 1 m and those at 2 m show a delayed response;
- Drying soils at a 3 m depth (Figure 4.13a), at the initial stages of the rains before the wetting front reaches this depth the soil water flux (infiltrating water) is directed downwards to replenish the moisture;
- ZFP locations were dynamic during the wet season with cZFP development at the depth of 0.9-1.0 m and 2m (Figures 4.13c and d, respectively);
- The zero flux zone disappeared in the course of time but only after the whole soil profile was fully wetted; and
- Soils beneath Teak attained field capacity towards the end of the rainfall season, in the month of April 2008/09, as indicated in Figures 4.13d, after which the flux of soil water beyond the root zone to recharge deeper soil layers (deep drainage) begins.

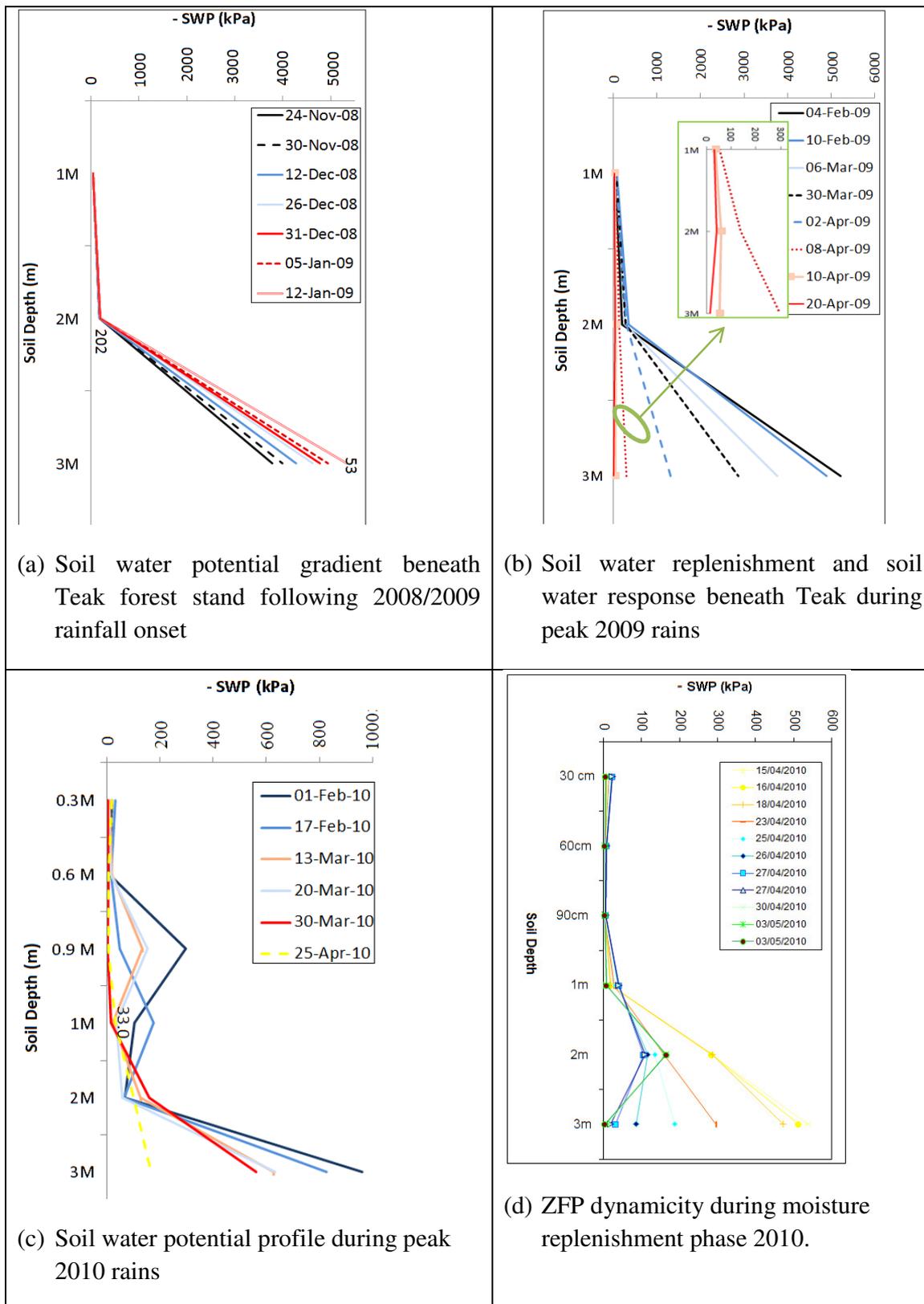


Figure 4.13 Total soil water potential profile during the rainy season in Teak forest

From the above observations it can be concluded that the soil water replenishment phase can be used to deduce the pre-existing magnitude of the soil water deficit. The time taken for the soils to get fully wetted gives an indication of the magnitude of the soil water deficit existing in the soils. According to Marshall and Holmes (1988), as cited in Veenendaal *et al.* (1996), soil water deficit is the amount of rainfall required to return the soil profile to field capacity. While it took a longer time for the Teak soils to attain field capacity (i.e. from the November to April rains) for both the 2008/9 and 2009/10 seasons, the Miombo soil profile was fully wetted a month before Teak. The difference of the total amount of the rainfall amounted to 180 – 200mm, signifying a difference in soil water deficit between Teak and Miombo.

## **4.5 Simulation Results of Soil Water Balance Response to Forest Conversion**

### **4.5.1 A comparative analysis of the water-limiting conditions**

The WAVES model satisfactorily reproduced the water use during the dry season, as depicted in Figures 4.14a and b. The dry season is characterised by a progressive decrease in Teak transpiration water use (cf. Figure 4.14a) while Miombo woodland transpiration appears to be more or less stable over the course of time (cf. Figure 4.14b).

Generally, the model was able to fairly mimic the transpiration pattern of Teak, with some discrepancy on extreme values (peaks and depressions) as indicated in Figure 4.14a. This was attributed to the fact that the modelled transpiration is atmospheric demand-driven (closely mimicking the VPD pattern) while in practice, as elaborated in previous paper (Chapter 3), Teak evaporative water use is more sensitive and limited by soil water conditions than it is to the atmospheric demand. This was attributed to the highly efficient stomatal control mechanism of Teak trees which, during the periods of very high evaporative water demand, limits the tree water use, a process not properly accounted for in WAVES. However, in Miombo both the observed and the simulated water use closely followed the atmospheric demand (VPD) trend.

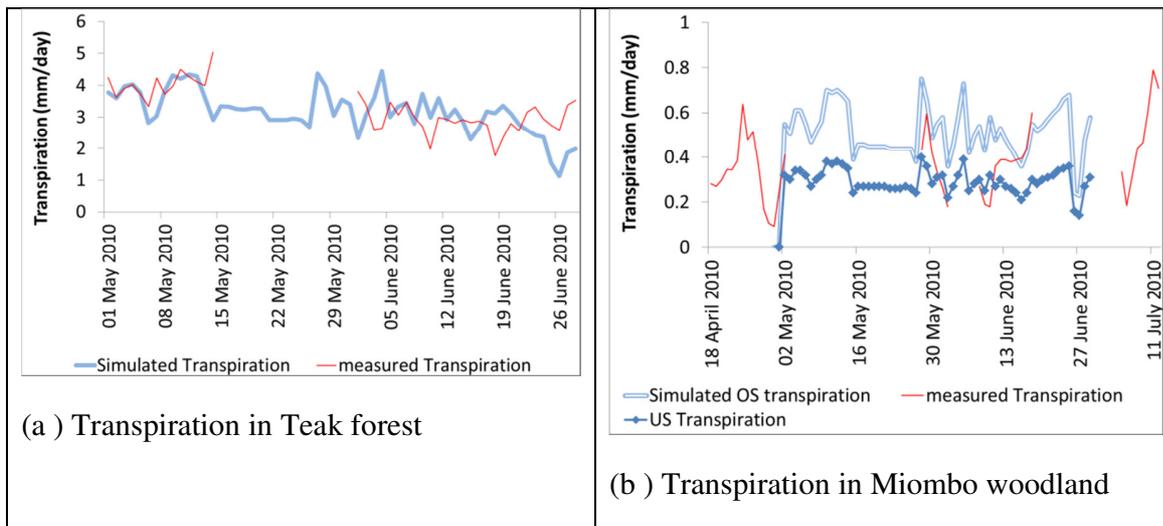


Figure 4.14 Comparison of the simulated and measured transpiration in both Teak and Miombo woodland after rainfall ceased in May–June 2010 (gaps in the measured transpiration data are missing data. US stands for understory vegetation; OS is overstorey vegetation). NB. The scales in the two figures differ due to a large difference in the values presented and for purpose of clarity.

It was noted that the model consistently over-estimated Miombo consumptive water use, as indicated in Figure 4.14b. However, the understory (US) water use was not monitored in the field thus no conclusive statement could be made concerning its dynamics. It should be noted that, during the modelling exercise, the US transpiration was set to the minimum possible water use, considering the vegetation structural parameters, while simultaneously constraining the soil water conditions (soil drying pattern) to within the measured range.

Further, the model was checked for its ability to reproduce soil water dynamics beneath Teak and Miombo forests, as depicted in Figures 4.15a and b. In spite of over estimations, the soil water status beneath Miombo was successfully reproduced by the WAVES model. The soils in the Miombo woodlands are characterised by the progressive drying of upper soil layers, as indicated in Figure 4.15b with the drying front gradually moving downwards. This indicates a progressive transition of root water uptake from shallow to deeper layers, in line with field observations, as highlighted in Section 4.4.1 of this paper. From the simulations, the soils in the Miombo forests maintained wet conditions in the first 30 days when  $\psi$  was about  $-20\text{kPa}$  (2 m of water) representing considerably wet soils.

The Teak forest, on the other hand, (Figure 4.15a) shows higher root water withdrawals at deeper depths beyond 1.5 m due to its exponential root density profile (cf. Section 4.3.3.1). Thus, access to deep soil water reserves at 4 m and below, is attainable by the use of its tap root system. Soils beneath the Teak forest stand show evidence of greater soil water deficits, compared to the soils beneath Miombo throughout the season, with the maximum zone of root influence extending to a 4 m depth as opposed to 3 m in Miombo.

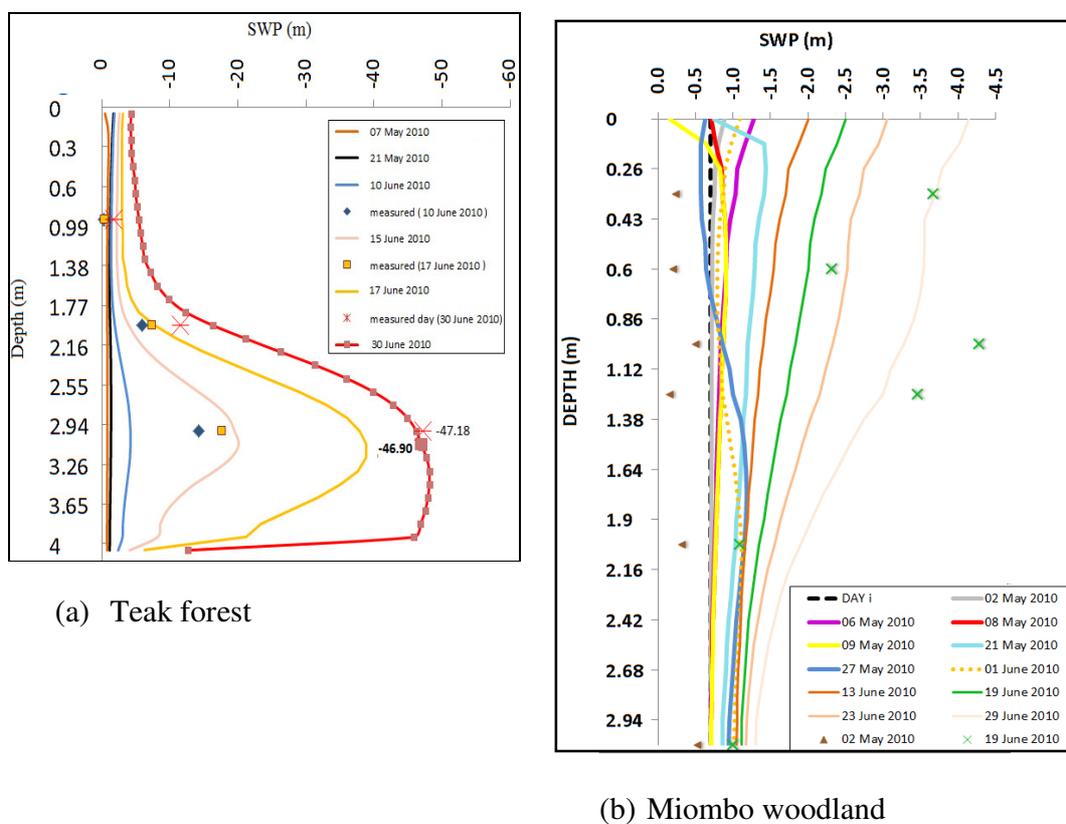


Figure 4.15 A comparison of the simulated and measured soil water potential profile beneath Teak and Miombo forest during the dry season

At the end of these 60 days, simulations of the dry season root water uptake resulted in significant soil drying beneath Teak, to a maximum depth of 4 m, while soils beneath Miombo were affected only to a maximum depth of 2 m (Figures 4.15 a and b).

#### 4.5.2 Modelling of the soil moisture replenishment phase during the non-limiting soil water conditions

The 180 days of wet season simulation results are illustrated in Figures 4.16 a and b, where it is shown that there was a better agreement between observed and simulated wet season forest transpiration. During this time, the transpiration of both Teak and Miombo forests seem to closely follow the VPD measurements, with the exception of Teak peak values, a discrepancy also observed during the dry season as highlighted earlier in Section 4.5.1.

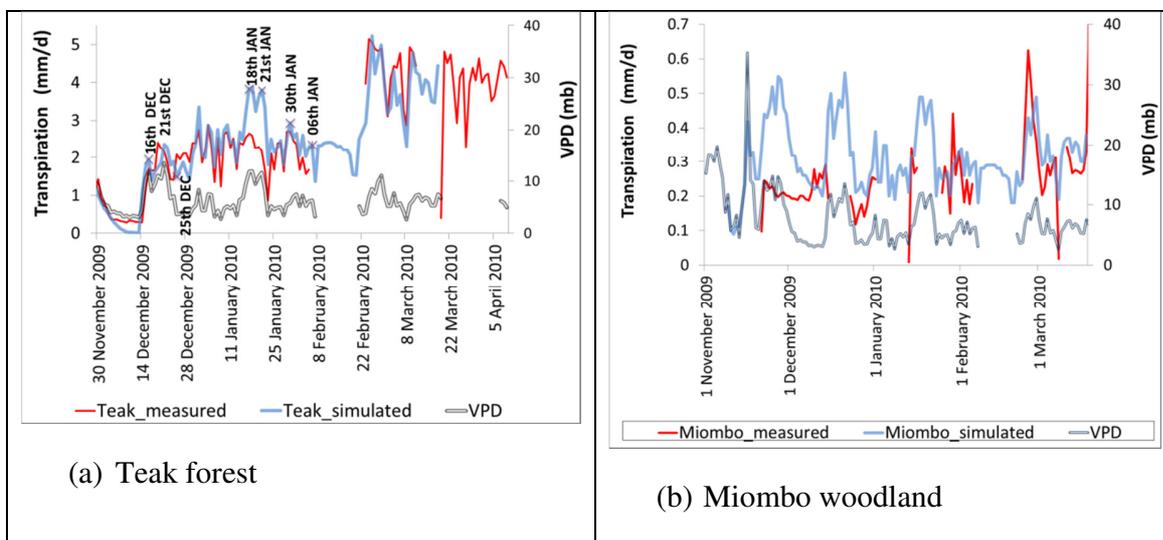


Figure 4.16 A comparison of the simulated and measured soil water potential profile beneath Teak and Miombo forest during the wet season. NB. The scales in the two figures differ due to a large difference in the values presented and for purpose of clarity.

There are a few occasions, specifically in Teak, where the model showed poor performance. These were mainly periods of dry spells, with stable or high atmospheric water demand. For instance, the period between the 18<sup>th</sup> and 21<sup>st</sup> January 2010 where the modelled transpiration was very high compared to the measured values, and the period between 30<sup>th</sup> January 2010 to 2<sup>nd</sup> February 2010 when in-situ measurements indicated a decreased transpiration rate (in response to soil water conditions) while the simulated transpiration remained stable (in response to a stable VPD).

Generally, the WAVES model appears to be driven more by VPD (evaporative water demand) during non-limiting soil water conditions with less sensitivity to soil water patterns. Teak evaporative water use is more influenced by soil water availability and is affected by dry spells. This is confirmed by observations on 25<sup>th</sup> Dec, 2009 (Figure 4.16a) where actual Teak transpiration rates seemed unresponsive to a decline in the VPD. This is probably due to the fact that it was raining at this time and hence the soil water conditions were non-limiting.

#### **4.5.3 Impact analysis of forest conversion on soil water balance**

The WAVES model provided a platform for linking the soil, vegetation and atmospheric characteristics separately monitored on the ground earlier in this study. It has already been established in Chapter 3 that the establishment of extensive Teak forests, at the expense of Miombo woodland, changes the transpiration regime of the forest. Forest conversion changes the forest canopy architecture, which subsequently changes the root water uptake characteristics, moisture storage and drainage pattern of the soils in the forest. Likewise, through modelling, it was established that the major impacts of forest conversion in the Kilombero Valley (i.e. from the indigenous Miombo woodland to the exotic broad-leaved Teak forest) relate mainly to the difference in the forest's evaporative water use (Figures 4.16a and b). Other partitioning points simulated by WAVES, but not monitored in this study, include the difference in interception losses and throughfall (Figures 4.17a and b). All these, in turn, enforce a change in the root zone soil moisture storage and drainage characteristics. Further, it was demonstrated that a change in the canopy structure of a forest changes the throughfall and soil drainage characteristics. Consequently, less net rainfall infiltrates into the soils under Teak as compared to Miombo, illustrated in Figures 4.17a and b. Teak's high LAI, in comparison with Miombo woodland, largely contributes to this difference.

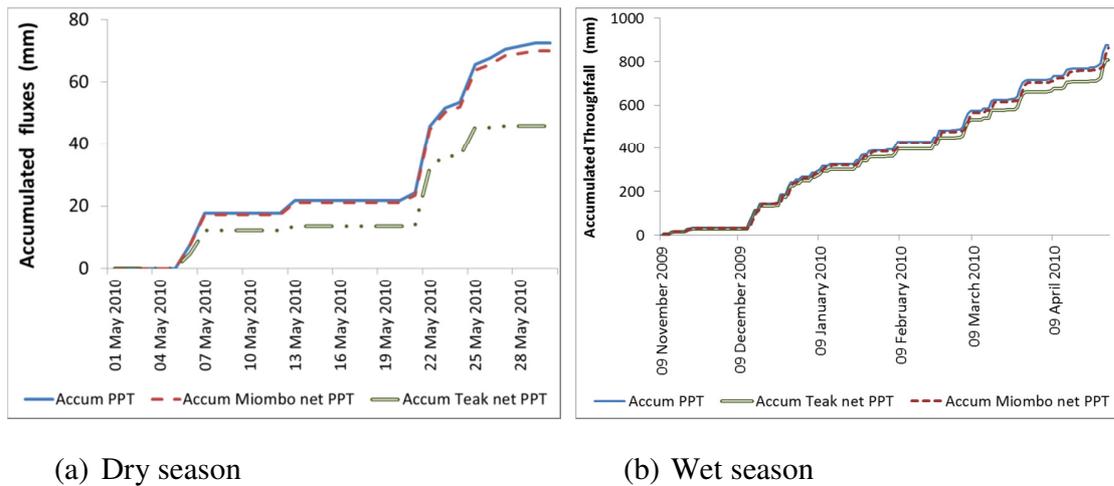


Figure 4.17 A comparison of the simulated net rainfall in Miombo and Teak during the model simulation period

Analysis of the net rainfall, both in Teak and Miombo, reveals that, out of the total precipitation recorded during the dry season, 4% was intercepted by the Miombo canopy while the Teak canopy intercepted about 37% (Figure 4.17). During the wet season, WAVES simulated 8% interception by Teak and 1% by Miombo. In both cases, Teak was found to have a higher canopy interception compared to Miombo.

Deep drainage flux is a crucial indicator in the assessment of the establishment, sustainability and productivity of vegetation biomass, since it directly affects the replenishment of soil moisture. Deep drainage occurs below the root zone, specifically below cZFP and influences the recharge mechanisms to groundwater. Figures 4.18a and b indicate that there was less contribution to recharge of soil moisture beyond the root zone of Teak forest compared to Miombo woodlands for both dry and wet seasons during the simulation period.

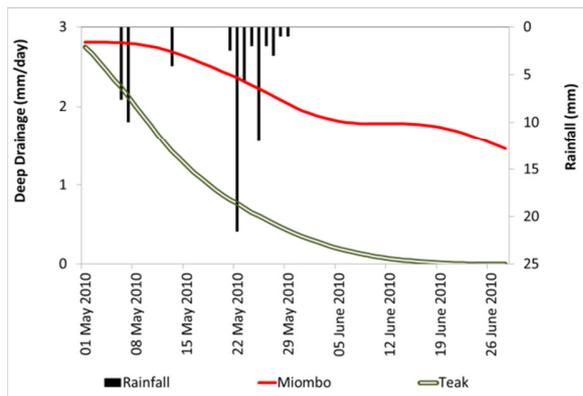


Figure 4.18a Deep water drainage decay beneath Teak and Miombo forest in the dry season

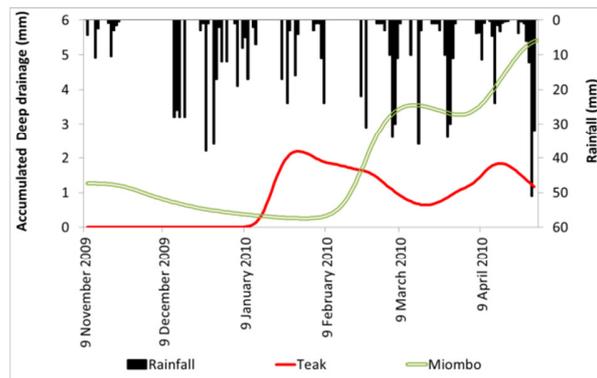
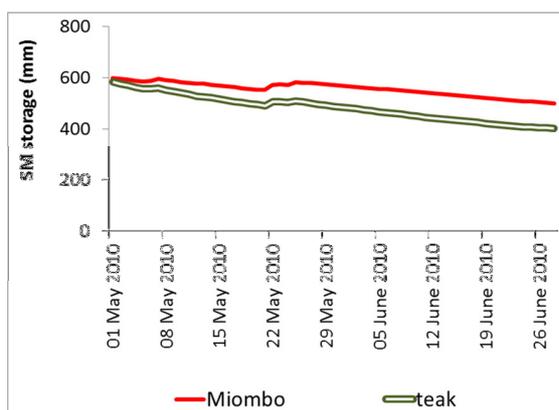
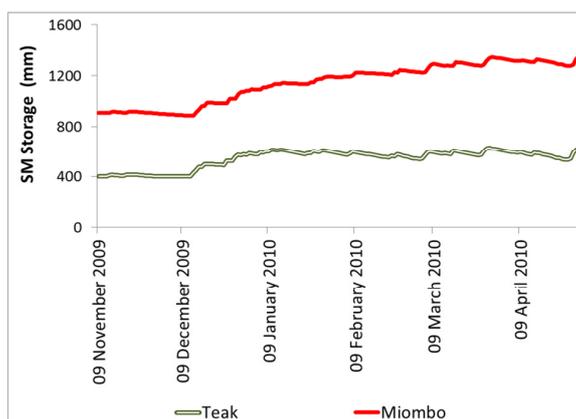


Figure 4.18b Deep water drainage recharge beneath Teak and Miombo during the wet season



(a) Limiting soil water season



(b) Non-limiting soil water season

Figure 4.19 A comparison of soil moisture storage changes in Teak and Miombo in the course of the two selected simulation seasons ( $\Delta$ SM storage = Rainfall – Interception – Evapotranspiration – Drainage)

With regard to the time taken for deep soil water to drain beneath the root zone, the soils in the Teak forest took less than 30 days after cessation of rainfall, decreasing progressively from the rate of 2.8 mm/day (Figure 4.18a), while Miombo soils continued to drain at a rate of 1.5 – 2.5 mm/day after cessation of rainfall. The latter is a good indicator and assurance of the continuance of recharge of deeper soil water reserves in the dry season under Miombo. This partly explains

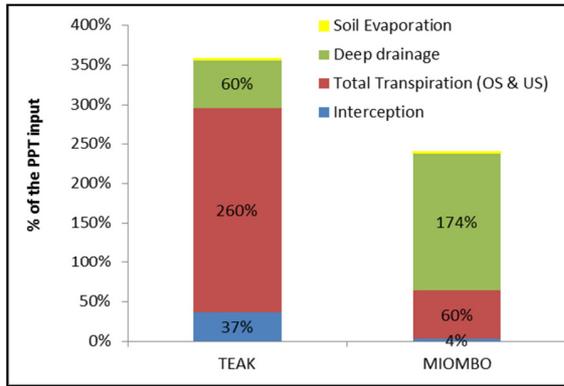
the observed phenomenon in the continued recession of the measured Teak transpiration (Figures 4.5 and 4.14a), as noted in the months of June to September, where only night time transpiration was observed in the month of September (as discussed in Chapter 3) and ceased completely afterwards. This clearly indicates that the soil moisture reserves beneath the Teak forest could no longer support transpiration by the end of August, three months into the dry season.

The impacts of the conversions were further assessed by studying the soil moisture reservoir, which determines the ability of the vegetation to withstand prolonged drought. The simulations show that the soil water storage beneath Teak was lower than that of Miombo throughout the simulation period (Figures 4.19a and b). This explains the observed prolonged and stable transpiration of Miombo further into the dry season (Figure 4.5).

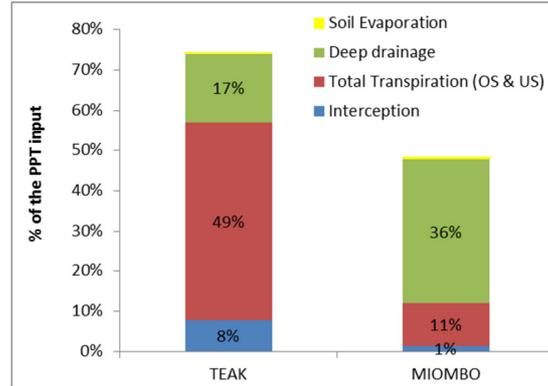
#### **4.5.4 Implications of forest conversion on the canopy partitioning of rainfall**

One of the documented impacts of forest conversion, as noted earlier, is on the hydrological partitioning of the precipitation. This analysis has indicated that 37% of incoming precipitation over the Teak forest is released back to the atmosphere through canopy interception. In addition, this study has established that Teak forests extract soil water for transpiration to the value of 2.6 times the total incoming rains during the period of light rainfall showers approaching the dry season (May and June in Figure 4.20a). Figure 20b shows that 50% of the incoming rains are used up by Teak for consumptive water use compared to 11% by Miombo. It was also noted that 17% of the incoming rainfall during the wet season was released to deep water drainage to recharge the ground water reserves in the Teak forest compared to 36% in the Miombo forest.

From this study, it was observed that during the dry months of May and June, Teak forests drew soil moisture reserves to the magnitude of 260% of the incoming rainfall while the rains that were received in the month of May were enough to cater for Miombo consumptive water use and the rest contributed to deep drainage, which was 174% of the received rainfall (Figures 4.20a and b).

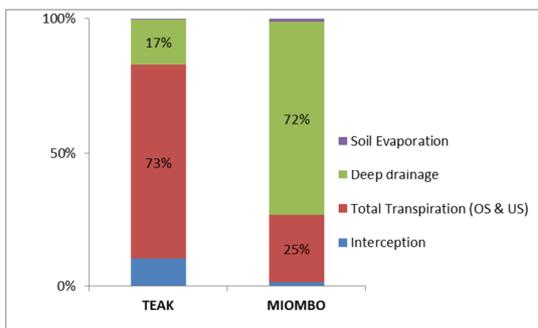


(a) Fluxes during the simulated dry season

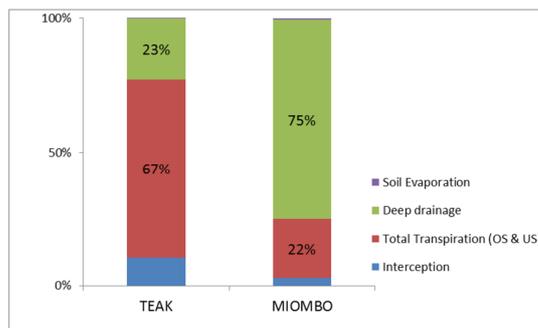


(b) Fluxes during the simulated wet season

Figure 4.20 Various fluxes expressed as a percentage of the incoming rainfall during the simulation period



(a) Simulated dry season



(b) Simulated wet season

Figure 4.21 Comparison of the soil water balance in the Teak and Miombo forests

The soil water balance analysis, illustrated in Figures 4.21a and b, indicates the consistent consumptive water use by the Teak forest stand of up to 70% of the total soil moisture reserve while the water use by Miombo woodland was about 25% of the total soil water storage in the respective forests. The remaining part of soil water storage contributed to deep percolation. Generally, from Figures 4.20–4.21, the Teak forest had the highest consumptive water use while more deep drainage was noted in the native Miombo woodlands.

#### **4.5.5 Impact of rooting depth on tree transpiration**

As was noted in the introductory section, with regard to challenges involved in determination of the forests' maximum zone of root influence, a prerequisite for running the WAVES model, attempts were made to study the sensitivity of this parameter, amongst others, on simulated vegetation water use. Particularly, difficulties were encountered with unusually high Teak transpiration rates requiring that several simulations to be run at different rooting depths. It was noted that, for Teak to sustain the measured overstorey consumptive water use, it has to have a zone of root influence beyond the maximum monitored at the field of 3 m. Increasing the maximum root depth increases the soil moisture storage zone, making greater quantities of soil water available to sustain transpiration during the dry season. The impact of the rooting depth on tree water use is depicted in Figure 4.22 below and the implications on the soil water are depicted in Figure 4.23.

Figure 4.23 represents the results of simulations with variations in rooting depth. Even though, both the model output and the measured data is in daily time step, only a few days (day 5, 40, 54, 59) were selected for presentation of the comparison between the simulated and the measured values. The maximum rooting depth of 4 m was selected as the most suitable, as it closely followed what was observed in the field. This was in agreement with what was noted earlier in Section 4.4.1 and the literature on Teak rooting architecture (Section 4.2.3.1.).

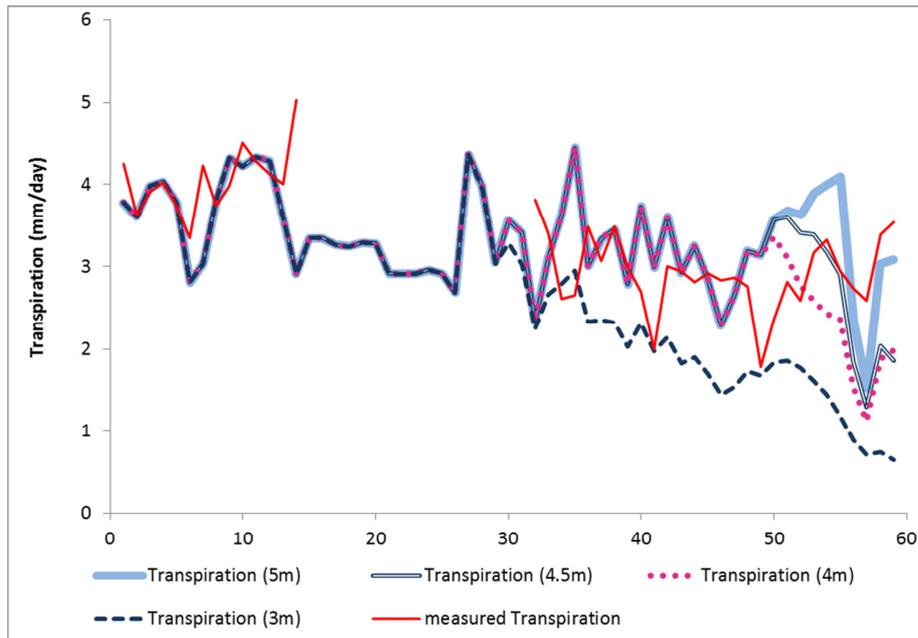


Figure 4.22 Effect of Teak tree maximum rooting depth on transpiration

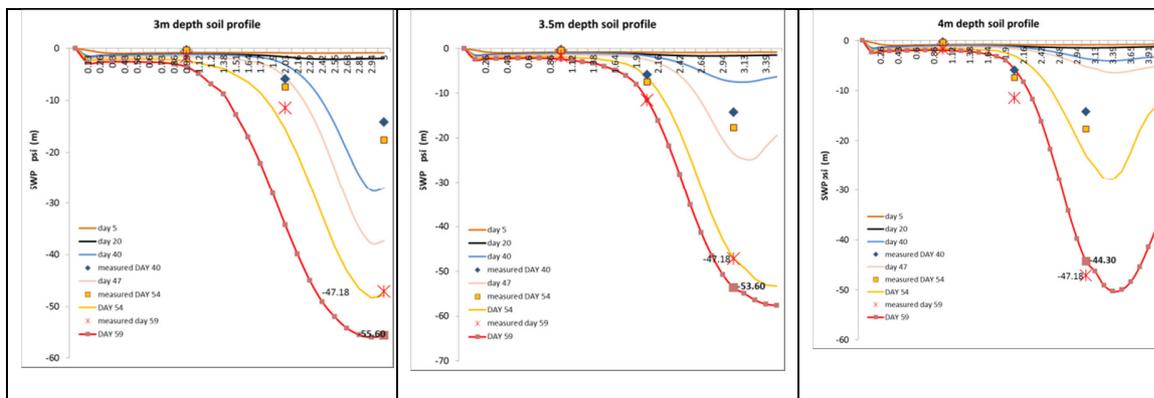


Figure 4.23 Comparison of simulated and measured total soil water potential ( $\psi$ ) in m beneath Teak forest depicting the effect of maximum rooting depth on soil water depletion pattern

## 4.6 Conclusions and Recommendations

This study has demonstrated that a change in the forest type, and therefore the forest stand structure, from indigenous Miombo woodlands to exotic Teak forest impacts negatively on the

replenishment of deep soil water reserves, both in terms of the amount and the period of contribution.

The most important components of the water balance in a forest ecosystem are tree water use, deep drainage and interception losses, the significance of each changing, depending on the forest stand structure. Thus, this study has established the impact of changing the forest structure of native Miombo woodlands with Teak forests, with regard to influencing the partitioning of incoming rainfall. It became evident that replacement of the well-adapted, deep-rooted, narrow-leaved native woodland with the broad-leaved exotic forest altered the partitioning of the incoming precipitation to different fluxes, such that there was eventually less drainage and more evapotranspiration, consequently reducing the soil water storage.

Further, the study established that the drainage response of soils beneath Miombo indicate a greater possibility of them acting as groundwater recharge zones since they continually drain, even after rainfall has ceased, while drainage of Teak soils is limited to rainfall availability.

The mechanism behind root water uptake in Teak follows a compensation approach, where root water extraction shifts with soil water availability, even though the root efficiency of deeper layers was observed. In line with studies like that of Markewits *et al.* (2010) and Romero-Saltos *et al.* (2005), forest root water extraction evidently goes beyond a 2 m depth in the dry season, with a subsequent upward soil water flux from deeper to shallow layers in response to hydraulic gradient.

Soil water profile beneath the Miombo woodland is characterised by a convergent plane. The lowest (most negative) soil water potential is located at a 1 to 2 m depth, with the minimum  $\psi$  of -4.4 MPa recorded on 8<sup>th</sup> November 2009, just before the rainfall onset, while Teak total potential profile ranges from -5.2 MPa at the driest profile of 3 m depth during dry the season to values around -10 kPa during the wet season. This implies that the Miombo woodland root water uptake dries up the root zone causing an upward flux of water from below the root zone.

During the dry season, the hydraulic potential gradients necessitate the movement of soil water upwards to cZFP locations. The mechanism of such soil water flux, especially from depths below cZFP, can either be through the usual capillary rise, or occasionally, by way of hydraulic lift (Richards and Cadwell, 1987; Dawson, 1996), where roots act as conduits to release moisture to

shallower depths. To ascertain this, further investigation of root water movement through tracer studies maybe necessary

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## 5. MAPPING EVAPOTRANSPIRATION IN THE KILOMBERO RIVER BASIN USING REMOTE SENSING TECHNIQUES

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### **Abstract**

Efficient management of water resources, at a river basin scale, requires up-to-date information on land cover types and their associated water use. Ground monitoring networks for providing such information encounter the challenges of inadequate spatial coverage. Some of stations are remotely located and are poorly maintained, a particular challenge in vast basins such as the Kilombero River Basin which covers more than 40,000 km and hosts national parks and game reserves.

This study examines the issues of data inadequacy by providing spatially averaged estimates of total evapotranspiration while considering the Basin's dominant land cover types and their historical transformation. The study used remote sensing techniques that were not limited to ground features or spatial extent. The Surface Energy Balance System (SEBS) algorithm was employed and a successful characterisation of the basin evapotranspiration (ET) regime was carried out. The study findings match the preliminary findings of the Kilombero Valley wetlands deterioration, as per Chapter 2. The study noted two distinct ET regimes, seasonally varying ET in floodplains and a more stable, almost constant mountainous ET regime. The Kilombero Basin (and the associated Ramsar site) has undergone drastic changes in the ET regime over time, in line with the historical land cover alterations. Further, development activities, like the establishment of broad-leaved exotic forests for timber production, have the potential to affect the ET and hence the hydrological regime.

**Keywords:** *Evapotranspiration, Land cover change, SEBS, Kilombero*

## 5.1 Introduction

Evapotranspiration (ET), a term referring to the combined sum of actual evaporation from land, vegetation and water surfaces, is one of the major fluxes in the hydrological cycle in the tropical region. In most of the landscapes in the tropical regions and sub-Saharan Africa, ET returns about 60% of the incident rainfall to the atmosphere (Kanae, 2006; Miralles *et al.*, 2011). Various approaches of obtaining evapotranspiration have been documented in the literature; however, there are numerous inherent challenges in obtaining reasonable estimates of evapotranspiration across spatial scales, due to the heterogeneity in landscapes and varying atmospheric dynamics across scales (Nordbotten *et al.*, 2006; Nouri *et al.*, 2013). Some of the point-based conventional methods of estimating ET include evaporation pans and lysimeters. Methods that integrate spatial surface heterogeneity include Eddy Covariance and Bowen Ratio (de Bruin *et al.*, 1995). The latter two methods are rather expensive for routine use over a long period of time and provide limited spatial coverage. They are also limited in that the area of enclosure does not allow the water loss from a representative surface to be measured (Dye *et al.*, 2008).

This study builds on the realisation of the challenges of extrapolating point meteorological measurements from observation stations to spatial averages, encountered as a result of surface heterogeneity (Su, 2002). Brutsaert (1999) expressed the same sentiments by highlighting the challenge of deriving the true regional average ET from an array of local point stations, given the usual variability of natural land surfaces. Recently, the scientific community has embraced the use of remote sensing techniques to quantify the evaporative water use of various land uses on a larger spatial scale due to their ability to estimate the evaporative water use across landscapes, thus addressing the spatial heterogeneity associated with varying terrains (Liu *et al.*, 2009; Evett *et al.*, 2012; Feng *et al.*, 2013).

However, these methods are applied with an understanding of their limitations. Availability of cloud-free images is the biggest challenges especially for mountainous areas. Most algorithms for satellite-derived ET estimates cannot function with cloud contamination due to the satellite sensors's inability to capture the land surface radiation critical in establishing land surface temperature. Another major setback is the frequency of availability of images, especially from high resolution sensor platforms (for example images from LANDSAT require 16 days). Also

important, as noted by Nouri *et al.*, (2013), is the fact that temporal differences in satellite imagery can originate from either ground spectral signatures or from sun position. Atmospheric corrections must be applied to account for this, as was the case with this study.

Critical to all physically-based approaches of estimating ET from remote sensing, is the accurate determination of sensible heat flux (H). This is particularly challenging since it is affected by multiple parameters including wind speed, temperature, surface roughness and atmospheric stability (Su, 2002; Gowda, 2008).

Furthermore, in Tanzania, like many other African countries, there are numerous challenges in installing and maintaining hydromet networks capable of capturing all the inherent flux dynamics across scales. Some of the obvious challenges include finances, technical capacity to maintain the monitoring systems and vandalism. Water resource management in Tanzania is implemented at river basin scale, in accordance with Tanzania's Water Resources Management Act of 2009 (GoT, 2009). The river basin management framework relies on hydro-climatological data collected by the respective basin water authorities and other relevant agencies in both the private and public sectors. However, the inadequacy of these datasets (as highlighted above) has been a major issue of concern and a limitation to the advancement of scientific research as well as effective water resource management in the country. Given the undulating landscapes, complexities associated with topography and poor accessibility in many river basins in Tanzania, most of the hydro-meteorological measurements have been carried out in locations that are easy to access.

The Kilombero River Basin, like most other basins in the country, lacks key information on past or current hydro-meteorological signatures, especially in the mountainous areas where most of the Kilombero streams have their source and which can thus be considered to be the 'water towers' of the Basin. This calls for efforts to monitor and determine the fluxes of the hydrological cycles at management scale, where the application of remote sensing techniques are proven to be beneficial and applicable. In this study, remote sensing techniques were preferred over conventional approaches of extrapolating point measurements to cover large spatial extents as they provided the opportunity to study the Basin ET, capturing the spatial variation across the different land covers and, in the course of time, including the remote and non-instrumented areas. This is the first attempt in the Kilombero Basin to apply this technique in assessing such fluxes.

A synthesis of remote sensing algorithms for estimating ET has been documented by Courault *et al.* (2003) and Zhao *et al.* (2005) and, more recently, as reviewed by Kalma *et al.* (2008), Li *et al.* (2009) and Bala *et al.* (2013). There has been a wide application of some of the algorithms with some countries adopting their use in routine water resource management and planning (Kramber *et al.*, 2008; Anderson *et al.*, 2012). The most common approach that has been adopted in estimating ET, using remote sensing techniques, is land surface energy balance modelling which relies on the principle of the conservation of energy on the earth's surface (Hantel, 1993), as illustrated in Equation 5.1.

$$R_n = H + LE + G_o \quad [5.1]$$

where  $R_n$  is the net radiation ( $\text{Wm}^{-2}$ ),  $H$  the sensible heat flux ( $\text{Wm}^{-2}$ ),  $LE$  the latent heat flux ( $\text{Wm}^{-2}$ ) and  $G_o$  the soil heat flux ( $\text{Wm}^{-2}$ ). Exchange of water in the soil-vegetation-atmosphere continuum is governed by the latent heat flux (the energy responsible for changing the liquid state of water on the earth's surface into vapour). Essentially, it is the energy that controls the ET process (Bastiaanssen, 2000; Wu *et al.*, 2006; Kimura *et al.*, 2007). In recent decades, a number of surface energy balance algorithms have been developed, including the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen *et al.*, 1998); the Surface Energy Balance Index (SEBI) (Menenti and Choudhury, 1993); Surface Energy Balance System (SEBS) (Su, 2003); S-SEBI derived from SEBS (Roerink *et al.*, 2000) and Mapping Evapotranspiration with Internalised Calibration (METRIC) (Allen *et al.*, 2002; 2005; 2007). Generally, the main difference in these energy balance algorithms is in the estimation of the sensible heat flux (Gowda *et al.*, 2007). The SEBS Model, an open source and less data intensive model, was used in this study.

This research was carried out in the Kilombero River Basin, host to a Ramsar site in the Kilombero Valley, which is also a “hot-spot” for uncontrolled settlement and agricultural development activities. Concerns exist around the rapid development within the Basin, such as the establishment of Teak forest plantations in 1992 and their subsequent expansion by more than 2400 ha (at the expense of indigenous Miombo woodland) between the years 2002 and 2008 (Chapter 2) and the expansion of other commercial plantations, such as sugarcane plantations, by more than 7,000 ha between years 1999 and 2005. Such human encroachment and exploitation has the potential to alter the water balance in the Valley and the river Basin at large. This study

was, therefore, carried out with the objective to: (1) validate the SEBS model in the Kilombero Basin; and (2) map the spatial-temporal variation of ET across the Kilombero landscape, with a view to assessing the impacts of the major land cover changes on the Basin's ET regime occurring between 2002 and 2008.

The SEBS model has been successfully applied in other parts of the world in a number of studies and validated over a range of catchment conditions (Su *et al.*, 2005; Rwasoka *et al.*, 2011; Gowda *et al.*, 2013). The need to estimate the spatial variation of evaporative water use of the human-induced landuses in the Kilombero Basin such as irrigated crops (mainly sugarcane plantations) and exotic deciduous Teak forests, while comparing the same against estimates from smallholder farming activities in the surrounding area, cannot be over-emphasised.

A common trend for hydrological impact studies is to consider the impact on catchment water yield, originating from land use/cover changes. However, the basis of such conclusions are derived mainly from acknowledging that land cover alterations directly alter the evapotranspiration regime. Deforestation impact studies link the impacts of forest clearance to a reduction in evapotranspiration, hence the increase in available water resources, while afforestation impact studies such as those of Calder (1993), Calder *et al.* (1995) and Legesse *et al.* (2003), argue that afforestation affects annual flow by increasing the interception storage during the wet periods and increasing transpiration during the dry seasons. A common argument, or assumption, in such studies being that afforestation or deforestation leads to an increase or decrease in evapotranspiration. A review of 94 catchment experiments by Bosch and Hewlett (1982) on the vegetation changes impacts on ET revealed that the impacts depend on the forest type such. For example, Coniferous and Eucalyptus cover changes resulted in about 40 mm change in annual water yield while deciduous hardwoods were responsible for 25 mm change in annual water yield. It is for this reason that this study embarked on the analysis of impacts of the land cover changes on the evapotranspiration regime.

## **5.2 Study area description**

The Kilombero River Basin, with an approximate area of 40,727 km<sup>2</sup> occupies the central and the southern part of Tanzania, with the Udzungwa mountain ranges towering on the north-western

side and the Mahenge Mountains on south-eastern side of the Basin. The Kilombero River runs as a series of parallel streams (braided river) between these two mountain ranges, as seen in Figure 5.1, traversing a flat valley which was designated as a Ramsar site in 2002 (Starkey *et al.*, 2002).

The major land covers in the Basin include the evergreen forests situated on the mountain ranges, deciduous woodlands, wetlands, settlement area and farming (both large- and small-scale, irrigated and rainfed agriculture) (Figure 5.1). The north-eastern part of the Basin is inhabited mainly by irrigated sugarcane growers, both large-scale (Illovo Sugar Company) and small-scale outgrower farmers. Figure 5.2 shows the area of sugarcane outgrowers over time in the Valley, which has increased significantly since 2001.

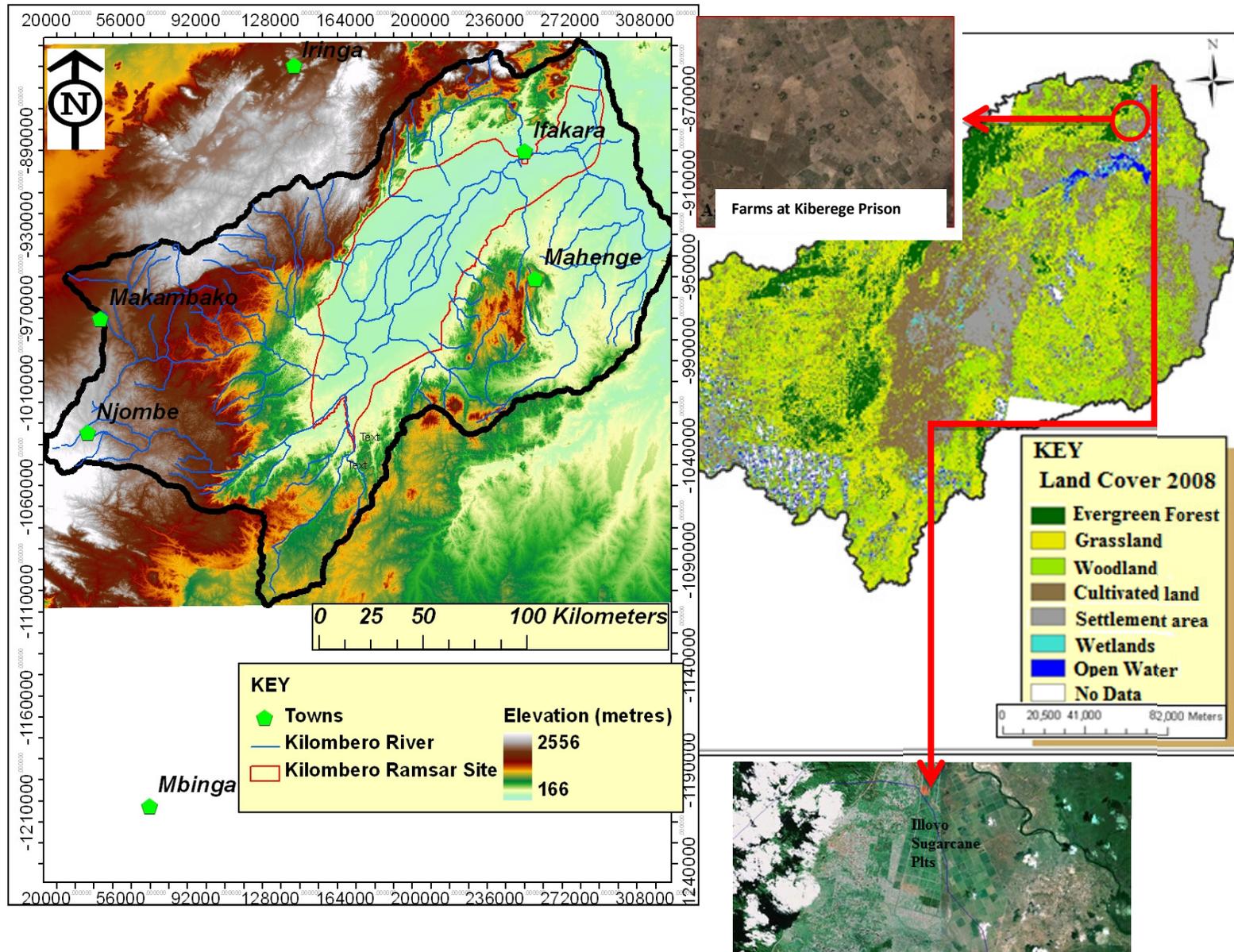


Figure 5.1: Relief map and land cover map of the study area derived from 2008 Landsat images

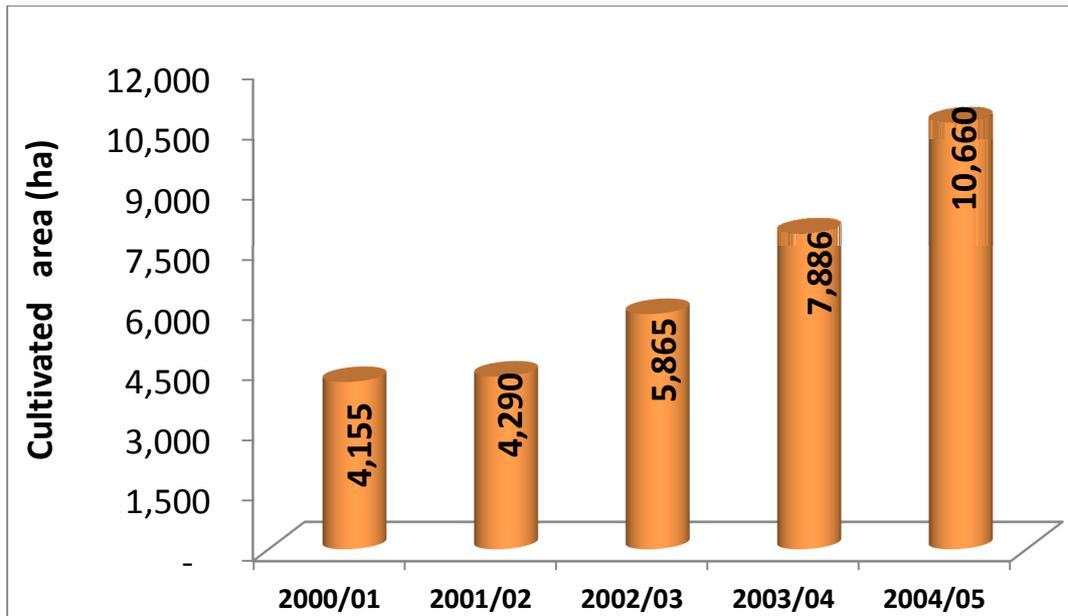


Figure 5.2 Out-growers' area under sugarcane over the years (data from GOT, 2006)

Climatologically, the study area is characterised by moderate rainfall amounts of about 1300 mm mean annual rainfall, where the wet season starts in December and peaks in April, while June to November are dry season months (Figure 5.3). The maximum daily temperature was found to be 34°C (Figure 5.3) between the months of November and January. Maximum humidity, frequently greater than 90%, was observed during the peak rainfall season in the months of March and April. During the dry season, the atmospheric demand increases, starting in the month of June and peaking just before the beginning of the short rains in November. It was also observed that the month of July was characterised by a vapour pressure deficit (VPD) of around 2-2.3 kPa, as indicated in Figure 5.4. The average wind speed in the Valley is around 2 m.s<sup>-1</sup>, with occasional events where wind speeds reach up to 4 to 5 m.s<sup>-1</sup>.

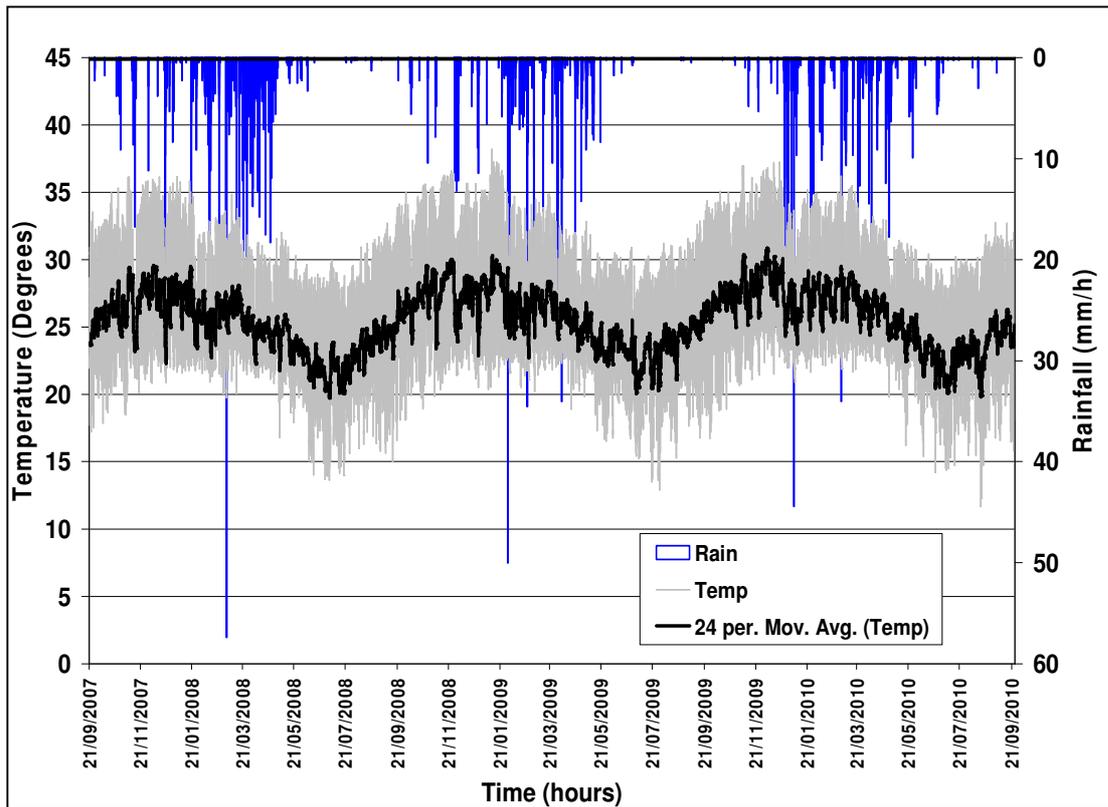


Figure 5.3 Rainfall and temperature regimes of the study area

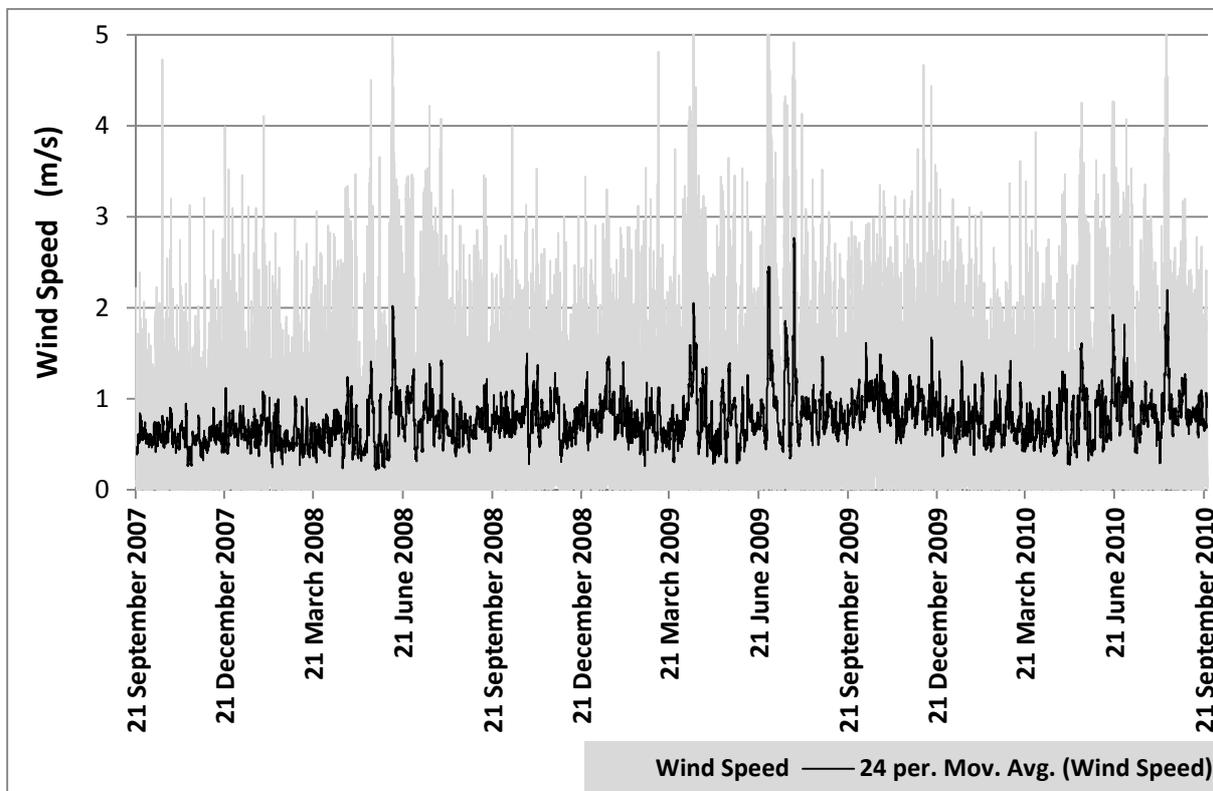


Figure 5.4 Seasonal characteristic of mean hourly wind speed at Illovo sugar plantation

### **5.3 Methods and Materials**

Evapotranspiration was estimated by remote sensing approach using a surface energy balance model as elaborated in Section 5.3.4. Field measurements of the components of the energy balance were undertaken so as to compare with the instantaneous model output for the sole purpose of checking the validity of the outputs of the surface energy balance model in the local conditions. These were accompanied by measurements of the meteorological conditions as elaborated in subsequent sections of this paper. In this study, both medium and low resolution satellite images were used in an attempt to map the Basin evapotranspiration.

#### **5.3.1 Meteorological data**

There were two automatic weather stations (AWS) utilised during the course of this study. The first, a Campbell Scientific CR800 (Campbell Scientific Inc., Logan, UT) was owned by Illovo Sugar Plantations and located within their premises (S7.698, E36.998). This station was installed in 2007 and logs data at one-hour interval. The other AWS, a Davis system (MC Systems, Steenberg, Cape Town) logging at one-hour interval, was installed in 2008 during this research study and located at the Ichima experimental site (S8.056, E36.505) in the forested lands of the Kilombero Valley Teak Company.

#### **5.3.2 Ground measurements of the surface energy fluxes**

The accuracy of surface energy balance modelling is dependent on the accuracy of the computed available energy ( $R_n - G$ ) which eventually influences the accuracy of sensible heat flux ( $H$ ) estimated by the model (cf. Equation 5.1). In-situ measurements of surface energy balance components, net radiation flux ( $R_n$ ), soil heat flux ( $G$ ) and sensible heat flux ( $H$ ), were carried out for the sole purpose of validating the estimated fluxes from SEBS. The SEBS estimates of sensible heat flux ( $H$ ), estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) images, were compared with field measured values obtained from a large aperture scintillometer (LAS) for pixels overlaying the measurement transect. Net radiation ( $Rn$ ) was measured by a net-radiometer (NRLite, Kipp and Zonen, Delft) and

logged into a Campbell Scientific CR800 data logger. Soil heat flux ( $G$ ) was measured, using 8 cm diameter disk soil heat flux plates (Model HFP01, Hukseflux) buried horizontally at 8 cm below the soil surface. The soil heat flux plates were connected and logged into the Campbell Scientific CR800 data logger

In this study, two sites were instrumented with monitoring devices at different times for the purpose of validating the remotely-sensed surface fluxes derived from SEBS. These were a mixed cropland area at the Kiberege Prison farm and a sugarcane plantation at Kidatu (Figures 5.1 and 5.5). Considerations relating to power supply and security were taken into account in the selection of sites. During the wet season (Dec 2009 – May 2010), the Kiberege Prison farm (Figure 5.5) was the main instrumentation site; but due to challenges with the power supply for the LAS as well as for security reasons monitoring equipment was moved to the Illovo Sugar Company premises at Kidatu. Measurements over sugarcane plantations were observed at this site between July and September 2010.

$H$  was measured using a BLS900 Scintec large aperture scintillometer (Meijninger and de Bruin, 2000) over a transect of 800 m. A large aperture scintillometer consists of two disc-shaped transmitters which in turn consist of an LED and a receiver (Figure 5.5) located at a distance from the transmitter (Meijninger and de Bruin, 2000). This is known as the next most accurate method for estimating ET after the Eddy Correlation (EC) system but with the advantage of a larger coverage area. LAS is also easy to install, relatively cheap and requires less human attention in the field compared to the Eddy Correlation systems (Ezzahar *et al.*, 2007). The LAS has been applied and tested with Eddy Correlation systems in several case studies and shown to be a viable method for estimating averaged  $H$  (Hill *et al.*, 1992; Nieveen *et al.*, 1998; Meijninger *et al.*, 2000). It has also been found to potentially provide good results over moderately inhomogeneous surfaces (Meijninger *et al.*, 2000; Beyrichet *et al.*, 2002).

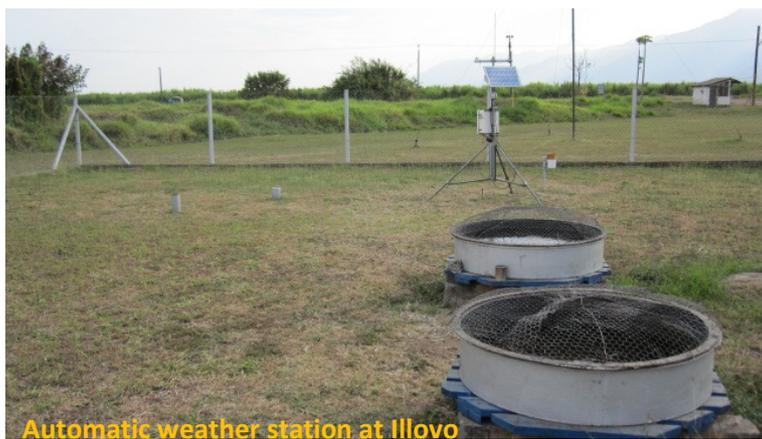


Figure 5.5 Instrumentation installed, large aperture scintillometer and automatic weather station, at Kiberege Prison farm and at Illovo sugarcane plantations

### **5.3.3 Satellite data acquisition and utilisation**

#### **5.3.3.1 Comparison of satellite derived products with field measurements**

The SEBS model, applied in this study, has been validated locally in a number of studies over a range of land covers (Jia *et al.*, 2003; Su *et al.*, 2005; Jia *et al.*, 2012). In this study, the comparison of in-situ measurements (at Kidatu area) and satellite-derived energy fluxes was carried out for the month of August 2010, the only month that was found to have cloud-free satellite images over the study site and which coincided with the field campaigns. As noted earlier, the availability of cloud-free satellite images was a significant challenge and a limitation to this study. Throughout the wet season, when the scintillometer was at Kiberege farms (December 2009 – April 2010), no suitable image for analysis could be obtained from either MODIS or Landsat. In fact, from June to September 2010, only two quality MODIS images for the Kidatu sugarcane farms ( 15<sup>th</sup> and 16<sup>th</sup> August) were obtained and none for Landsat were available. Therefore, the satellite-derived ET estimates from MODIS, at the time of satellite overpass, were overlapped with the LAS measurements and net radiometer measurements.

It is important to note that model evaluation entails analysing the accuracy of results and consistency of the spatio-temporal estimates. Given that only two images were suitable, providing essentially a “snapshot” of the instantaneous dataset,, model performance under local conditions could not be evaluated. Comparison between the measured and remotely-sensed data were, therefore, based on event observations in the month of August 2010, as detailed in the Results section.

#### **5.3.3.2 Historical analysis of the ET regime with satellite-derived products**

A total of nine satellite images from two different sensors (Landsat covering the years 1991 and 2002, obtained from the public [www.glovis.org](http://www.glovis.org) platform, and MODIS Level 1B images freely obtained from the NASA’s Level 1 Atmosphere Archive and Distribution System, LAADS, covering May 2010 to October 2010) were obtained.. Unfortunately, no good quality (cloud-free) Landsat images were available for the validation (field campaign) period in 2010. As a result, MODIS images were used instead. The latter has a daily temporal resolution, with a spatial resolution ranging from 250 m to 1000 m, depending on the band attributes. These images were used in the SEBS algorithm to derive the surface energy balance components and ET for the period represented.

### 5.3.4 Surface energy balance model (SEBS) for actual evapotranspiration estimation

The SEBS model is a single source, physically based model developed by Su (2002) for deriving daily actual ET by making use of the evaporative fraction ( $\Lambda$ ) obtained by remote sensing techniques. Evaporative fraction, assumed in this model to be nearly constant during the daytime, is the fraction of the available energy that is utilised in evapotranspiration (Su 2002, Gentine *et al.*, 2007). Latent heat flux energy, responsible for the evapotranspiration process, is determined as a residual of the energy balance equation (cf. Equation 5.1) after the determination of  $H$  and  $G$ . Sensible heat flux in this algorithm is obtained by constraining the energy balance modelling between wet limits (when ET is at its potential rate) and the dry limit (when ET is limited to the extractable moisture and hence the latent heat is assumed to be zero). This provision reduces the uncertainties that most surface energy balance models face with regard to the estimation of sensible heat flux. Ultimately, the model derives daily evapotranspiration (Equation 5.3) from daily net radiation and evaporative fraction which, in turn, is computed as a function of relative evaporative fraction  $\Delta_r$ , a function of  $H_{wet}$  and  $H_{dry}$  (Equation 5.2).

$$\Lambda = \frac{\lambda E}{R_n - G} = \frac{\Delta_r \lambda E_{wet}}{R_n - G} \quad [5.2]$$

$$E = 8.64 \times 10^7 \times \frac{\Lambda Rn_{day}}{\lambda \rho_w} \quad [5.3]$$

where,  $\rho_w$  is density of water ( $\text{kg m}^{-3}$ );  $Rn_{day}$  is daily net radiation ( $\text{W m}^{-2}$ );  $G$  is soil heat flux ( $\text{W m}^{-2}$ );  $H$ ,  $H_{dry}$  and  $H_{wet}$  are the actual, dry limit and wet limit sensible heat flux ( $\text{W m}^{-2}$ ), respectively;  $\lambda E$  and  $\lambda E_{wet}$  are the actual latent heat fluxes ( $\text{W m}^{-2}$ ) at the overpass and the hypothetical wet limit.

In this study, the pre-processing of the Landsat images for the retrieval of relevant land surface attributes necessary for the model operation was carried out in the ERDAS Imagine Ver 9.1 (Erdas, Inc., Atlanta, Georgia) model builder platform. This is due to the fact that the inbuilt Integrated Land and Watershed Management Information System (ILWIS) plug-in for SEBS does not have the provision for the pre-processing of Landsat images. The top atmospheric brightness temperature, commonly referred to as sensor temperature, was calculated using the inverse of Planck's function (Chander *et al.*, 2007; 2009) for both

Landsat and MODIS. Albedo was computed using the equation of Liang *et al.* (2001), while land surface temperature for Landsat images was computed using the mono-window algorithm (Qin *et al.*, 2001) and the thermal band. Surface emissivity was derived using the Normalized Difference Vegetation Index (NDVI) based approach after Liu and Zhang (2011), while the vegetation indices, leaf area index (LAI) and fractional vegetation cover (Fc) were computed using the inbuilt functions in the ILWIS plug-in for SEBS.

SEBS has proven to be dependable in a range of applications with the use of both moderate resolution satellite images like MODIS (Su *et al.*, 2005; Lin, 2006; Timmermans *et al.*, 2013; Rwasoka *et al.*, 2011) and high resolution data like Advanced Spaceborne Thermal Emission and Reflection Radiometer i.e. ASTER (Timmermans *et al.*, 2005; van der Kwast *et al.*, 2009; Badola, 2009) and Landsat (Jarmain *et al.*, 2009; Gowda *et al.*, 2013).

### **5.3.5 Corrective measures adopted in SEBS model parameterisation**

Challenges were encountered in the surface energy balance modelling of the Kilombero Basin due to the mountainous terrain and tall vegetation in the area. Specifically, the estimates of ground heat flux and sensible heat flux were questionable at high elevations, a concern also raised also by Timmermans *et al.* (2013). The relatively high resolution of Landsat images made them particularly useful in this exercise as they provided outputs at a field scale, allowing model performance to be assessed.

### **5.3.6 Challenges of higher canopy vegetation**

A higher surface roughness length ( $z_{om}$ ) of forests result in a reduced sensible heat flux ( $H$ ), an increased latent heat flux and relatively higher evaporation rates (Pitman, 1995; Harding *et al.*, 2000; Zhang, 1999; Birol *et al.*, 2009; Zhang *et al.*, 2010; Zhou *et al.*, 2012). Evaporation rates have been confirmed by a number of studies to occur at rates where the latent heat energy expended exceeds the supply of net radiation (Hashino *et al.*, 2010, Harding *et al.*, 2000; Klaassen, 2001; Stewart, 1977; Zhang, 1999; Calder, 1982). In most cases this is reported to occur on wet forest canopies. According to Stewart (1977) and Calder (1982), the

extra energy is supplied by advection which brings in the dry air mass, resulting in the cooling of the air mass above the forest and the evaporative fraction becoming greater than one.

In the preliminary observations of this study (results not presented here), it was observed that SEBS failed to produce reasonable estimates of sensible heat flux in areas with higher canopy (tall) vegetation such as forests. This was traced back to a failure to accurately parameterise  $H_{wet}$ , and, subsequently, the evaporative fraction and LE retrieval. Analytically, this can only be caused by a failure to solve the equation for wet limit external resistance ( $r_{ew}$ ) (Equation 5.4) in the event that  $z \leq d$  (i.e. zero displacement height exceeds the (reference) height from which the meteorological measurements were obtained) i.e.

$$r_{ew} = \frac{1}{ku_*} \left[ \ln \left( \frac{z-d}{z_{oh}} \right) \right] \quad [5.4]$$

Similarly, the horizontal wind speed at the canopy height  $U(h)$  that makes reference to the term  $\ln(z-d)$  could not be calculated when  $z \leq d_o$ . This occurrence, which takes place when the study area is composed of tall trees or forest canopies while the meteorological measurements are taken from a normal weather station at 2 m height, was also noted by Klaassen and van den Berg (1985) and Gibson *et al.* (2011). Usually,  $d$  is obtained from the maximum canopy height as  $d = 0.67h_c$  implying that, if the meteorological measurements were taken at  $z = 2 \text{ m}$ , the maximum canopy height  $h_c$  must be  $\geq 3$  for the equation to be solved. To alleviate the problem temperature, wind and humidity profiles from radiosonde observations are usually used in upscaling the meteorological data to higher reference height. However, radiosonde data were not available for the study site, thus the 2 m meteorological measurements for wind speed were extrapolated to a 9 m height (to match the nature of the forest vegetation present) using a logarithmic wind speed profile equation (Equation 5.5). Wind speed at a reference height  $u(ref)$  above the ground was, therefore, derived after Allen and Wright (1997) as follows;

$$U(ref) = U_{2m} \left( \frac{\ln \left( \frac{(h_{ref}-d)/z_{om}}{(2-d)/z_{om}} \right)}{\ln \left( \frac{(2-d)/z_{om}}{(2-d)/z_{om}} \right)} \right) \quad (5.5)$$

where  $d=0.67h$  and  $z_{om} = 0.123h$

In summary, throughout this analysis the measured wind speed at 2 m was scaled to reflect wind speed at 9 m in both Landsat and MODIS images.

Other corrective measures in the SEBS computation adopted by this study include the parameterisation of leaf area index (LAI). LAI derivation within SEBS uses the formula after Su (1996; 2002) which is a function of NDVI i.e.:

$$LAI = \left( NDVI \times \frac{1+NDVI}{1-NDVI} \right)^{0.5} \quad (5.6)$$

This formula systematically under-estimated the LAI of dense forest canopy due to the fact that LAI is known to be insensitive to high NDVI values (Gitelson *et al.*, 2003). In addition, Myneni *et al.* (1997) linked the same phenomenon to the weak relationship between the earth's surface reflectance and optical properties of the canopy, from which NDVI and LAI are derived. Similar concerns of LAI saturation at high NDVI in SEBS have recently been raised by other studies, including Timmermans *et al.* (2011) and Gowda *et al.* (2013). In light of these concerns and observations, an approach using attributes of land cover types in deriving LAI was sought. As a result, the LAI of grassland vegetation was derived by the formula  $LAI = 0.21 \exp\left(\frac{NDVI}{0.264}\right)$ , after Kite and Spence (1995); while for cultivated and mixed

cropping agriculture the formula  $LAI = -2.5 \ln(1.2 - 2NDVI)$ , after Rosenthal *et al.*, (1977), was applied. LAI for higher canopy vegetation, especially forests and woodlands, applied the formula after Peterson *et al.* (1987)  $LAI = \left( 0.52 \left( \frac{NDVI + 1}{1 - NDVI} \right) \right)^{1.715}$ ; whereas for those canopies whose  $NDVI < 0.7$  or for coniferous forests and a formula after Nemani and Running (1989) .

$LAI = 0.65 \exp\left(\frac{NDVI}{0.34}\right)$  was. In the event that the agricultural land had a high LAI ( $> 0.5$ ), as was the case for some mature sugarcane plantations, this approach is not suitable requiring the original SEBS formula be used. All this pre-processing was done in an ERDAS environment outside the SEBS platform.

Another cause for concern in the SEBS computation process was the roughness length for momentum transfer ( $z_{om}$ ) retrieval algorithm (Equation 5.7) which, according to Su and Jacobs (2001), is solely derived in SEBS from NDVI.  $z_{om}$ , according to Zhou *et al.* (2012), is the height above the surface at which the mean logarithmic wind profile reaches zero and which is derived in SEBS by the following formula:

$$z_{om} = 0.005 + 0.5 \left( \frac{NDVI}{NDVI_{max}} \right)^{2.5} \quad [5.7]$$

A comparison of  $z_{om}$  estimates from SEBS, with values from literature, revealed that the SEBS estimates were unsatisfactory, especially with regard to forest vegetation. The inadequacy of NDVI-based methods in estimating  $z_{om}$  is also highlighted in Rauwerda *et al.* (2002), while citing Lettau (1969) and Hassager and Jensen (1999). All highlight that  $z_{om}$  depends on vegetation structure, such as spacing, shape, vegetation distribution and density, as well as landscape structure and orography. These factors cannot be adequately represented by NDVI, as expressed in Equation 5.7 above.

The importance of the accurate parameterisation of  $z_{om}$  is stressed by Zhang *et al.* (2010) and Timmermans *et al.* (2011), who found that errors in the estimation of  $z_{om}$  translate into errors in the derivation of  $H$ . In particular, an underestimation of  $H$  fluxes was noticed as a result of unrealistic parameterisation of roughness. According to Pitman (1995), the propagation of error from  $z_{om}$  translates to errors in sensible heat flux estimation, in the order of  $8 \text{ Wm}^{-2}$  and  $LE$  errors of about  $10 \text{ Wm}^{-2}$ . Thus, this study adopted an approach that assigned appropriate roughness values to specific land covers from a look-up table (Table 5.1), as suggested by Wieringa (1993) and Hasager and Jensen (1999). Hasager and Jensen (1999) and Hasager *et al.* (2002; 2003) applied a land cover classification scheme to assign the roughness values, using an aggregation model, and derived not only  $z_{om}$  but also  $kB^{-1}$  and  $z_{oh}$  values. Other parameters were then obtained, as per Brutsaert's (1982) formulation i.e.  $h = z_{om}/0.136$ , while  $d=0.667h$ .

Table 5.1 Land cover based surface roughness used

Land cover type	Land cover as used in this study	$z_{om}$ (Hasager, 2002)	$z_{om}$ (Wieringa, 1993)
Water	Water	0.0002	0.0002
Permanent short grass	Grassland	0.03	0.034
Grazing land		0.08	
Bush/forest		1.8	
Deciduous forest	Woodland	1.8	1.2214
Agricultural land	Intensive cultivation	0.05	0.0639
Discontinuous urban		0.5	
Continuous urban		1.2	
Built-up area	Settlement area		0.5488
Young forest		1.8	
Mixed forest		1.8	1.2214

Clearings (small open areas with scattered trees)		0.3	
Sparse coniferous (mainly spruce)		1.8	
Heathland		0.08	0.0408
Agriculture/grassland		0.05	

## 5.4 Results and Discussion

### 5.4.1 Comparison of the modelled energy fluxes with the ground measurements

Daily time series of the surface fluxes obtained from *in-situ* measurements at the Illovo sugarcane plantations are compared with the daily modelled fluxes, as illustrated in Figures 5.6a to 5.6c. Notably, SEBS estimates of the various components of these fluxes did not deviate much from the measured value, given the fact that SEBS outputs are averaged over 1 km of MODIS pixel, while the measured values of  $G_o$  and  $R_n$  are point measurements within that pixel. Sensible heat flux ( $H$ ) compared well to the ground measurements obtained from the LAS. This is mainly due to the fact that the LAS footprint (an 800 m transect) almost matches that of the MODIS pixel. Moreover, all the fluxes show a strong diurnal variation and, are therefore, time-dependent such that, it is important for one to consider a satellite overpass time for any comparison or when computing the daily averages.

In spite of frequent instrument breakdowns (either due to power or lightning) experienced with the LAS during the field campaign, the daily averages suggest that SEBS is capable of accurately estimating  $H$  over this study area. The minor discrepancies noted in these outputs are a result of the internal parameterisation of the model and attempts to account for mountainous terrains, as highlighted in previous sections

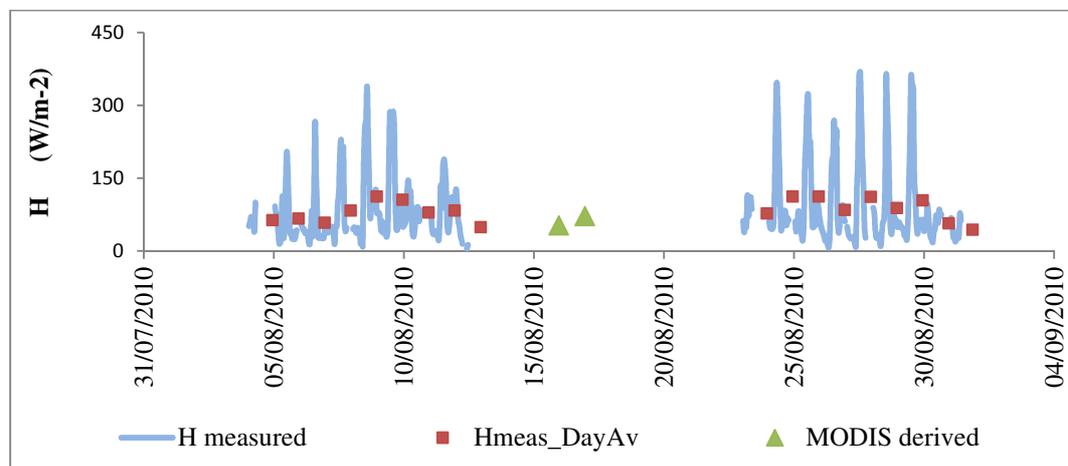
The highest discrepancy between observed and estimated fluxes from SEBS was noted in net radiation ( $R_n$ ). This is expected in complex terrain or non-homogeneous landscape, where conditions may be stable or advective, as highlighted in Kwast *et al.* (2009) and Gokmen *et al.* (2012). Advective conditions lead to the under-estimation of  $H$  and  $R_{net}$ . In recognition of this weakness and in an effort to address this problem, Chen *et al.* (2013) recently developed a topographically corrected solar radiation parameterisation scheme for SEBS in a Matlab

environment. Due to time constraints, it was not possible to adopt this scheme for the purpose of this study; however it is recommended for any follow-up project.

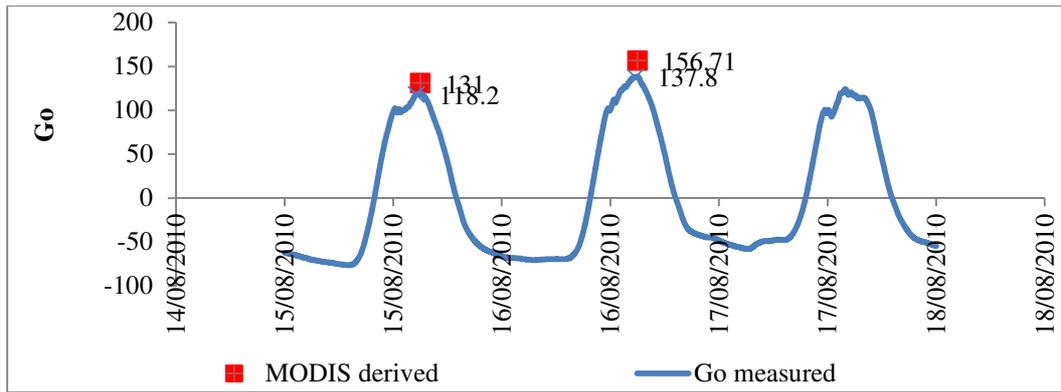
#### 5.4.1 Spatial and temporal variations of surface energy fluxes

The net radiation varies both spatially and temporally across the study area due to soil moisture availability and the vegetation cover changes. Highest net radiation, as derived from the SEBS calculations, was observed on the forest mountains ( $800 - 990 \text{ Wm}^{-2}$ ) and lowest on the lowland irrigated sugarcane ( $720 - 850 \text{ Wm}^{-2}$ ), including the low-lying cropped areas in the Kilombero Valley under smallholder farming systems ( $670 - 842 \text{ Wm}^{-2}$ ), as indicated in Figure 5.7a.

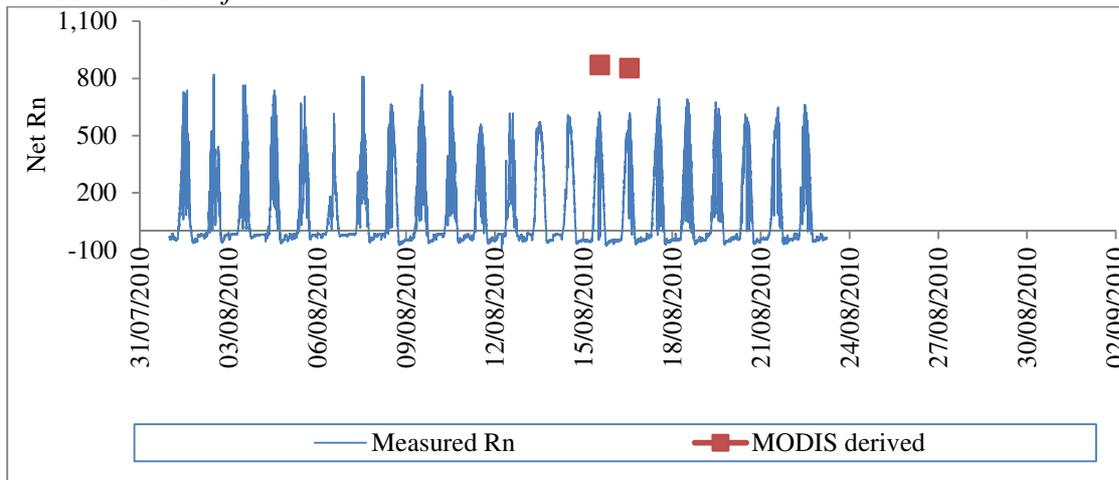
Likewise, SEBS's sensible heat flux shows a wide range with lowest values being observed on the forest mountains, where negative  $H$  fluxes were noted (i.e. downward flux of  $H$  from the atmosphere towards the earth's surface), and maximum values were observed in the Valley, an area mainly under cropland, floodplain wetlands with patches of settlement and bareland areas (Figure 5.7b).



a. Sensible heat flux



b. Soil heat flux



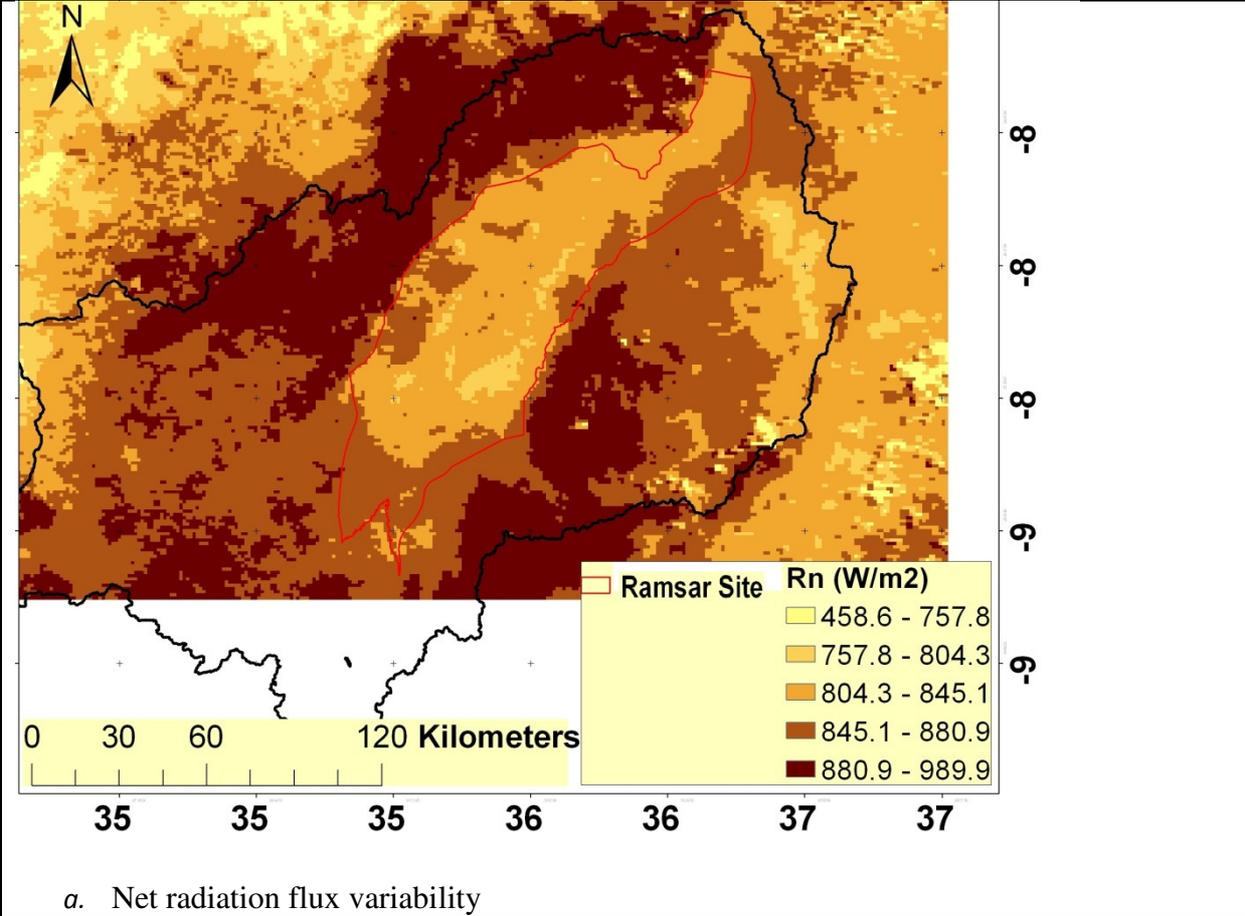
c. Net radiation

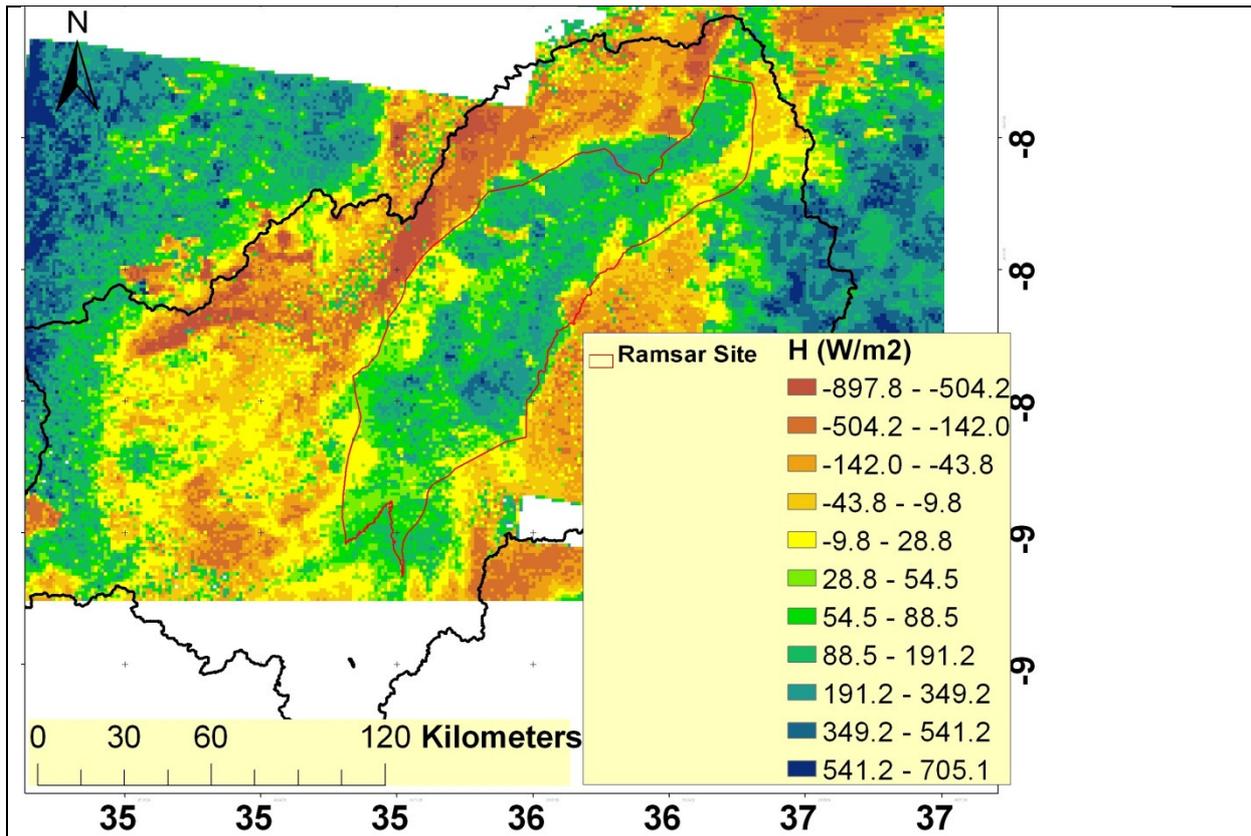
Figure 5.6 Comparison of the satellite derived surface energy fluxes against the *in-situ* measurements at Illovo sugar estate

Negative  $H$  is a common occurrence on wet surfaces with considerably high ET and which are subject to advection, a phenomenon commonly referred to as the ‘oasis effect’ (Stull, 1987) and believed to be necessary for the maintenance of wet canopy evaporation (Blyth *et al.*, 1994). It is worth noting that the greater part of the forests presented here are located on elevations ranging between 1800 and 2000 masl and which are most often covered by clouds. Energy flux to the ground is more or less uniform throughout the Basin during the wet season with clearer contrast in the dry season. Also noted is the strong dependence of  $H$  fluxes on the prevailing climatic conditions causing the fluxes to vary greatly with seasons.

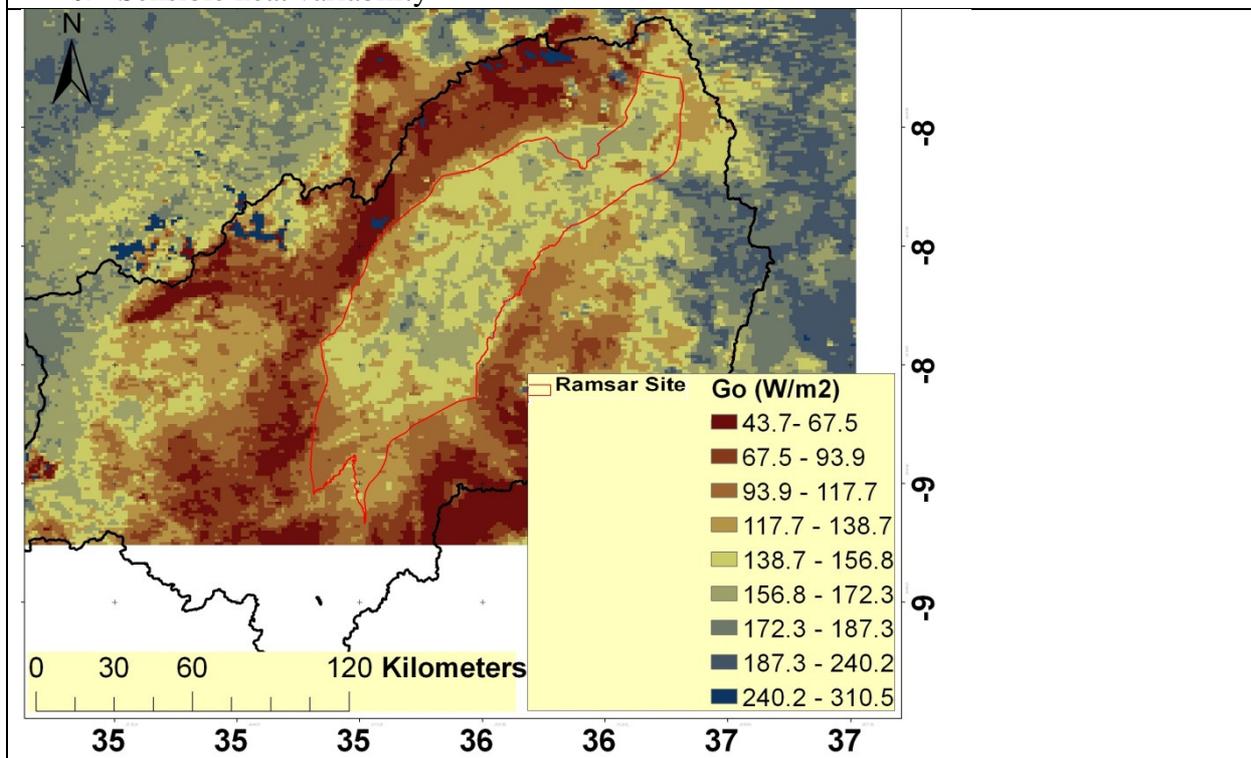
Soil heat flux is more or less uniform throughout the Basin during the wet season, given the fact that a greater part is fully vegetated and the soils hardly exposed. However, later into the dry period, when the cropping land is bare and surrounded by tall, evergreen forests on the

mountain ranges, the contrast is clearer, as depicted in Figure 5.7c. It is evident that much more of the ground heat flux is consistently experienced on the dry non-cropped Kilombero Valley (145 – 160  $Wm^{-2}$ ) than the forests on the periphery (45 – 80  $Wm^{-2}$ ) and irrigated land (130- 148  $Wm^{-2}$ ) which experience much lower  $G$  because of the high LAI. At the peak of the dry season (October), the cropland  $G$  is about 234  $Wm^{-2}$  while irrigated land is at the range of 37 – 43  $Wm^{-2}$ .





b. Sensible heat variability

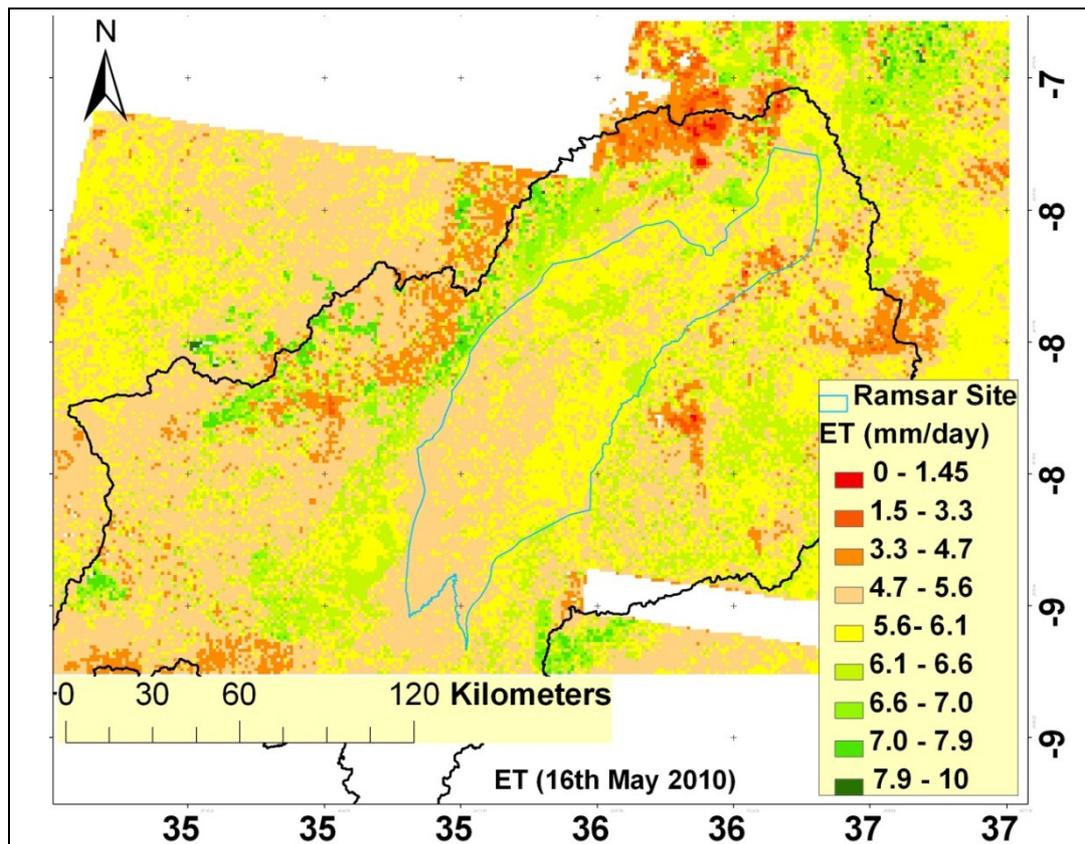


c. Ground heat flux

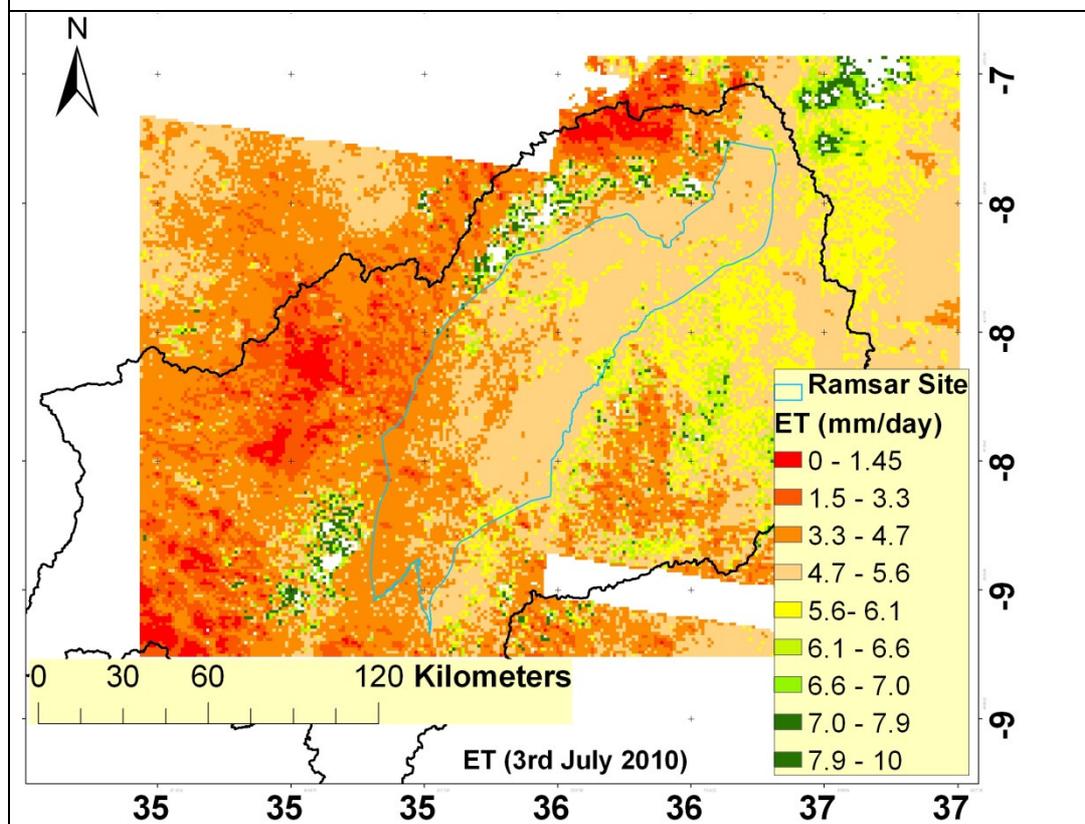
Figure 5.7 Spatial variations of surface energy fluxes of the Kilombero River Basin as established with SEBS (MODIS 16<sup>th</sup> August, 2010)

#### **5.4.2 Spatial-temporal variation of actual evapotranspiration across the Basin**

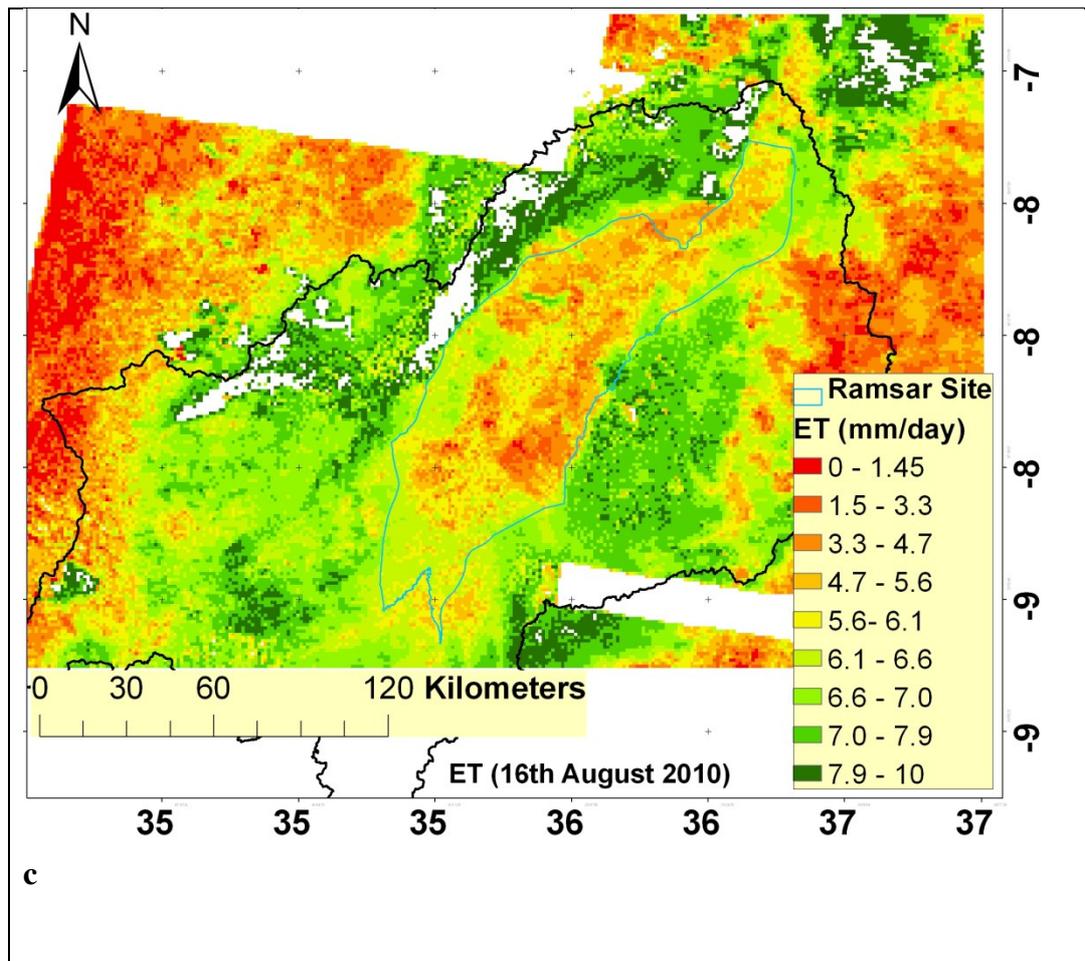
The Kilombero floodplain actual ET (AET) was found to progressively decline in time as the year transitioned from the wet rainy to the dry season (Figures 5.8 and 5.9). This trend continued such that, at the climax of the dry hot season in October, the floodplain valley, with the exception of a few permanent streams, runs almost completely dry (Ramsar Bulletin Board, 2002) (Figures 5.8d and 5.9d). The Miombo woodland on the periphery of the Valley maintained high ET rates late into the dry season with rates ranging between 6 and 6.6 mm for the period between May and August (Figure 5.8a –c). This is in line with the pattern of the phenology explained by Chidumayo and Frost (1996) that Miombo maintains its leaves late into dry season and starts leaf emergency weeks prior to the rainfall onset. Figure 5.8d depicts the period just before the rainfall started in November during which time the Miombo was observed to have tender, reddish-like leaves, explaining the non-zero evapotranspiration rates. The evergreen forests in the mountains maintain high evapotranspiration rates regardless of the season with daily AET ranging between and 6 – 8 mm for the evergreen forests on the Udzungwa mountain ranges.



a



b



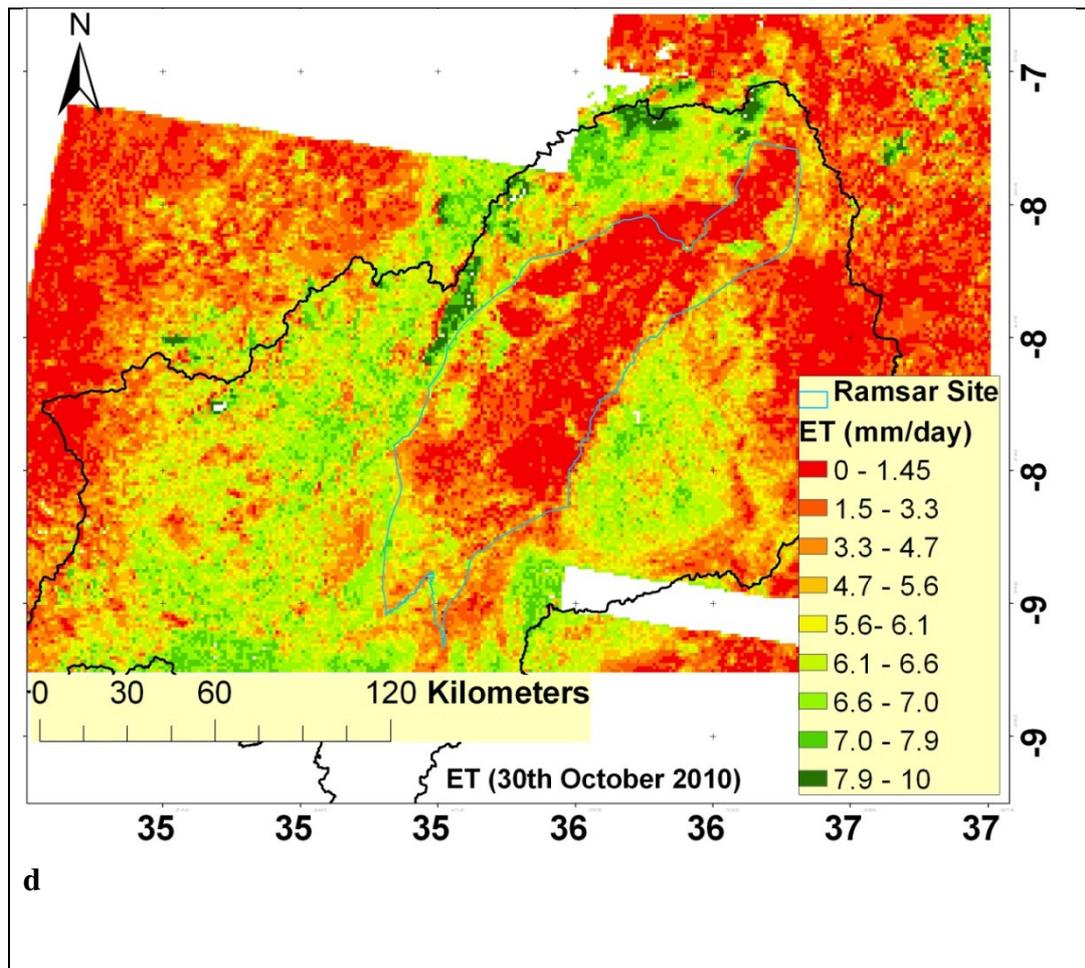
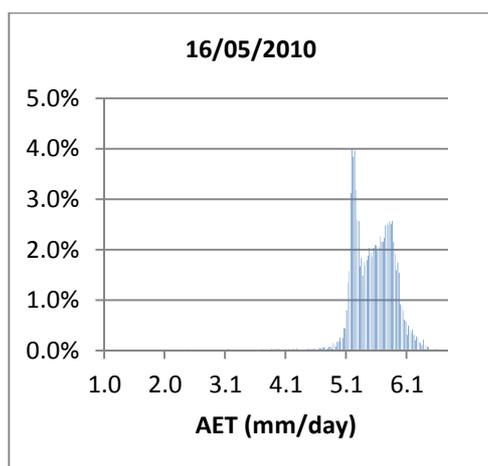
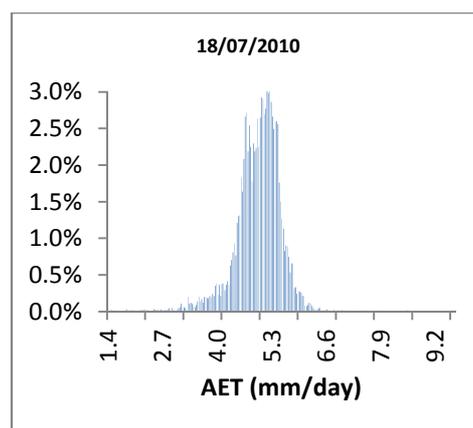


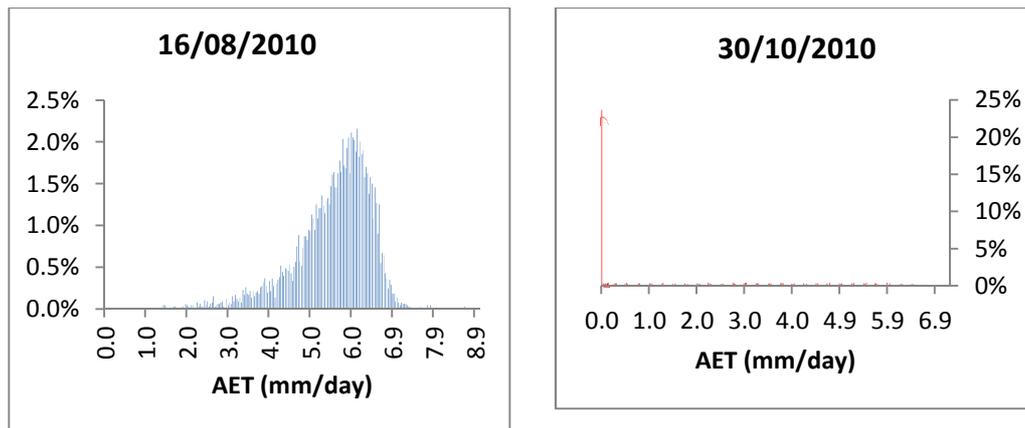
Figure 5.8 Kilombero Basin spatial distribution of AET ( $\text{mm}\cdot\text{day}^{-1}$ ) during the transition from wet to dry months of the year 2010



(a) End of wet season



(b) Dry season AET



c) Dry season AET

(d) End of dry season

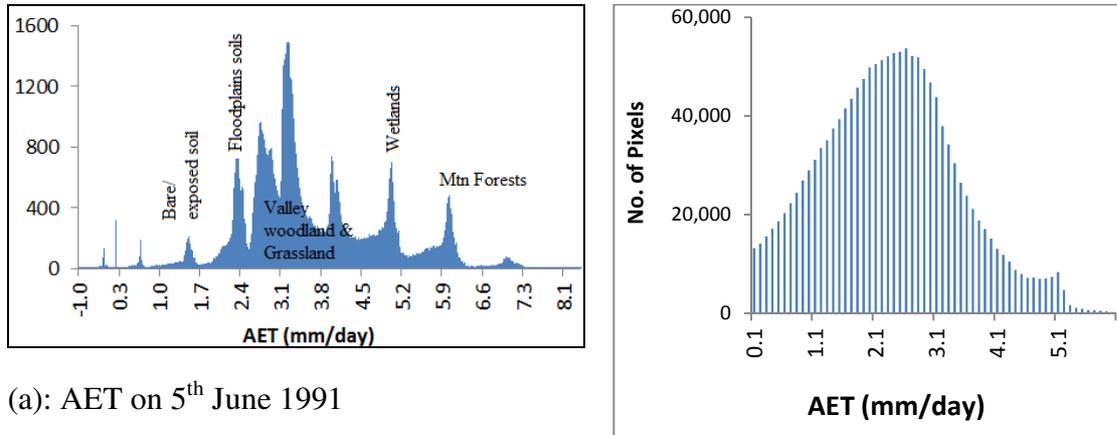
Figure 5.9 Frequency distribution of daily Kilombero Valley ET on selected days of the year 2010 as derived from SEBS

The study observed that evapotranspiration varies spatially across the Basin with two distinct regimes; a dramatically changing seasonal ET and a stable mountainous evapotranspiration regime. As noted earlier, the floodplain areas, formerly a wetland zone, show hardly any evapotranspiration towards the end of the dry season, implying the absence of actively growing vegetation. This suggests the loss of wetland habitat and lower soil moisture conditions, contrary to what is expected of the Valley area that formerly had permanent wetlands. These observations are in line with the findings in Chapter 2 showing that the Valley is currently dominated by seasonal croplands that lie dormant during the dry season. This analysis supports observations by other scholars, like Mombo *et al.* (2011), who noted that permanent flowing streams, such as the Kiberege, Idete, Kikwawila, Namawala and Idandu, have now changed to seasonal streams and many swamps have dried up due to the over-exploitation of the Kilombero Valley wetlands.

### 5.4.3 Historical land cover based basin total evapotranspiration

A comparative analysis of the 1991 and 2002 AET (both wet years) for similar seasons of the year shows a dramatic decrease, specifically in the Valley where the mean value of 3.59 mm.day<sup>-1</sup> in 1991 decreased to 2.13mm.day<sup>-1</sup> by 2002 (Figures 5.10a and b). A change in the ET regime over the course of time is observed with the Valley's actual evapotranspiration ranging from 0 – 2 mm/day 2002 while highest values are experienced on the mountains

where evergreen forests are situated. The evaporative fraction (EF) indicates that the forest's evapotranspiration exceeds the potential values.



(a): AET on 5<sup>th</sup> June 1991

(b) AET on 10<sup>th</sup> May 2002

Figure 5.10 Histogram of the AET derived from LANDSAT

High forest EF is the result of the lower land surface temperature over the forest land cover, compared to the air temperature immediately above it. This results in negative sensible heat fluxes being experienced over the forests providing an additional energy source to that available on site (either through a horizontal advection of warm air or a downward movement of heat) which provides the energy required for the evapotranspiration of these forests (Stewart, 1977; McNaughton and Jarvis, 1983). Generally, EF retrievals show a decrease with values ranging from 0.8 -1.7 in 1991 to a range of 0 – 1.2 in 2002. EF values  $\Lambda > 1$  are experienced only in the mountains, while the low-lying floodplain experiences values of 0.7 to 1.0. According to Rauwerda et al., (2002),  $\Lambda > 1$  (i.e. greater than the theoretical limit) is expected in areas experiencing advection-driven evapotranspiration.

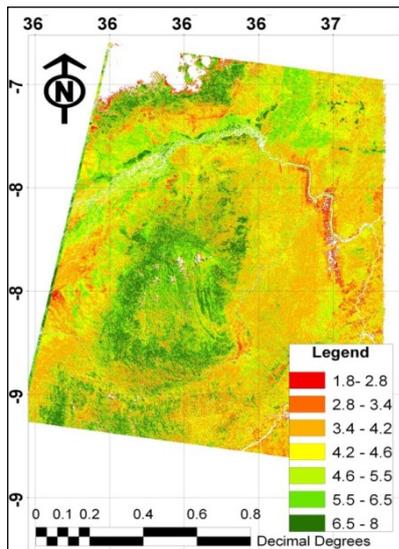


Figure 5.12a Average daily ET  
(Landsat 5<sup>th</sup> June 1991)

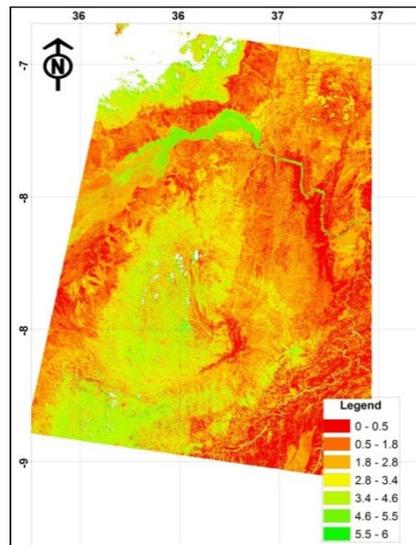
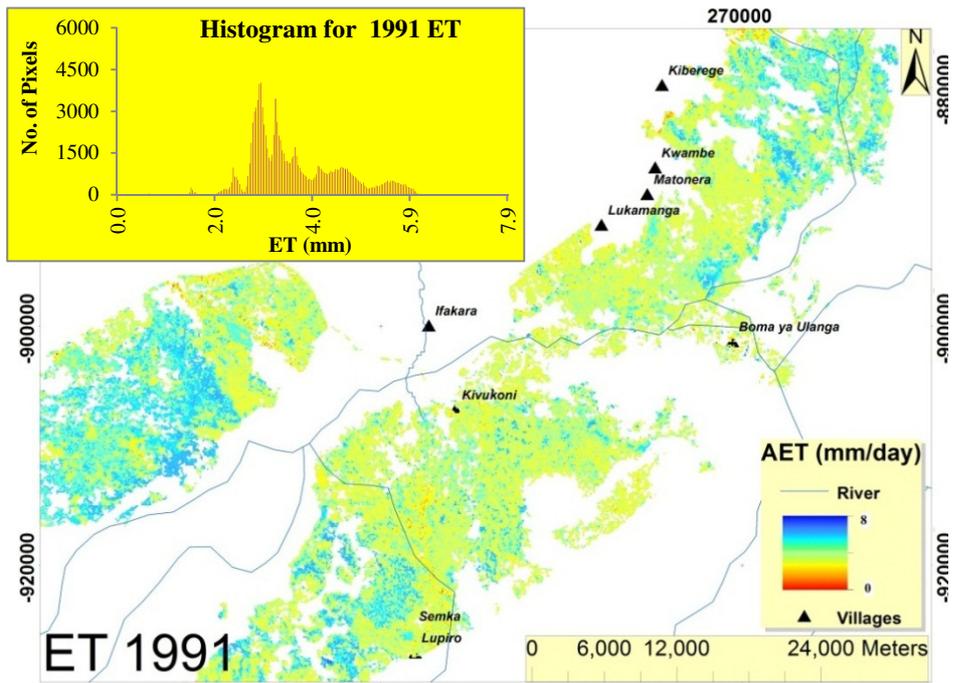


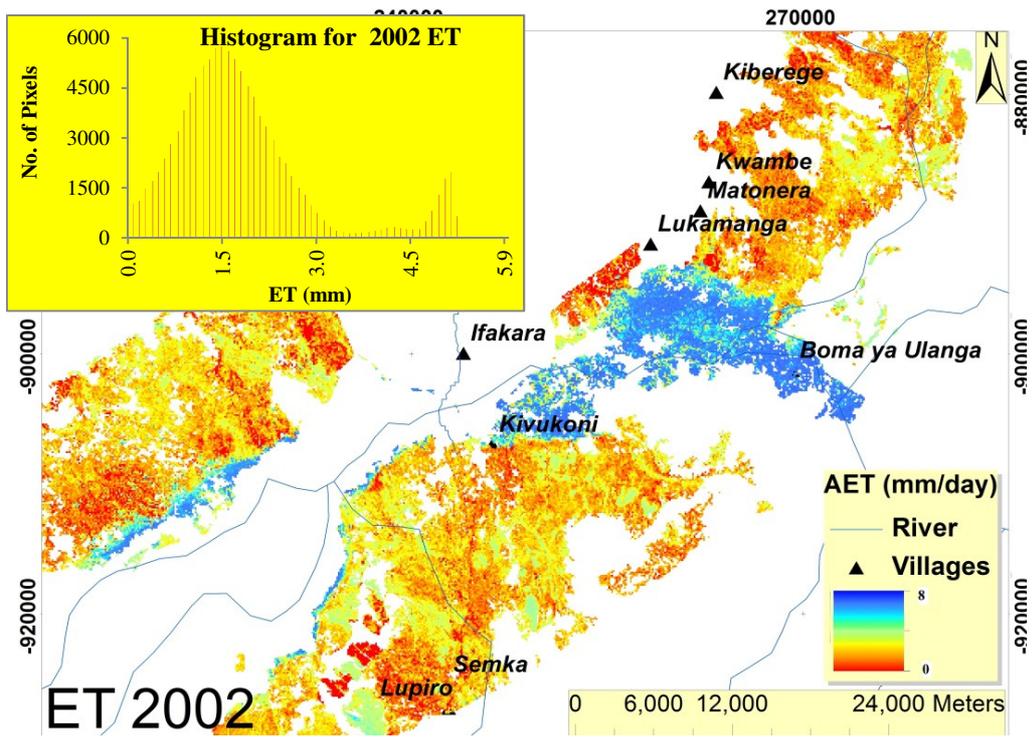
Figure 5.12b Average daily ET  
(Landsat 10<sup>th</sup> May 2002)

#### 5.4.4 Evapotranspiration over cropland in the Kilombero Valley floor

A change in the total evaporative regime is evident in the 1991 and 2002 period, where a shift of the predominant daily average ET from 3.5 to 1.2 mm.day<sup>-1</sup> is observed (Figures 5.13a-b). Notably, the two years compared have similar meteorological conditions as both are wet with mean annual rainfalls of 1447 and 1530 mm p.a respectively. Both also mark the beginning of the dry season, the first month after the long rains. The images compared cover the same location but show the dry season greatly reduced ET. This is most likely due to the fact that the Valley's former wetland vegetation, able to withstand dry conditions, has been largely replaced with seasonal rainfed crops (as elaborated in Chapter2) which were harvested during the overpass time of this particular satellite image. Thus, the seasonality of crops in the wetlands leaves the land bare, especially after the harvesting of the crops, which coincides with the dry season (June – October). The eco-hydrological system of the Kilombero Valley, as described in Chapter 2, has been affected by the extensive anthropogenic activities and the greater part of the wetlands has been converted into cropland.



a: 1991 June total ET (mainly wetland vegetation)



b: 2002 May ET (mainly cropland vegetation)

Figure 5.13 Comparison of ET at the floor of the Kilombero Valley for the years 1991 and 2002

ET during the rainy season could not be quantified in this study due to the unavailability of good quality satellite images. However, a significant reduction in ET between 1991 and 2002 is noted during the dry season, as indicated in Figure 5.13, implying a reduction in the available soil moisture. It is likely that the agricultural activities have resulted in the drying up of the wetlands which previously dominated the valley. As a result, almost the entire Valley dries up following the cessation of rain. This is confirmed by a further assessment of the inter-annual variability of ET for the year 2010.

The seasonal progression of ET over the cropland areas (Figure 5.14) shows a progressively declining trend in ET for the year 2010, where ET is reduced to negligible levels by the end of the dry season, post-harvest when the Valley is dry with no crops (Figures 5.14c and d). This implies that agricultural land (mainly rain-fed) in the Valley, currently occupying about 60% of the Valley, has transformed the area from perennial wet and vegetative wetlands with relatively high ET throughout the year to the current dry areas with patches of bare and built up landscapes during the dry season. It is interesting to note that the ET regime of 1991 and 2000 are different. The ET of the replaced wetland vegetation was not limited to rainfall patterns compared to the current cropland vegetation, the ET of which is seasonal, as indicated in Figure 5.14a to c.

Thus, the implications are that the cropland dominated landscape changed the seasonal evapotranspiration regime in the Valley from what was, most likely, atmospherically demand-driven ET to soil moisture controlled (or soil moisture limited). This implies that the current ET regime exhibits a seasonal variation that closely mimics the rainfall pattern. Likewise, a change in ET regime changes the hydrologic cycle partitioning and water fluxes in a basin. Liu *et al.* (2010) noted a similar trend with cropland ET for non-irrigated areas which were observed to have lower ET than the other neighbouring land cover types during the dry or non-growing season.

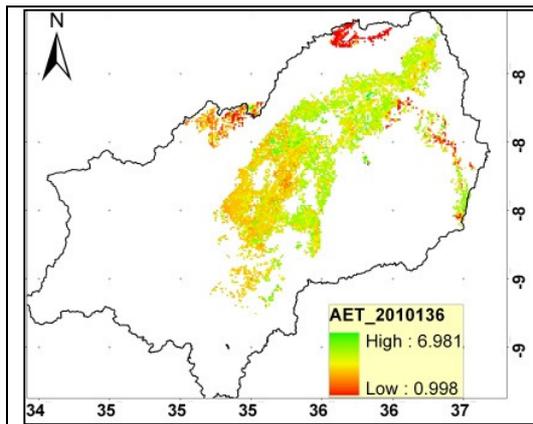


Fig. a: SEBS estimation for 16<sup>th</sup> May 2010

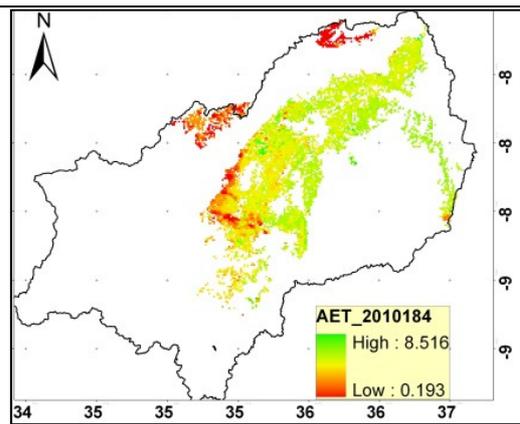


Fig. b: SEBS estimation for 3<sup>rd</sup> July 2010

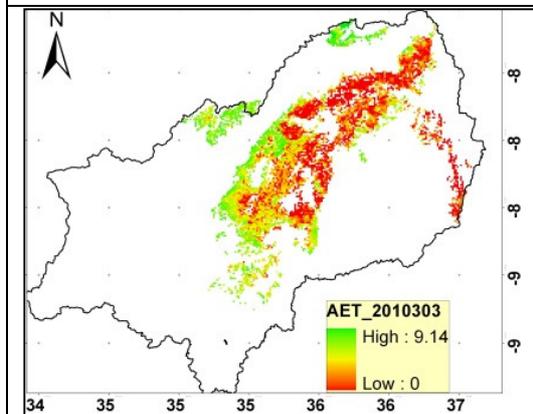


Fig. 5.14c: SEBS estimation for 30<sup>th</sup> October 2010

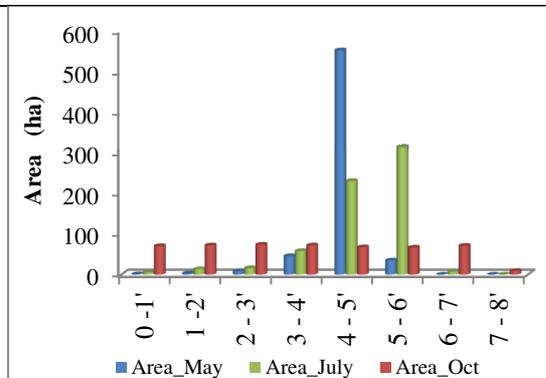


Fig. 14d: Histogram distribution of AET (mm/day) for different seasons of 2010

Figure 5.14 Seasonal progression of the cropland ET (mm/day) for the months presented in the year 2010

It should be noted that the observations of reduced ET over the years are not unique. Similar findings have been reported in China by Xu and Levy (2011) where land cover degradation resulted in reduction of soil moisture, increased albedo and a rise in what was referred to as the drying capacity of the land surface. Global land ET studies have highlighted a similar decreasing trend of ET from 1998 onwards, especially in sub-Saharan Africa and east Africa, that clearly matched a decrease in soil moisture supplies (Jung *et al.*, 2010). Specifically, a land use transition to non-irrigated cropland was reported by Sterling *et al.* (2012) to have the highest impact in reducing evapotranspiration.

### 5.4.5 Evapotranspiration over Miombo woodland and Teak plantation forest

As reported in Chapter 2, Teak forest was established in the Valley replacing the Miombo woodland. A SEBS analysis provides information on the situation prior and after this establishment (Figure 5.15). A reduction in ET is noted during the non-growing season in areas that are currently under Teak plantations (Figure 5.15d).

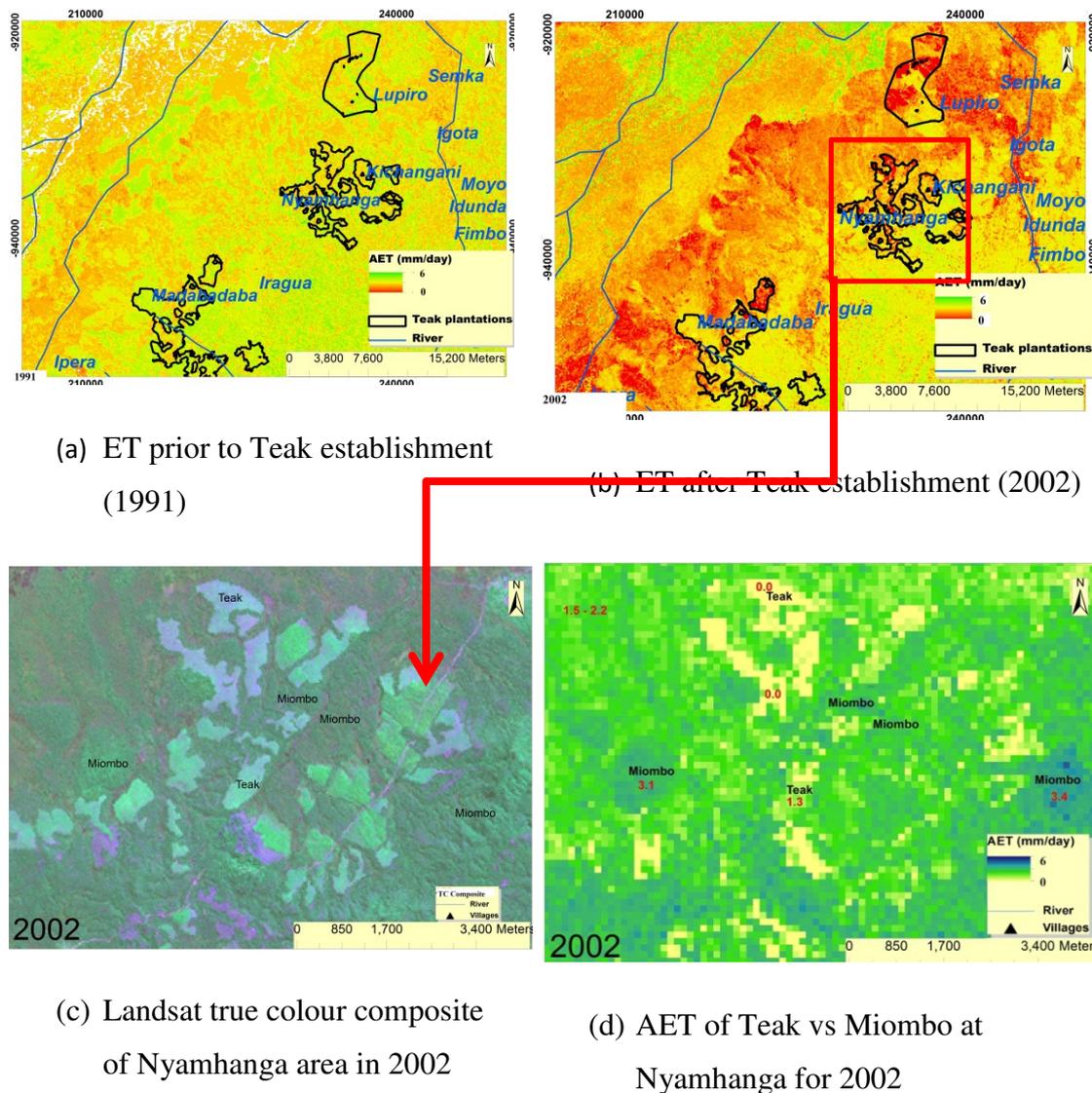


Figure 5.15 Spatial estimates of ET over Miombo woodland zone (1991) in Ulanga District now dominated by Teak forests (2002)

In Chapter 3, it was highlighted that Teak trees shed their leaves earlier than Miombo trees during the non-growing season (i.e. the dry season). While the indigenous Miombo woodland

seems to maintain a relatively high ET of 6-7 mm.day<sup>-1</sup>, even after the onset of the dry season, Teak forests have a relatively low ET attributable to the shedding of leaves soon after the cessation of rain.

However, in-situ measurements of transpiration (Chapter 3) indicated that while Teak is known to have low transpiration rates during the dry season it has high rates during the wet season. The Miombo woodland has a stable consumptive water use even though it delays the senescence stage. It, therefore, follows that this particular study could not draw conclusive results on the impacts on ET regime of replacing Miombo with Teak on an annual time scale. Unfortunately, the total ET of the growing season could not be estimated due to a lack of cloud-free datasets rendering remote sensing ineffective in this regard.

#### **5.4.6 Total evapotranspiration from irrigated sugarcane**

Analysis was carried out to estimate the evaporative water use over the irrigated Illovo sugarcane plantations around Kidatu (Figure 5.16) where the crop is under irrigation almost throughout the year. Accurate accounting of the evaporative water use of the vast sugarcane plantations, both on spatial and temporal scales, is of great importance in managing water resources in the Kilombero Basin, including the management of field irrigation scheduling on the farm. Previous attempts to quantify the irrigation water requirements of Illovo sugarcane plantations were made by the Government by assessing the capacity of the company's irrigation equipment. This assessment, conducted in 2009 (GoT, 2010), is the only study in literature that provided estimates of irrigation water use in the Illovo sugarcane plantations. However, the procedure used and the derived estimates of irrigation water use are somewhat crude and outdated, especially since the company's irrigation equipment was refurbished and expanded to cover a bigger area in 2010. The SEBS approach, as applied in this study, of retrieving actual ET over the sugarcane plantations while taking into account the outgrowers' schemes that are not serviced by company irrigation equipment is an optimum approach and can be applied regularly, often and on a real-time basis.

SEBS results indicate that there is persistent relatively high ET, ranging from 5–6 mm.day<sup>-1</sup> over the plantations throughout the year regardless of the climatic seasonal changes (Figures 5.16 and 5.17). In contrast, neighbouring rain-fed agricultural areas show a progressive reduction in ET in the course of the dry season, indicative of a continued depletion of soil

moisture reserves. The cropland areas adjacent to Illovo irrigated land indicate that ET reduces dramatically to range between 1.6 - 0.7 mm.day<sup>-1</sup>, mostly likely due to die-back of remnant crops in the dry season; with only few exceptional areas having ET rates of 3.2 -4.6 mm.day<sup>-1</sup> during the dry month of October (Figure 5.16d). The latter observations could be attributed to supplemental irrigation during the dry months.

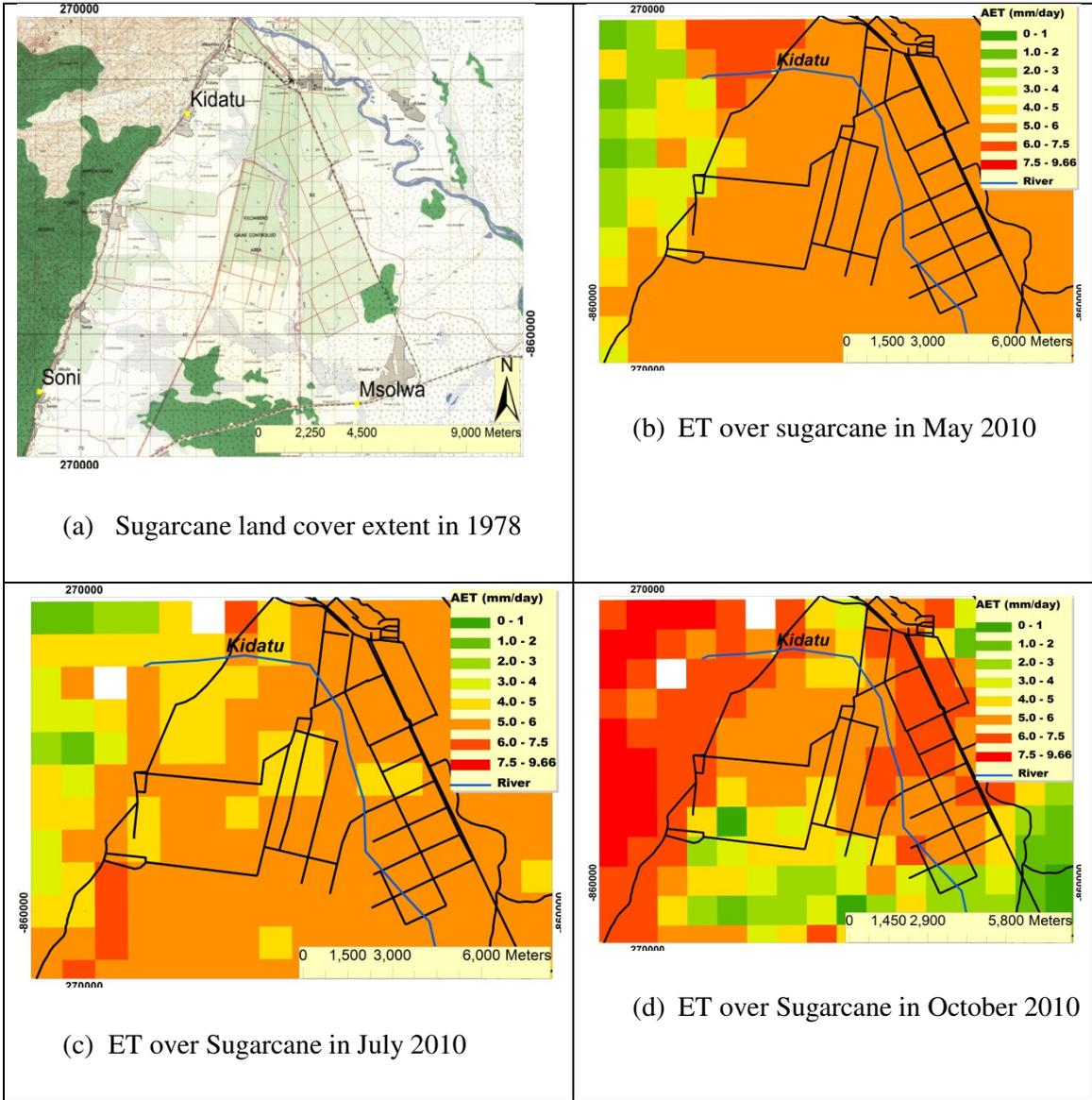
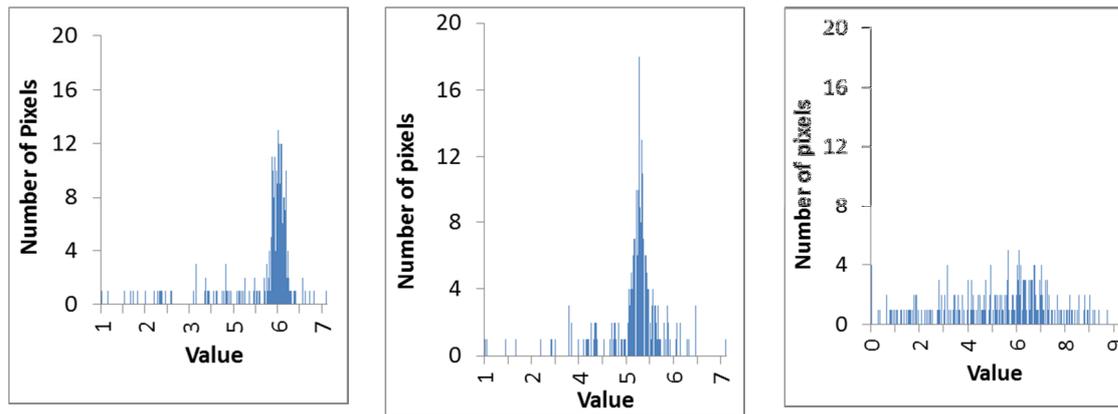


Figure 5.16 Evapotranspiration over the sugarcane growing areas in Kidatu



(a) ET histogram for 16<sup>th</sup>  
May 2010

(b) ET histogram for 3<sup>rd</sup> July  
2010

(c) ET histogram for 30<sup>th</sup>  
October 2010

Figure 5.17 Histogram of ET values over the sugarcane growing area on selected days

#### 5.4.7 The influence of land cover type on the surface energy flux partitioning

Changes in vegetation cover are known to change the surface energy balance by altering the partitioning of the energy fluxes. According to Brunzel *et al.* (2011), energy partitioning is a mechanism by which land surface heterogeneity in moisture, vegetation and surface temperatures alters atmospheric boundary layer dynamics. The alteration is much more appreciable and pronounced at the boundary of two different vegetation types, given the fact that the dominance of an energy flux component changes with vegetation type, also implying a change in the boundary layer characteristics.

Naturally, the change in albedo, due to a shift in land cover, alters the partitioning of the radiation energy. Clearing of vegetation results in increased albedo, decreased vegetation indices and lowered surface roughness (Figure 5.20). Such a change not only results in a difference in radiation balance (increased reflected radiation), but also a change in the partitioning of net radiation ( $Rn$ ) into sensible heat flux ( $H$ ) and latent heat flux ( $LE$ ). In this study, the availability of high resolution Landsat satellite images made it possible to clearly assess the influence of spatial heterogeneity of vegetation on the partitioning of surface energy fluxes. However, since land cover characteristics are subject to seasonal changes in response to soil moisture availability and atmospheric forcing, it is expected that the partitioning of the net radiation will also change while mimicking the same pattern. Due to the difficulties of acquiring multiple cloud-free Landsat images to cover a year, MODIS images

(Figure 5.19), with a higher temporal resolution but lower spatial resolution, were used to augment the data for this analysis in an attempt to track the seasonal trend of the surface energy partitioning for the year 2010. MODIS images, representing the full vegetative growth stage for most of the Valley vegetation (July) and the dormancy stage (October), were selected for presentation in this paper. In this analysis, the respective components of surface energy balance were standardised, with respect to the net radiation, and presented as fraction indices, as indicated in Figure 5.18 and 5.19.

From Figures 5.18 and 5.19, it can be seen that forest land-cover partitions more than 65% of the net radiation for evaporative flux while bare soil surfaces have the least influence in the partitioning process. There was a clear contrast between vegetation types when analysed, based on the partitioning of sensible heat flux ( $H$ ) and soil heat flux ( $G$ ), as indicated in Figures 5.18 and 5.19.

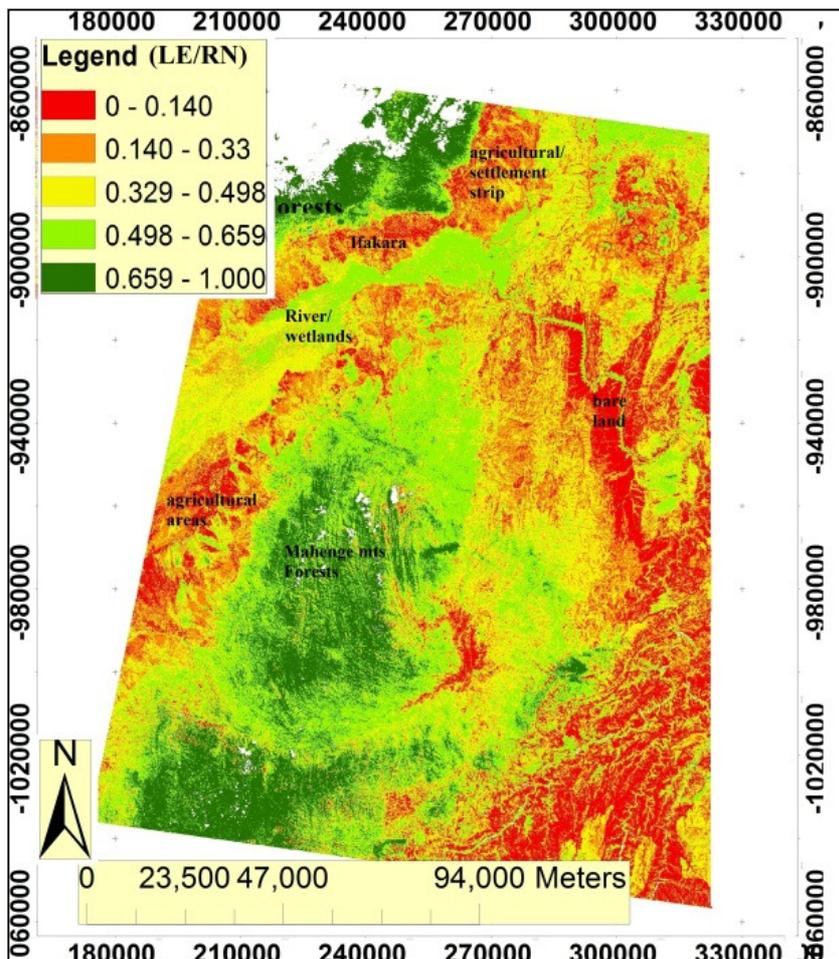


Figure 5.18 Spatial variation of the surface energy flux partitioning (10<sup>th</sup> May 2002 scene)

During the dry season, the latent heat flux ( $LE$ ) over forestry vegetation accounts for more partitioning of the net radiation ( $R_n$ ) while the river floodplain areas and agricultural areas account for a smaller percentage due to the absence of a canopy cover (Figure 5.18). Moreover, although soil heat flux ( $G$ ) on closed forest canopies is negligible, with  $G/R_n$  being between  $<0.05$  and  $0.1$  for open woodland vegetation, it is much significant in non-irrigated cropland where it accounts for about 20-25% of the  $R_n$ . This is due to the fact that during the dry season (when the images were captured) the soils are dry with no crop covers (post-harvest). All this is consistent with other literature documenting that partial canopies often have a ratio of  $G/R_n > 0.2$ , while closed canopies have  $G/R_n < 0.05$  (AHAS, 2002).

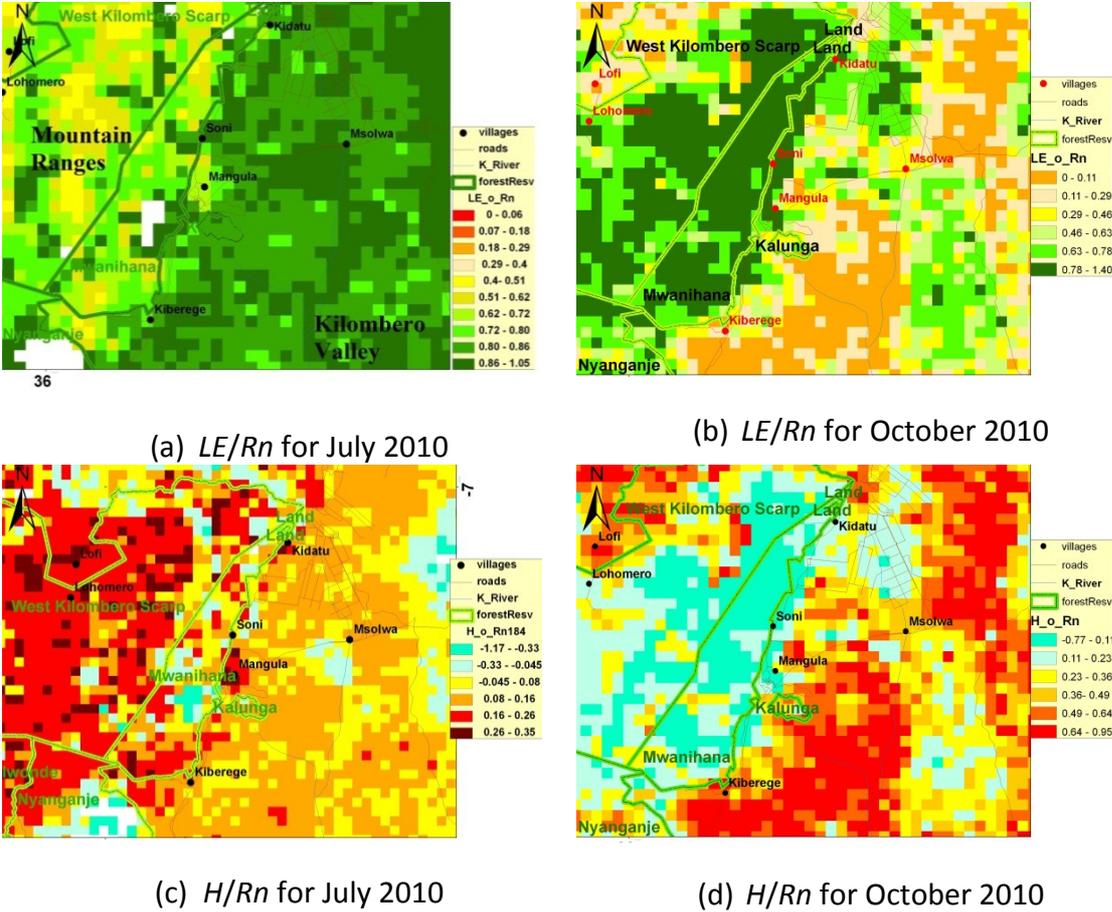


Figure 5.19 Comparison of the surface energy fluxes partitioning during full vegetative stage (a) and (c) and during the dormant stage (b) and (d)

It is noted from Figure 5.19 that throughout the time when the vegetation was actively growing,  $LE$  was the dominant flux in the Kilombero Valley area (Figures 5.19a and c),

contributing to over 80% of the partitioning process of  $R_n$ , while the contribution of sensible heat flux ( $H$ ) is negligible and even negative in some areas due to the influence of terrain. As previously highlighted in this Chapter, the main land uses in the Kilombero Valley are agricultural activities, hence during the dry season (post-harvest) the land cover in the Valley becomes predominantly bare soils resulting in a shift in the partitioning process where the dominant energy flux becomes  $H$  compared to  $LE$  on the surrounding mountains. This phenomenon is the opposite to that observed during the vegetative stage of the crops, as indicated in Figure 5.19b and d.

Further analysis revealed that during the fully vegetative season (Figures 19a and c) a significant portion of the net radiation was used for evapotranspiration in almost the whole River Basin. Cropped areas accounted for 82-95% of  $R_n$ , wetlands 80-85% and woodlands and natural forests ranged between 96 to 100%. The relatively high  $R_n$  in woodlands and forests is due to high canopy density and high LAI, where less than 5% of the  $R_n$  is lost to the ground and  $H$  flux is very low or, occasionally, negative. While seasonality is evident on farming areas and wetlands, natural forests have a stable partitioning of net radiation with 75-100% of the net radiation being used for evapotranspiration. An insignificant proportion of  $R_n$  is directed to bare farmland areas of the Valley, as shown in Figures 5.19a and b. During the dry season the percentage of partitioning of the  $R_n$  decreases in the cropland and wetland areas, while higher values are maintained in areas under natural forests.

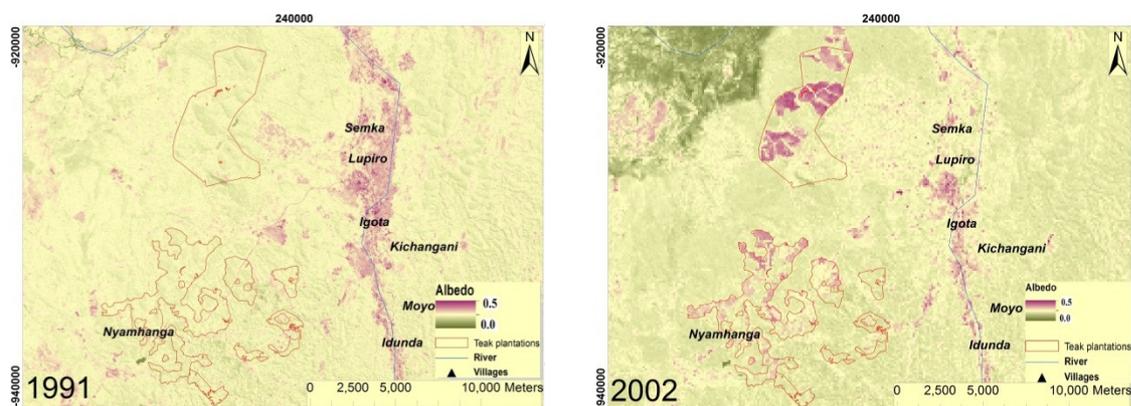


Figure 5.20 Albedo for areas including Teak plantations in two different years about a decade apart

## 5.5 Conclusions and Recommendations

There are numerous challenges experienced with obtaining useful evapotranspiration data from ground monitoring networks to guide water management at a basin scale. This has led the scientific community (and likewise this study) to assess the suitability and applicability of remotely sensed ET products for application in the local environment. This study analysed the spatio-temporal variations in ET across the Basin with a view to contributing to the understanding of the impacts of land cover changes on the hydrological regime of the Kilombero River Basin through the analysis of the dynamics of the evaporation in the hydrological cycle.

In this study, satellite-based estimates of ET proved to be fairly useful in tracking the historical changes originating from the changing land utilisation. However, the study established that the benefits of such estimates are limited to the availability of cloud-free satellite images, proving challenging for much of the year in mountainous and densely-forested regions such as the study site. Reliable estimates of ET at field-scale were obtained but only for seasons that are less cloudy ( mostly dry seasons). Therefore, other tools such as hydrological models are required to provide a full analysis of the basin ET and streamflow responses. These estimates, when combined with the ground estimates, have the potential to improve inputs to hydrologic models.

Land cover changes have been shown to alter the evapotranspiration regime due to the induced shifts in the structural vegetation and biophysical parameters, albedo and LAI. This study observed that the ET regime in the Kilombero Valley has been altered by the intensification of agricultural activities which have transformed many wetlands into agricultural lands. It was evident that ET over the Mahenge and Udzungwa highlands, located on the periphery of the Valley, exhibited a very stable regime even during the dry season. This is not the case at the floor of the Valley where ET was noted to have a strong seasonal variation, mimicking the seasonal soil moisture variations. Most parts of the Valley, previously observed to be wet throughout the year, have currently been transformed into seasonal dry landscapes with relatively low ET during the dry season. The conversion of the Miombo woodlands to exotic Teak forests in the Valley have, to a large extent, led to the alteration of the partitioning of rainfall in the Valley through the enhancement of evapotranspiration. In particular, the dry season ET over Teak forests was noted to be relatively lower when compared to other forest areas in the vicinity. This phenomenon did not hold during the wet season, where ET in Teak forests was noted to be significantly higher when compared to other forests (and particularly Miombo woodlands) as detailed in Chapters

3 and 4 of this thesis. The Teak forests are known to grow actively under wet conditions, where soil moisture is not limited. However, the Miombo trees have a constant growth rate that is adapted to local soil moisture conditions. The indigenous Miombo woodlands are, thus, more adaptive to seasonal variations of rainfall by their phenological characteristics.

Irrigated sugarcane plantations in the Kilombero Valley were found to exert a higher demand on the water balance, due to relatively higher ET throughout the year. Sugarcane is grown throughout the year, with irrigation meeting all the water requirement needs of the crop during the dry season. It is useful to note that adverse impacts, or alterations of hydrological regimes in rivers, have been noted to be more severe during the dry season due to dwindling river flows (water resources) and the escalation of competing demands of water users.

Moving forward, it would be useful to extend the study and assess the impacts of possible land use management scenarios and their associated implications on the hydrologic cycle. Efforts should be made to replicate the study in other river basins in Tanzania, considering the inherent challenge of the inadequacy of relevant data and on-going rapid land cover transformation across the country.

Lastly, it is opined that future surface energy balance modelling efforts could benefit from the experience derived from this study relating to improvements of the original SEBS parameterisation, especially to account for topographic effects as elaborated in this paper. Future SEBS modelling endeavours in the region could improve their results by considering the possibility of the diurnal instability of the evaporative fraction.

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## **6. INTEGRATION, CONCLUSIONS AND RECOMMENDATIONS**

### **6.1 Integration**

This study applied different techniques across varying spatial and temporal scales, from detailed field (plot) process studies to basin scale assessment. The assessment on larger spatial scales covering the whole Basin was necessitated by the need to assess the water use characteristics of dominant land uses in the Basin. It should be noted that most of the original land uses in the Basin have been altered through anthropogenic interventions, as highlighted in Chapter 2. In Chapter 5, the SEBS framework was successfully applied to the entire Kilombero River Basin, thus integrating the field studies (Chapter 3) with the basin wide assessment. The basis for the scaling up of the field studies of evaporative water use of Teak and Miombo woodlands, to cover larger spatial scales with different land uses, is the fact that land covers on the earth's surface (e.g. vegetation, bare lands, etc.) affect the partitioning of incoming solar radiation energy on the earth's surface. On reaching the earth's surface, the net solar radiation is partitioned into sensible, soil and latent heat fluxes, of which the latter is the main driving force behind the evaporative water use of all land uses. Thus, in Chapter 5, the estimation of evapotranspiration over the entire Kilombero River Basin using remotely sensed satellite images, based on the surface energy balance approach, scaled out in line with the field studies on evaporative water use in Miombo and Teak forests to cover other land uses in the entire Basin. Through the SEBS modelling approach, it was possible to estimate the evapotranspiration of other land covers such as sugarcane plantations and natural forest. in the Kilombero River Basin, while maintaining the field assessments as validation points. However, the study was limited by the availability of cloud-free images. The application of the various remote sensing techniques in this study, which formed one of the pillars of the study, made it possible to integrate and analyse the dynamics of land use changes across scales. In summary, all the Chapters in this thesis are linked and integrated in their philosophy and focus, with subsequent Chapters building on the strength and outcomes of previous Chapters, as highlighted in Figure 1.5 in Chapter 1.

The Kilombero Basin, and especially the Kilombero Valley, have substantially changed in the past 30 years. These changes were found to be predominantly driven by uncontrolled wetland agriculture both from small holder and large-scale farmers, transforming the formerly

wetland-dominated Valley into a popular agricultural zone (Chapter 2). This, in turn, has resulted in alterations to the hydrological cycle and, ultimately, the water resources in the Valley thereby threatening the sustainability of this formerly rich and bio-diverse ecosystem.. The effects of these changes have been shown in this study to affect process both at local and basin scale.

Commercial agriculture for example, an emerging and fast growing industry in the Kilombero Basin, has been shown by this study to have the potential to impact on the water resources of the Basin. Commercial forestry afforestation, a case study in this research, generally involves the transformation of the vegetation structure, as observed in this study, resulting in changes in the surface energy balance and, thus, the evapotranspiration regime. Depending on the nature of the introduced species, substantial changes in the transpiration could be experienced, as was demonstrated in this study with Teak forest (Chapter 3). Change in evapotranspiration and subsequently the water balance due to forest conversion, translated into reduced ground water recharge and a resultant alteration of the soil water balance (Chapters 4 and 5). Forest water use and the magnitude of its impact on the available water resources, according to the findings of this study, is highly dependent on the forest canopy structure, phenology, root architecture and stand density (Chapter 3).

Of a great concern, owing to its recent expansion in the Basin, is irrigated agriculture practiced mainly by large-scale commercial farmers, especially in paddy and sugarcane plantations. Irrigated sugarcane agriculture is currently being widely adopted and new farms established at several locations within the Basin for the purpose of biofuels production and also in response to the Kilimo Kwanza Agricultural Initiative Government policy. This study demonstrated that this practice has the potential to alter hydrology, especially processes like evapotranspiration. It was shown that the water use of this system is persistently high throughout the year (Chapter 5), implying that this development eventually would have the highest total annual water withdrawals. This study reported amounts ranging between 5 and 6 mm day<sup>-1</sup> across sugarcane fields. These rates approximate those estimated on the forests (6 – 7 mm day<sup>-1</sup> during the growing season) most likely because of the irrigation system practiced in the study area, the surface irrigation methods including sprinklers. The impacts are likely to be more pronounced if other losses as a result of river diversions and drainage canals are taken into account.

Further, the study established that the Basin was subjected to high rates of wetland conversion to agricultural and settlement areas. Wetland agriculture has led to the drainage of these wetlands, totalling transforming the Kilombero Valley landscape into a seasonally vegetated system. As a result, the surface energy balance and hydrological cycle partitioning are changed (Chapter 5). The historical vegetation water use in the Valley has subsequently changed, both in season (because of the dormant dry period) and in space or coverage.

## **6.2 Synthesis**

Sound management decisions in water resource management can only be successfully reached with an in-depth understanding of the on-going dynamics in the Basin. This study demonstrates the importance of combining field-based measurements with tools that have the potential to capture the spatial-temporal changes in the landscape for sound water resource management. Particularly for data-scarce watersheds, the use of remote sensing techniques is necessary. This explains why, until recently, the detailed hydrology of data-scarce river basins like the Kilombero in Tanzania, have barely been understood. For example, a recent attempt by Fischer (2013) to study the water balance of the Basin from historical time series data was unsuccessful due to inadequacy of data. The study then concluded that there was still inadequate knowledge of the rainfall-runoff processes in the Basin, with inadequate data available to capture the inherent heterogeneity across landscapes. In this study, an attempt has been made to highlight the evaporative water use characteristics of various land uses in the Basin, which previously had not been done. This study has thus tried, with appreciable success, to capture the inherent dynamics of evapotranspiration across scale in the Kilombero River Basin which is a valuable step in understanding the variation of hydrological processes across scales.

The findings of this study provide important contributions to the understanding of the hydrology of the Kilombero Basin, especially in the context of land use change and associated hydrological impacts. This study has clearly indicated the extensive land use changes in the Basin, starting from the 1990s to early 2000, a period that marked the beginning of extensive human exploitation of Valley wetlands resources.

Unfortunately, this period also coincided with a time when most of the streamflow gauging stations in the Basin were not operational due to lack of financial support and increased

vandalism. The latter could be attributed to increased human presence in the Basin, sadly an uncontrolled dynamic.

Thus, this study was timely due to the fact that it provided another dimension of analysis where the focus has been on evapotranspiration. This is a departure from the conventional assessments on impacts of land use changes in the study area which focused on streamflow discharge. Previous attempts to forecast the hydrological behaviour of the Basin, using historical rainfall-runoff signatures while assuming stationarity of the system, are unlikely to give reliable predictions of streamflows. Moreover, for watershed that are changing in landscape, such as the Basin under study, past observations may not be a good guide to future hydrological prediction (Wagener et al., 2010). This calls for the use of innovative hydrological methods and models that are adaptable to the changes in land surface features, energy and water cycles, as induced by human interactions. It is on this premise that more research work is needed, to fully understand the complexities of the Kilombero hydrology. It is envisaged that remote sensing coupled with SVAT (Soil Vegetation Atmosphere transfer) models or any of such catchment hydrological models will provide a useful platform in future research endeavours in the Kilombero Basin, building on the extensive and intensive application of various remote sensing techniques applied in this study.

This study is a good example of research that was undertaken with challenges in both the availability of historical observed data and physical accessibility. However, its achievements demonstrate the possibility of working with minimal past hydrological information to gain sufficient insight into the hydrological processes in the study area before detailed field experimentation takes place. The process of engaging different stakeholders in the Basin, ranging from smallholder entrepreneurs, private companies (such as the Kilombero Valley Teak Company and Illovo Sugarcane Company) as well as the water resource management authorities, provided a good insight on the importance of engaging all stakeholders in such a study. It is good to highlight the fact that the results of this study have been requested by different stakeholders in the Basin, including the Rufiji River Basin Office.

This study has led to the identification of the major agents of change to the hydrology of the Basin. From the analysis, it is clear that more attention needs to be given to managing the increasing agricultural activities in the wetlands in the Valley. In particular, the continuous fragmentation of the indigenous forests and clearance of the Miombo woodlands requires immediate attention. Forest conversion from indigenous to exotic type, likely to introduce

structural changes either in canopy and/or roots architecture, needs to be carefully guided by a detailed assessment of the potential dynamics of such an intervention on both surface and subsurface water. Although it is generally thought that replacing forests with a structurally similar vegetation type has no adverse impacts on water resources, this study has proven otherwise.

Furthermore, the findings of this study and other similar undertakings in the past (Jewitt, 2002; Van der Walt *et al.*, 2004; King, 2013) have revealed the significant role that plantation forests play as water consumers. The results of this study point to the possibility of categorising commercial plantation forests as water users in Tanzania. South Africa provides an example to follow where policy categorises commercial forest plantations as net water users (or a stream flow reduction activity) which require a license and adherence to water pricing regulations and billing (Tewari, 2007; Jewitt *et al.*, 2009).

It is useful to note that, regardless of the popularity of applying remote sensing techniques in water resource management, challenges should be expected when applying the surface energy balance approach, especially in hilly terrain or cloud-covered areas and forests. In such situations, ground measurements should be prioritised with remote sensing techniques being applied to gain more in-depth understanding of the Basin or regional processes. This explains why an attempt by Armanios and Fisher (2012) to develop a purely satellite-based hydrological budget in the Kilombero, totally depending on satellite imagery data, was unsuccessful. Thus, this study further affirms the importance of ground validation of data across scales. Again, the resolution (in space and time) of the satellite images has vast implication for the surface energy balance analysis. The higher the pixel resolution the better (e.g. Landsat data is very instrumental in comparative analysis of water uses, as was the case with Miombo and Teak forest plantations in this study). It is also more applicable for retrieving and distinguishing the water use of smallholder farmers' cropland areas, given their small sizes in rural catchments like that of Kilombero.

### **6.3 Conclusion**

In conclusion, this study has established that the Kilombero River Basin has undergone dramatic land use change, as a result of agricultural intensification over the past two decades, especially on the Valley floor. This has affected the hydro-ecological system of the Valley, including the loss of perennial wetlands. The study has established that settlement and agricultural land occupied 24% of the whole area in the Valley in the 1990s increasing to 62% in 2008/09. Sugarcane plantations at Illovo and the Kidatu area alone increased by 5,400 ha between 2002 and 2008, mostly replacing the areas that were previously under smallholder farming for food production. The area under commercial forests has also increased, with Teak forests replacing 2,200 ha of indigenous Miombo woodland.

Plot scale studies, with the aim of quantifying the hydrologic implications of converting land covers and changing land uses in the Basin, pointed to the possibility of these conversions significantly altering the water balance of the Basin. It was shown that the conversion of natural Miombo land covers to Teak plantation forests resulted in a change in the dry season total transpiration, with Miombo recording 51 mm and Teak 225 mm. This translates into the alteration of rainfall partitioning by Teak forests where a significant amount of incident rainfall is transpired back to the atmosphere, with less being released for soil moisture replenishment. Evidence of change in the evapotranspiration regime in the Kilombero Valley was confirmed, using the remote sensing SEBS modelling platform, where the Valley area's latent heat flux (i.e. evapotranspiration) was noted to reduce over time with dry seasons becoming drier (evapotranspiration approaching zero such as in 2010). This is a good indication of the loss of the Valley's wetlands and their hydrological functioning. Wetlands are naturally supposed to store water during the wet season and sustain the eco-hydrological system during the dry season. Unfortunately, this system has been altered with the extensive land use change in the Valley and most of the perennial wetlands have been turned into agricultural lands. Similar alterations were noted in areas where commercial forestry plantations have replaced the natural Miombo woodland.

In addition, subsurface hydrodynamics in the root zone revealed that the consumptive water use of Teak results in less soil moisture storage and deep water drainage in comparison to Miombo. While deep drainage is dominant in the soil water balance of Miombo, root zone soil water extraction is dominant in soil water balance of Teak.

This study shows that all the above-mentioned human interventions in the Kilombero Valley alter local hydrological functioning and hence have a potential impact on the water resources in the Kilombero Basin.

#### **6.4 Recommendations for Future Research**

Given the national and international importance of the Kilombero River Basin in both biodiversity and food security, there is an urgent need for a more elaborate monitoring network of hydro-meteorological parameters supported by dedicated research initiatives, such as that undertaken through this study, which highlights, in detail, specific entities of the larger water balance in the Basin. Hydrological regimes of most of the tributaries draining into the Kilombero River are unknown due to a lack of river gauging stations. The monitoring of the groundwater regime in the Basin is seldom in place (currently there are only two functional observation wells in the Basin). It is of paramount importance to maintain the automated streamflow monitoring system at the outlet of the Basin, comprising the remotely located (station code 1KB17 (within a game reserve) and station 1KB2, for the assurance of timely and high resolution data. However, the challenges of accessibility for many areas of the Basin, due to complex terrain and lack of access roads, must be appreciated. This study, therefore, strongly recommends the automation of the river gauging stations in the Basin. Likewise, it is the proposition of this study that automatic weather stations need to be installed on the mountain ranges surrounding the Valley since most of the streams feeding the larger Kilombero River originate from these highlands. Unfortunately, there are currently no weather stations on these mountain ranges presenting a significant barrier to accurately quantify or understand the hydrological systems of the entire Kilombero River Basin.

Moreover, river basin management in the Kilombero Valley, and Tanzania as a whole, could learn from South Africa's experience in managing evaporative water uses in commercial forestry. This is important as commercial forestry is an emerging industry in the country and needs guidance in ascertaining the sustainability of water resources in the respective basins. Currently, the estimated total gross area of all commercial forestry plantations is 250,000 ha (Chamshama and Nshubemuki, 2010) with the majority planted to *Cupressus lusitanica* (70%), *Pinus patula* (20%) and *Eucalyptus saligna* (10%) species. In the case of the already established forests, the adoption of management strategies that best minimise the evaporative

water use (e.g. reducing stand density) could make a significant difference, as proposed in Chapter 3 of this thesis.

Further research is required for a comprehensive impact assessment on canopy water storage of commercial forests in comparison with the native Miombo woodlands. Moreover, other plantation forests within the basin such as eucalyptus and pine plantations, currently being expanded to cover large spatial extents and known to be heavy water users, need to be studied and their water use characteristics profiled. More research is required on the on-going wetland agricultural practices that have the potential to significantly modify the hydrology of the River Basin.

Lastly, future field campaigns and research initiatives in the Basin should take into consideration the challenges of accessing many areas of the Basin particularly with regard to sources of electrical power supply and a lack of skilled personnel to operate sophisticated equipment in the field. Thus, this study recommends the use of simple technologies that do not require access to the main electrical power supply to complement intensive high tech field campaigns while taking into consideration the relatively low skill levels in the area.

## **6.5 References**

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