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**Water-use, growth and water-use efficiency of indigenous tree species  
in a range of forest and woodland systems in South Africa**

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## **Abstract**

South Africa's indigenous forests and woodlands provide valuable goods and services to the country. However, their slow growth rates, and the limited extent of indigenous forests in particular, have rendered them unable to meet the timber needs of a developing economy. This necessitated the establishment of a plantation forest industry using fast-growing introduced tree species. While the benefits of this industry in terms of production, income generation and job provision are undisputed, these come at some environmental cost, not least the impact of the industry on water resources. This has been the subject of considerable research, and led to regulation of this industry in 1972 due to water-use concerns. Conversely, there is widespread belief that indigenous tree species use little water, and that there is merit in their wider establishment and utilisation. However, data on the water-use and growth rates of indigenous trees and forests in South Africa are scarce.

This study was initiated to explore whether indigenous tree species use less water than introduced plantation tree species, whether they use that water more efficiently in terms of biomass accumulation, and consequently whether there is scope for the expansion of indigenous tree production systems in South Africa. Eddy Covariance and Scintillometry techniques, combined with stem sap flow measurements, were used to derive water-use volumes for a mixed species evergreen Afro-temperate forest, dry savannah woodland, an even-aged single-species indigenous tree plantation, and a selection of individual indigenous tree species, over periods ranging from 12 to 24 months. Above-ground annual biomass increments were simultaneously measured or modelled at selected sites. Rates of growth and water-use were compared to existing data for introduced plantation tree species, and were used to calculate water-use efficiency.

Growth and transpiration rates observed in indigenous tree species were both consistently lower than for introduced plantation tree species. However, above-canopy total evaporation volumes were noticeably greater than scaled up tree transpiration volumes, underscoring the contributions of under-storey transpiration and soil evaporation to overall water-use. Ratios of growth to water-use indicated that the indigenous trees had lower biophysical water-use efficiency values, compared to genetically-improved introduced tree species. The lower WUE of the indigenous tree species was attributed primarily to slow growth rates as opposed to high water-use rates, highlighting their potential as a viable land-use option in appropriate locations within water-constrained catchments having forestry potential.

## **Declaration**

The work described in this thesis was carried out for post-graduate degree purposes within the Botany Department, University of Cape Town, under the supervision of Dr. E. February and co-supervision of Dr. P. Dye (Wits University); and as an externally funded contract research project. The study was based on projects K5/1462 and K8/801 (“Water-use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions”), solicited and funded by the Water Research Commission (WRC) and the former Dept. of Water Affairs and Forestry (Working for Water Programme), under the management of Dr. Gerhard Backeberg (WRC). The actual project work on which this thesis is based was carried out by a project team comprising Dr. P.J. Dye (CSIR - project leader), Mr. M.B. Gush (CSIR), Dr. C.S. Everson (CSIR), Dr. C. Jarmain (CSIR), Mr. A. Clulow (CSIR), Dr. M. Mengistu (CSIR), Dr. C.J. Geldenhuys (ForestWood cc), Dr. R. Wise (CSIR), Dr. R.J. Scholes (CSIR), Ms. S. Archibald (CSIR) and Prof. M.J. Savage (University of KwaZulu-Natal). Some project contributions by various members of the above team are incorporated in this thesis and their respective inputs are detailed below.

The total evaporation (scintillometry) measurements described in chapters 4 and 5 were conducted under the guidance of Dr. Everson, with assistance from Mr. Clulow. Initial tree growth estimates for the Groenkop forest (Chapter 4) were provided by Dr. Geldenhuys, and the Eddy Covariance measurements described in chapter 6 were conducted by Dr. Everson, Dr. Jarmain and Mr. Clulow. Mindful of the above, the content of this thesis represents original work by the author, and has not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others it is duly acknowledged in the text.

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**The Tables Turned**  
**(An Evening Scene on the Same Subject)**

Up! up! my Friend, and quit your books;  
Or surely you'll grow double:  
Up! up! my Friend, and clear your looks;  
Why all this toil and trouble?

The sun, above the mountain's head,  
A freshening lustre mellow  
Through all the long green fields has spread,  
His first sweet evening yellow.

Books! 'tis a dull and endless strife:  
Come, hear the woodland linnet,  
How sweet his music! on my life,  
There's more of wisdom in it.

And hark! how blithe the throstle sings!  
He, too, is no mean preacher:  
Come forth into the light of things,  
Let Nature be your Teacher.

She has a world of ready wealth,  
Our minds and hearts to bless  
Spontaneous wisdom breathed by health,  
Truth breathed by cheerfulness.

One impulse from a vernal wood  
May teach you more of man,  
Of moral evil and of good,  
Than all the sages can.

Sweet is the lore which Nature brings;  
Our meddling intellect  
Mis-shapes the beauteous forms of things:  
We murder to dissect.

Enough of Science and of Art;  
Close up those barren leaves;  
Come forth, and bring with you a heart  
That watches and receives.

**William Wordsworth (1770-1850)**

“Thank Goodness it’s Friday. Only two more working days until Monday.”

Simon Lorentz

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# Chapter 1

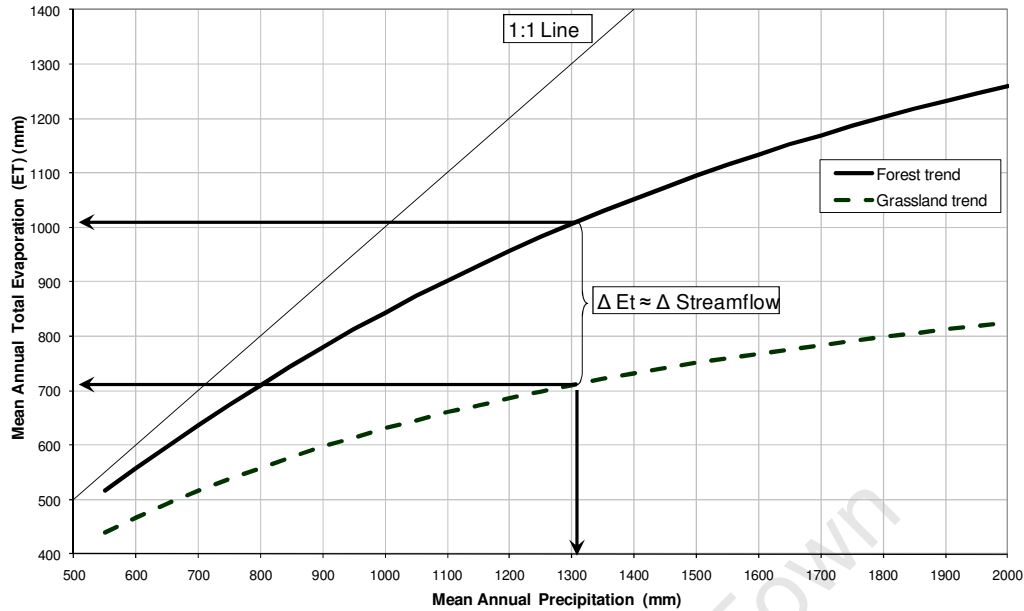
## **INTRODUCTION**

South Africa has always had limited indigenous timber-producing forests. Following the arrival of Jan van Riebeeck and Cape settlers in the 17th century, naturally occurring forests were heavily exploited up until the late 19th century, by which time wholesale destruction had halved their original extent (Sim, 1907). By this stage demand for timber had significantly exceeded the capacity of indigenous forests to supply in the wood needs of the country. Consequently, in 1876 the first commercial introduced (exotic) tree plantation was established near Worcester by the Railway Department, followed by plantations at Tokai State Forest in 1883 and at Kluitjieskraal, near Wolseley, in 1884 (Olivier, 2009). After 20 years, the planted area had reached 8401 ha, predominantly in the Cape, and by 1910, at the time of the establishment of the Union of South Africa, the afforested area was more than 100 000 ha (van der Zel, 1987).

The harvesting of indigenous timber continued unabated however, until the promulgation of the 1913 Forest Act stemmed the destruction of the country's natural forests. Simultaneously, severe shortages of timber during historical events such as the First World War in 1914 and the "Great Depression" in 1936 forced South Africa to accelerate the development of its own forest industry, so that towards the end of the Second World War in 1945, 600 000 ha of commercial exotic plantations were in existence (van der Zel, 1987). Plantations of fast-growing introduced species (pines, eucalypts and wattle) continued to be established in the high-rainfall regions of the country, which largely constituted mountain catchments (i.e. important water-yielding areas). Commercial plantation forests subsequently expanded to a maximum of approximately 1.5 million hectares in 1996/1997 but declined thereafter to the most recent estimate of approximately 1.25 million hectares in 2009 (FSA, 2010).

Plantations of introduced tree species are characterized by tall, dense evergreen canopies and deep-rooted systems. The physiology of these plantations contrasts strongly with the predominantly short, seasonally dormant shrubland or grassland vegetation that they typically replace (Dye and Versfeld, 2007). Consequently, as the area under introduced plantations has grown, so have concerns about their impacts upon water resources (Nänni, 1970; Water Matters Committee, 1970; Bosch and Hewlett, 1982; Bosch and von Gadow, 1990). In South Africa, water-use concerns first led to the initiation of forest hydrological research in 1935, and the subsequent establishment of long-term paired catchment research stations around the country (Scott *et al.*, 2000).

Considerable forest hydrological research using paired catchment experiments has subsequently been conducted nationally and internationally (Brown *et al.*, 2005). In South Africa long-term trials aimed at assessing the impacts on streamflow associated with land-use changes (primarily afforestation with introduced plantation species) were conducted over a period of approximately 50 years (Scott *et al.*, 2000). Once sufficiently long data sets had been accumulated, detailed analyses were subsequently carried out; resulting in the development of a number of tools, such as the CSIR curves (Scott and Smith, 1997), to estimate the impacts of afforestation on streamflow at larger scales. Numerous local and international studies have now indicated conclusively that plantations of introduced tree species consume more water than grasslands or shrublands (Fig. 1.1) and thus reduce water yield (stream flow) from afforested catchments (Bosch and Hewlett, 1982; Zhang, 1999; Scott *et al.*, 2000; Zhang, 2001; Farley *et al.*, 2005; Jackson *et al.*, 2005; Dye and Versfeld, 2007; Scott and Prinsloo, 2008; Silveira and Alonso, 2009).



**Figure 1.1 The relation between mean annual precipitation and mean annual total evaporation (ET) for different vegetation types. Lines indicate the global trends in mean annual total evaporation from forested (solid) and grassland (dashed) catchments (after Zhang *et al.*, 1999). An example of the difference in ET between grassland and forest sites for a given mean annual precipitation, and how this could translate into a corresponding difference in streamflow, is illustrated.**

In order to manage the conflict for a limited water resource, and based on the findings and recommendations emanating from forest hydrology research both in South Africa and internationally the state introduced legislation in 1972 to regulate the forest industry through the so-called Afforestation Permit System (APS) (van der Zel, 1995). The APS required timber growers to apply for permits to establish plantations of introduced tree species. The water-use of forestry was consequently regulated through control of the area that could be planted to trees. The policy underwent a series of refinements since then, notably the declaration in the National Water Act (NWA, Act No. 36 of 1998) of commercial afforestation as a stream-flow reduction activity (SFRA) or land use that may reduce the amount of water in rivers and thus what is available to downstream users. Under the new SFRA Water Use Licensing System (which fully replaced the old APS) the requirement for afforestation permits (now called “licences”) was continued (DWAF, 2004).

The current afforestation licensing and regulation system utilises results from a modelling exercise which first verified an appropriate model (ACRU) against data from paired catchment studies, and then conducted simulations to estimate streamflow reductions in all potential forestry areas in South Africa (Gush *et al.*, 2002). Stream-flow reduction estimates at a national scale were calculated using a simplified water balance equation (streamflow = precipitation minus total evaporation) where a change in total evaporation (caused by a change from the natural vegetation to commercial forestry) constituted a change in stream-flow (usually a streamflow reduction). These streamflow reductions were individually simulated for the three principal introduced plantation tree genera at a national quaternary catchment (QC) scale, and results were displayed in the form of maps and tables. The results were implemented by regional offices of the then Department of Water Affairs and Forestry (DWAF) in water resource management decision-making processes (Chamberlain *et al.*, 2005). The expansion of introduced plantation forestry is now restricted in most areas because of the environmental impacts (primarily in terms of water-use, but also bio-diversity loss) of commercial plantations.

On the other hand, with over 1000 species of indigenous trees in the country, South Africa is extremely rich in natural arboreal diversity (von Breitenbach, 1990). The numerous benefits of indigenous trees and forests, in terms of the goods and services that they offer, are widely recognised (Lawes *et al.*, 2004; Shackleton *et al.*, 2007). There are also widespread, although unsubstantiated perceptions in this country that indigenous tree species use less water than introduced tree plantations. While work in Latin America (Licata *et al.*, 2008) and Ethiopia (Fetene and Beck, 2004; Fritzsche *et al.*, 2006) provides some evidence for lower water-use by indigenous tree species, data on the water-use of indigenous trees and forests in South Africa is scarce, and relationships between growth and water-use within indigenous forests have until now not been investigated. This information is required in order to evaluate biomass production relative to plant water-use (water-use efficiencies) in indigenous tree species and facilitate sustainable land-use planning from a hydrological perspective (Dye *et al.*, 2008). With a growing

awareness of the socio-economic and environmental challenges being posed by finite water supplies in a developing country such as South Africa, there is renewed interest in the possibility of low water-use forms of forestry. Fortunately, new and innovative techniques to quantify the water-use (transpiration\* and total evaporation†) of a range of tree species and forest types are available (Jarman *et al.*, 2008), and these may be used to broaden our understanding of forest hydrological processes, and their associated effects on water resources in this country.

It is an appropriate time in the development of the South African forest industry to reconsider whether indigenous tree species can form the basis of new, viable kinds of “**Indigenous Forestry**” to supplement existing introduced plantation forests. Evidence of low and efficient water-use would promote their potential as an attractive alternative forestry solution, particularly in catchments that are water-stressed. The overall efficiency of water-use for biomass production, and the net benefit of the water used are important criteria that need to be understood to permit the evaluation of different land use scenarios. Expanded indigenous forestry systems in South Africa could, under certain conditions, offer attractive alternative land-use scenarios to plantations of introduced timber species, but the feasibility of their expansion needs to be thoroughly evaluated from socio-economic and environmental perspectives.

Mindful of this background, the research described in this study was motivated by two primary interests. Firstly, recognition that the negative water-resource impacts of introduced plantation forestry in South Africa are a reality, thereby constraining the further expansion of this industry, and highlighting the need for alternative solutions. Secondly, that there is merit in exploring the potential

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\* Throughout this dissertation **Transpiration (T)** refers to water taken up by plant roots, passed through plant tissues and eventually vaporized, principally through leaf stomata, into the atmosphere (Allen *et al.*, 1998).

† Throughout this dissertation **Total Evaporation (ET)** refers to the sum of (a) evaporation from the soil surface, (b) transpiration by vegetation, and (c) evaporation of water intercepted by vegetation. Also referred to as Evapotranspiration, although use of this term has been discouraged (Savenije, 2004).

of indigenous tree species and natural forest systems as a means of expanding forests and/or plantations, with numerous potential benefits and without undue negative effects (particularly in terms of water-use). Answering these questions conclusively is a long-term objective, and beyond the scope of this particular study alone; however an initial foray into this field of research has been the subject of this dissertation. This is the first study of this kind to have been conducted on indigenous tree species in South Africa. Four individual experiments (or case studies) on the water-use and growth of indigenous tree species and natural forest systems were carried out to explore if:

- 1. indigenous tree species use less water than introduced plantation tree species?***
- 2. indigenous tree species use water more efficiently than introduced plantation tree species?***

The principal aim of the study was consequently to determine the relationship between biomass production and plant water-use for a range of indigenous tree species and production systems, for comparison against introduced plantation tree species. This was done through a series of tree- and stand-level field measurements (case studies) within mixed evergreen Afro-temperate forest, savannah woodland, even-aged indigenous tree plantations and selected individual indigenous tree species. Seasonal above-canopy total evaporation rates and continuous stem sap flow (transpiration) rates were used to derive water-use volumes for the indigenous tree systems over periods ranging from 12 to 24 months. Above-ground annual biomass increments were simultaneously measured or modelled. Rates of growth and water-use were used to calculate water-use efficiency and results were compared to existing data for introduced plantation tree species. Measurements were carried out over four years, and augmented with additional information gleaned from literature.

In the next chapter (Chapter 2) I provide an overview of indigenous tree systems in SA (definition, classification, distribution and utilization), after which I briefly review the concept of WUE (Chapter 3), citing definitions and current understanding from international literature, and discussing these in the context of the South African situation. The following three chapters comprise actual case-studies on growth, water-use and WUE, conducted in representative examples of the three indigenous tree systems, namely; a mixed species evergreen Afro-temperate forest (Chapter 4), dry savannah woodland (Chapter 5) and an even-aged single-species indigenous tree plantation (Chapter 6). A subsequent chapter (Chapter 7) covers a similar case-study conducted on a selection of individual indigenous tree species occurring over a wide bio-climatic range. The thesis concludes with a synthesis chapter (Chapter 8), reviewing the results of the study, discussing the implications of those results and suggesting some future research needs.

# Chapter 2

## OVERVIEW OF SOUTH AFRICAN INDIGENOUS TREE SYSTEMS

Indigenous trees in South Africa occur predominantly in natural forests and savanna woodlands; however limited areas of planted indigenous stands do exist. In this chapter I provide an overview of these indigenous tree systems, citing relevant definitions and summarising their classification, distribution, utilisation and management.

### Definitions

The definition of what constitutes an indigenous forest in South Africa has changed over the years, and at the outset it is important to distinguish between **forest** and **natural forest**. The National Forest Act (NFA) of 1998 broadly defines **forest** as:

*“including a natural forest, a woodland and a plantation, the forest produce in it, and the ecosystems which it makes up.”*

The legal definition of a **natural forest** in the NFA (1998) is:

*“a group of indigenous trees, which a) in the undisturbed state have overlapping crowns (>75% crown cover of their combined tree strata); b) in the disturbed state may be open-grown, or not present at all, but the associated remnant indigenous plant species of all life forms are generally associated with natural forest; c) forms part, or had formed part in the last 50 years, of the stages of a mature forest, whether in degradation or recovery; and d) is not a woodland or a plantation or another woody vegetation unit; or e) have been declared by the Minister to be a natural forest under Section 7(2).”*

Shackleton *et al.*, (1999) defined the term **woodland** (or savanna) as:

*“a suite of tropical and subtropical vegetation types in which fire-adapted, co-dominant, continuous or discontinuous herbaceous and largely deciduous woody strata experience markedly seasonal growth patterns and processes in relation to the seasonal delivery of precipitation, which occurs during hot summers, followed by cooler, but warm, dry winters. Generally the herbaceous stratum is dominated by C4 grasses and sedges, but this, and the overall cover of the woody and herbaceous strata, may be temporarily altered by a range of disturbance phenomena.”*

Woodlands constitute all those vegetation types in South Africa commonly referred to as bush, bushland, bushveld, thicket, thornveld and scrub. The NFA (1998) defines **woodland** on the basis of canopy cover as:

*“a group of trees which are not a natural forest, but whose crowns cover more than five percent of the area bounded by the trees forming the perimeter of “the group”.*

In the NFA (1998) a **plantation** is simply defined as:

*“a group of trees cultivated for exploitation of the wood, bark, leaves or essential oils in the trees.”*

All plantations are, somewhat controversially, classified as **forest** under the current NFA (1998), however no formal distinction appears to have been made between plantations of indigenous species as opposed to those of introduced species. For the purposes of this discussion the definition of a plantation follows that drafted by the Global Forest Resources Assessment (FAO 2001), namely:

*“a collection of trees of one or more species, planted at the same time, in regular rows of known spacing, and managed with the objective of maximizing the production of utilizable above-ground biomass.”*

This distinguishes plantations of indigenous tree species from regenerated / natural forests of mixed species and mixed ages of trees, and excludes trees planted in gardens or cities.

## Classification

South African indigenous forests were formerly classified into two principal types, namely Afromontane Inland Forests and Coastal Subtropical Forests (White, 1978), and then into just one Forest Biome (Low and Rebelo, 1998). A national forest type classification conducted by von Maltitz *et al.*, (2003) subdivided the biome into twenty natural forest types in 7 groups, with an additional 4 azonal forest types. These same forest groupings have largely been retained in the most recent natural vegetation mapping exercise for South Africa (Mucina and Rutherford, 2006), with the addition of Sand Forest and Ironwood Dry Forest as new groups, and the removal of Licuati Sand Forest as an azonal forest type. The actual areas and relative proportions of the different forest groups and azonal forest types now considered to make up the forest biome (Mucina and Rutherford, 2006) are represented in Table 2.1.

**Table 2.1** Areas represented by the various natural forest groups in South Africa (from Mucina and Rutherford, 2006), and their respective proportions of the entire forest biome.

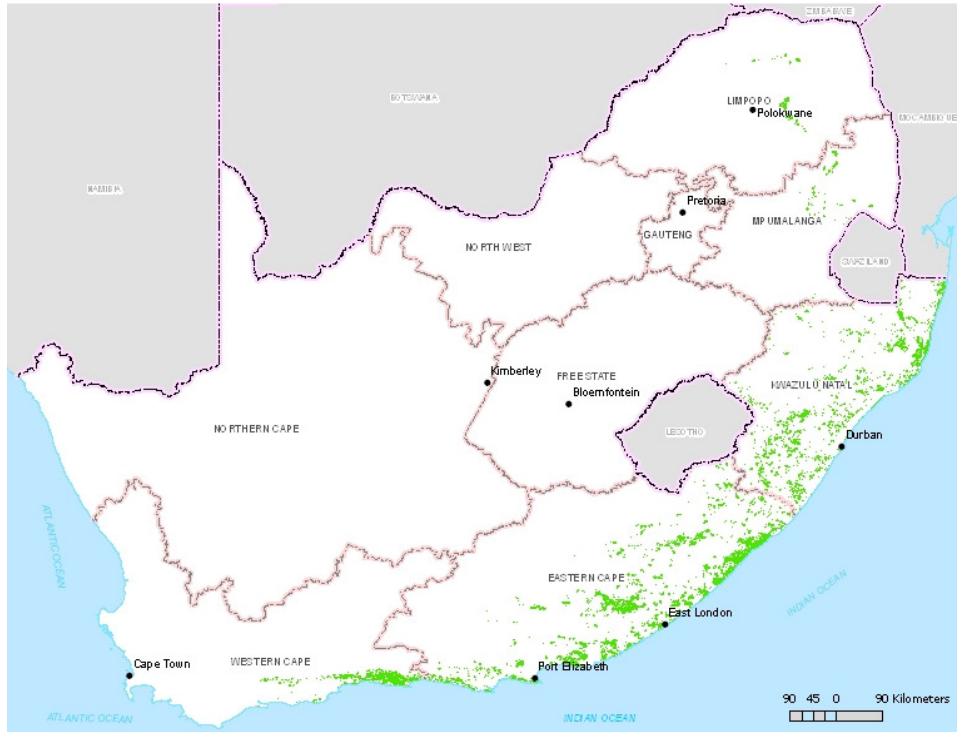
<b>Forest Group</b>	<b>Area (km<sup>2</sup>)</b>	<b>Percentage of Biome</b>
Southern Mistbelt Forest	1100.15	23.34%
Scarp Forest	867.18	18.39%
Southern Afrotropical Forest	799.8	16.96%
Northern Mistbelt Forest	613.38	13.01%
Northern Coastal Forest	467.05	9.91%
Sand Forest	242.75	5.15%
Northern Afrotropical Forest	169.74	3.60%
Southern Coastal Forest	165.45	3.51%
Lowveld Riverine Forest	158.4	3.36%
Ironwood dry Forest	59.19	1.26%
Swamp Forest	38.03	0.81%
Mangrove Forest	33.4	0.71%
<b>Total</b>	<b>4714.52</b>	<b>100.00%</b>

A great number of woodland (savanna) types have also been classified for South Africa (Acocks, 1988; Low and Rebelo, 1998). This is attributable to the tremendous diversity and geographical range of this biome. In the most recent vegetation assessment for South Africa, Mucina and Rutherford (2006) now classify the savanna biome into 87 different vegetation types within six groups or bio-regions.

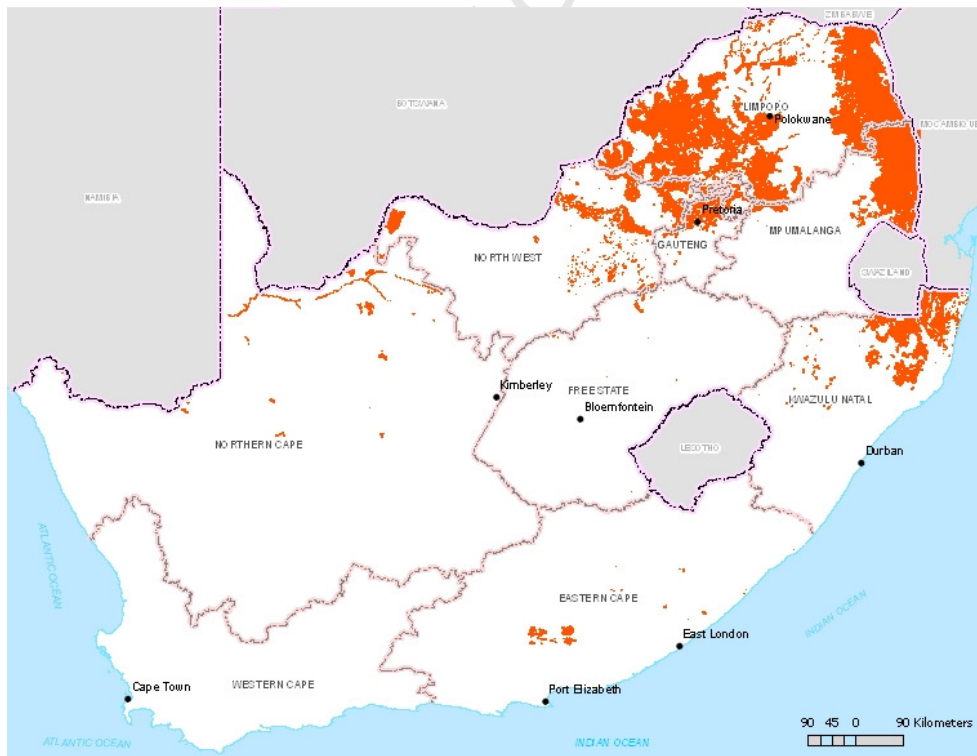
### **Distribution**

The natural indigenous forests of South Africa, although limited in extent, occur scattered over a wide latitudinal gradient along the eastern and southern margins (escarpment, mountain ranges and coastal lowlands) of the country (Fig. 2.1). Their distribution ranges from the Soutpansberg in the north of Limpopo province (inland, 22°40'S), through Mpumalanga to Maputaland in the east (coast, 27°S), in the eastern Freestate and along the Drakensberg Mountains of KwaZulu-Natal (inland, 29°S), discontinuously through the midlands of KwaZulu-Natal and the Eastern Cape to the coast, down through the Outeniqua and Tsitsikamma Mountains of the southern Cape to the Cape Peninsula in the south-west (34°S) (Mucina and Geldenhuys, 2006).

Typically, indigenous forests occur as a series of scattered small to very small patches (<10 ha), and most forests are smaller than 100 ha in size (Cooper, 1985). While at least 7% of the country is a potential habitat for indigenous forests owing to the favourable combination of climate and substrate suitable for forest growth, only approximately 4700km<sup>2</sup> (0.1%) of the land surface of South Africa is actually covered by natural forests (Mucina and Geldenhuys, 2006). Woodlands on the other hand are estimated to cover approximately 290 000 km<sup>2</sup> (6.2 %) of South Africa (Mucina and Rutherford, 2006), and are distributed over a significantly wider land area (Fig. 2.2).



**Figure 2.1** Map showing the extent and distribution of natural forests in South Africa (DAFF, 2009).



**Figure 2.2** Map showing the extent and distribution of savanna woodlands in South Africa (DAFF, 2009).

In terms of indigenous tree plantations in South Africa, there is very little information available on their current extent and distribution. Nevertheless, the desire to establish viable indigenous tree production systems in South Africa can be traced back over 100 years. One of the earliest efforts was experimental plantings of *Ocotea bullata* (Burch.) Baill. (Black Stinkwood), *Curtisia dentata* (Burm.f.) C.A.Sm. (Assegai), *Apodytes dimidiata* E.Mey. ex Arn. (White Pear) and both local Yellowwoods, *Podocarpus latifolius* (Thunb.) R.Br. ex Mirb. (Real Yellowwood) and *P. falcatus* (Thunb.) R.Br. ex Mirb. (Outeniqua Yellowwood) at Concordia (Knysna) between 1897 and 1900 (Stapleton, 1955). Additional trial plantings of indigenous yellowwood trees are known to have been established at sites in the southern Cape (Witfontein), Mpumalanga (Frankfort) and Limpopo provinces (De Hoek) of South Africa in the early 1980's (Geldenhuys and von dem Bussche, 1997). Some experimental plantings of *Khaya anthotheca* (Welw.) C.DC. (East African Mahogany) took place on Frankfort State Forest near Sabie, Mpumalanga and at Entabeni State Forest, Limpopo province (von dem Bussche and Ellis, 1987). While this species is not indigenous to South Africa, it does occur naturally in eastern Zimbabwe. Also in Limpopo Province, experimental plantings of *Trema orientalis* (L.) Blume (Pigeonwood) were initiated at the Westfalia Estate near Tzaneen (Keet, 1962). In addition to these controlled plantings, observations of indigenous species (e.g. *Podocarpus spp.*) regenerating beneath pioneer indigenous trees as well as beneath plantations of introduced tree species have been noted over the years by Wicht (1949), Taylor (1962), van der Schyff (1963), Seagrief (1965) and Geldenhuys (1997).

### **Utilisation and Management**

Indigenous forests and woodlands in South Africa provide numerous goods for the benefit of society, primarily valuable timber for building and craft materials, fuel-wood and non-timber forest products (Mckenzie, 1988; Everard and Hardy, 1993; Shackleton and Shackleton, 2000; van Wyk *et al.*, 2003; Lawes *et al.*, 2004). They also provide ecosystem services such as carbon

sequestration, nutrient cycling and watershed protection, and are important cultural and recreational sites, supporting high levels of biodiversity (Geldenhuys, 1999; Shackleton *et al.*, 1999). They are home to approximately a quarter of all South Africans (Shackleton *et al.*, 1999), and as such are heavily relied upon in rural areas and have the potential to make a marked contribution to the economy of the country (Shackleton *et al.*, 2007). The southern Cape indigenous forests have been extensively utilized for timber almost continuously since their discovery by the Dutch in 1711. The history of this exploitation has been well documented in the literature and, through gradual advancement of policy from 1778 onwards, a formal system of multiple-use with close monitoring to ensure sustainability has been developed (Phillips, 1931; Laughton, 1937; Phillips, 1963; von Breitenbach, 1968; Geldenhuys, 1980, McKenzie, 1988; Seydack *et al.*, 1990; Geldenhuys 1994b; Seydack, 1995; Seydack *et al.*, 1995; Geldenhuys, 1996; Vermeulen, 2000).

In the next chapter I review the definitions and concepts associated with water-use, growth and water-use efficiency. To test hypotheses in this regard, a series of relevant case studies are presented in subsequent chapters.

# Chapter 3

## **GROWTH, WATER-USE AND WATER-USE EFFICIENCY**

### **Introduction**

Estimates of Water-Use Efficiency (WUE) are useful in evaluating different land-use scenarios with the objective of maximising returns (socio-economic and environmental) from the landscape in the face of finite water supplies (Hubbard *et al.*, 2010). This is of particular relevance in high water-using or water-constrained environments, such as those associated with commercial afforestation in South Africa (Dye, 2000). Consequently, a need for WUE information is expected to develop as Catchment Management Agencies in South Africa are constituted to manage water resource allocations in the various Water Management Areas of the country (Nomqophu *et al.*, 2007). The volume or value of product generated per unit of water utilized by a crop, orchard or forest is anticipated to become an important criterion in deciding on competing land-use scenarios (Calder, 2005). However, the necessary scientific information required for this purpose is currently inadequate, and requires a combination of bio-physical data (e.g. yields produced or growth observed per volume of water used) and economic data (e.g. value or profit of yield per unit of water used). This study deals only with bio-physical estimates of WUE, although some preliminary economic WUE assessments have been done (Wise *et al.*, 2011).

The vast majority of bio-physical WUE studies in South Africa have been conducted on introduced commercially grown tree species (Olbrich *et al.*, 1993; Olbrich and Olbrich, 1995; Le Roux *et al.*, 1996; Olbrich *et al.*, 1996; Dye *et al.*, 1997b; Dye *et al.*, 2001). Limited WUE information is available for indigenous trees native to South Africa, and addressing this knowledge gap was the primary motivation for this study. Nevertheless, some valuable insights into WUE may be gleaned from the existing body of international

literature, and interpreted in relation to what is known about growth and water-use amongst South African indigenous tree species. In this chapter a suitable definition of WUE is discussed, and appropriate units to quantify it are suggested. The determinants and drivers of WUE are discussed through a brief review of international literature, after which a summary is provided of historical WUE-related research in South Africa (focusing on introduced plantation species). The chapter concludes with a discussion of what is known about growth and water-use within indigenous tree systems in South Africa.

### **Definition of Water-Use Efficiency**

Many different definitions of WUE exist in the literature, consequently it is important to clarify the specific definition of WUE being referred to at any particular time, as well as the methods used to determine it and the units employed. The bio-physical water-use efficiency (WUE) of a plant or vegetation type relates some measure of growth (e.g. carbon assimilation or gross primary production), to some measure of water-use (e.g. transpiration or total evaporation), over a particular time period. The links and tradeoffs between carbon uptake and water loss that take place through photosynthesis and stomatal control have been well researched (Jarvis, 1981; Whitehead, 1998; Law *et al.*, 2002). However, the estimation of WUE may be conducted at vastly different scales, which requires different measurement approaches (Lindroth and Cienciala, 1996), and occasional application of differing measurement techniques across a range of scales in a single study (Tu *et al.*, 2008).

At the molecular level stable carbon isotope ratios, when combined with an estimate of the leaf-to-air vapour pressure difference, provide a measure of the efficiency of water-use in photosynthesis (Farquhar *et al.*, 1982; Marshall and Zhang, 1994; Dawson *et al.*, 2002). As Whitehead and Beadle (2004) explain, the trade-off between photosynthesis and transpiration in leaves of C<sub>3</sub> plants, regulated by stomatal conductance, determines the ratio of the intercellular to ambient partial pressures of carbon dioxide and determines the

degree of discrimination against the heavier  $^{13}\text{C}$  isotope relative to the lighter  $^{12}\text{C}$  isotope during photosynthesis. The ratios of  $^{13}\text{C}/^{12}\text{C}$  relative to a standard or  $\delta^{13}\text{C}$  ratios of plant material may be used as a determination of intrinsic water-use efficiency (Farquhar and Richards, 1984). More negative  $\delta^{13}\text{C}$  values denote higher efficiencies of water-use (Farquhar *et al.*, 1982).

In leaf-level studies instantaneous WUE may be determined through a combination of gas-exchange measurement techniques consisting of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  measurements using instruments such as porometers and Infra-red gas analysers (IRGAs). These describe a plant's demand for water relative to its photosynthetic production (Cernusak *et al.*, 2007).

At the single-tree or stand scale, water-use and growth measurements are usually conducted on a number of individual trees over a certain period, typically using heat dissipation / sap flow measurement techniques (Gyenge *et al.*, 2008), and are scaled up according to the planting density (Hatton and Wu, 1995; Wullschleger *et al.*, 1998).

At a canopy scale estimates of WUE are possible using micrometeorological measurements of carbon and water fluxes (Lamaud *et al.*, 1997; Law *et al.*, 2002). For example, Krishnan *et al.* (2006) describe WUE at this scale as a measure of the amount of Carbon taken up during photosynthesis ( $P$ ) relative to the water lost by the ecosystem ( $E$ ) ( $\text{WUE} = P/E$ ). Similarly, Lamaud *et al.*, (1997) define WUE as the ratio of photosynthesis over canopy transpiration, representing the loss in water associated with the gain of carbon. In the absence of specific measurements of photosynthesis and transpiration rates, they suggest the use of carbon uptake (net  $\text{CO}_2$  flux) and water loss (ET) by the vegetation as surrogates.

At wider regional scales, estimates of WUE are possible using remotely sensed data from which values of total evaporation (ET) and biomass production (e.g. Gross Primary Production) may be derived (Lu and Zhuang, 2010). At all scales the period of measurement is ideally a year or longer, to incorporate seasonal variation, however this may not always be practically

feasible, and instantaneous or short term estimates of WUE may be resorted to. The slope between changes in biomass accumulation (growth) and water-use represents a measure of WUE. It is thus a ratio that can be altered through changes in growth rate and/or changes in water use.

### **Choice of Units**

In describing bio-physical WUE, units applicable to the variables of interest, namely growth / yield and water-use, need to be employed. In terms of growth increment this could be described as total growth both above and below the ground. However, since it is difficult to estimate below-ground root growth accurately, and since it is mostly the above-ground biomass that provides the economic benefit, it is common when referring to trees for WUE to be defined as above-ground biomass increment per unit of water consumed (Dye, 2000). In a forestry environment, productivity is most often described in terms of utilizable stem volume increments and yields, however in published WUE studies, it is the convention to express growth in units of mass (dry matter) rather than volume (Jones, 2004). This is advantageous where wood density varies in the trees under study. In a forestry environment it is consequently pragmatic to define growth increment as the dry mass increment of utilizable stem, in which case WUE could be expressed as tons of yield per m<sup>3</sup> (or tons) of water utilized. However, as this usually equates to a very small number because of the small numerator and large denominator, grams may be used to describe mass of yield produced, while kilograms may be used to describe the water transpired or evaporated by the crop, at whatever scale is practical (single tree, m<sup>2</sup>, ha; km<sup>2</sup>).

Regarding the water use component of WUE, this is sometimes taken to be equal to rainfall (plus irrigation in some cases) received by a stand of trees (Dye, 2000). However, with the increasing application of heat dissipation and micro-meteorological techniques to measure vegetation water-use, actual plant water-use data are able to be used (Asbjornsen *et al.*, 2011). Distinction

needs to be made between whole plantation / forest total evaporation rates (i.e. water-use of the land-use as a whole, including trees, undergrowth and soil evaporation), as opposed to single-tree transpiration rates (i.e. water-use of the trees alone). This requires two different measurement techniques, the former measuring total evaporation (ET) above the forest canopy, and the latter measuring transpiration only (sap flow) through the stems of individual trees (Er-Raki *et al.*, 2009). The quantity of water in each case may be expressed in units of mass or volume, or as mm equivalent depth, where 1 mm of water is equivalent to 1 litre or kg of water per square meter of ground. The preferred definitions of WUE applicable to this project are the mass increment of utilizable stem (g) per unit of water transpired or evaporated by the tree (kg).

### **Determinants of Water-Use Efficiency**

The water-use efficiency of plants is influenced by numerous internal and external variables, but these may be grouped into three broad categories. Firstly there are the effects of the numerous physiological processes plants undertake (e.g. water and nutrient uptake and gas exchange), secondly the influence of the environmental conditions that they exist in (e.g. site and weather conditions) and thirdly the genetic and physical attributes that they exhibit (e.g. plant type, size and growth rates). The processes of growth and water-use that are influenced by these variables, and which ultimately determine WUE, occur across wide-ranging spatial and temporal scales, from instantaneous leaf-level changes in water vapour and carbon exchange by means of stomatal control, through to decadal patterns of growth and water-use within a forest. Understanding the linkages in space and time between all the processes and drivers associated with water-use, growth and the resultant WUE presents a formidable challenge. Physiological processes include photosynthesis; stomatal control and carbon allocation patterns. Environmental drivers include water, nutrient and light availability; climatic conditions; water, soil and air quality; fire and herbivory. Physical attributes include plant species/type; plant size; leaf area and canopy characteristics;

albedo; hydraulic architecture and rooting characteristics. Nearly all of the above may be influenced anthropogenically, through human-induced effects such as climate change, pollution, genetic modification, landscape alteration and management practices (e.g. site preparation, weed control, fertilisation, pruning, thinning and irrigation).

Leaf-level mechanisms of optimal stomatal control that balance water lost through transpiration against carbon taken up through assimilation, in response to environmental drivers, have been well studied (Cowan, 1977; Farquhar and Sharkey, 1982; Law *et al.*, 2002; Nogueira *et al.*, 2004). Determinations of gas exchange suggested that annual productivity increases with mean annual temperature and precipitation (Lieth, 1972; O'Neill and DeAngelis, 1981). More recently however, attention has shifted from gas exchange to how effectively plants intercept and utilise light (Law *et al.*, 2002; Hutrya *et al.*, 2007). In a review of the physiological processes associated with observed rates of growth and water use in Eucalyptus forests Whitehead and Beadle (2004) adopted a process-based approach which focussed on intercepted irradiance as the determinant of growth. This was linked to leaf area distribution and radiation transfer in canopies and physiological processes regulating photosynthesis, transpiration and carbon allocation. They concluded that high rates of productivity occurred at sites well supplied with water and nutrients, where there was high interception of solar radiation and high light-use efficiency. They classified the most productive species as those with high values for leaf area index, stomatal conductance and photosynthetic rate. In this way, WUE was deemed to be a function of Light-use Efficiency (LUE) (Whitehead and Beadle, 2004).

The effects of physiological mechanisms on WUE are also highly dependant upon environmental conditions prevailing at the time, particularly the availability of light, nutrients and water. Early work on single tree WUE by Webb *et al.* (1978) found that above-ground nett primary production (NPP) was independent of water-use in forest systems which were not water-stressed. For the forests they studied (hardwood forests dominated by *Quercus* and *Acer* spp.) NPP was found to be consistent while water-use

varied considerably, which resulted in a wide range of WUE. Measurements conducted at the canopy scale have detected increases in WUE with increasing drought stress and an associated reduction in surface conductance (Baldocchi, 1997; Williams *et al.*, 1998; Krishnan *et al.*, 2006). Krishnan *et al.* (2006) found that although WUE is reported to be sensitive to both vapour pressure deficit (*VPD*) and cloud cover (Williams *et al.*, 1998 and Rocha *et al.*, 2004), the existence of a relationship between growing season WUE and *VPD* was not apparent in their study - a result consistent with observations made in deciduous forests by Law *et al.* (2002). They note that increasing atmospheric CO<sub>2</sub> levels could also improve WUE through an increase in stomatal resistance and resultant reduction in water-use, but a very long data record is required to detect the presence of this effect. To this end tree-ring studies have been used to investigate long-term changes in growth rates relative to climatic conditions (February and Stock, 1999).

Whitehead and Beadle, (2004) suggest that the consequence of the marked sensitivity of decreasing stomatal conductance to increasing vapour pressure deficit, *VPD*, is that, in well-watered conditions, transpiration from Eucalyptus forests can be explained largely by leaf area index and *VPD*. They concluded that higher growth rates in trees were attributable to higher hydraulic conductance and an increase in the ratio of leaf area to sapwood cross-sectional area in larger trees. Evidence is emerging that physical attributes such as these and the associated growth rates of plants are linked to WUE. Using case studies from Eucalyptus plantations, Binkley *et al.*, (2004) and Stape *et al.*, (2004) have both demonstrated that more productive sites tend to have higher efficiencies of resource use than less productive sites, and silvicultural treatments such as thinning and pruning may increase both resource supply and efficiencies of resource use. This is consistent with results from other studies, which have also shown that WUE is often positively correlated with growth rate (Almeida *et al.*, 2007, Forrester *et al.*, 2010). Stape *et al.*, (2004) go so far as to suggest that high productivity Eucalyptus stands in Brazil could produce wood in shorter (6-yr) rotations on half the land area required for low productivity stands, using only half as much water. In South Africa, long-term tree breeding programmes for increased growth rates

(Verryn, 2000) together with improvements in silvicultural practices have vastly increased the productivity of commercial plantations of introduced tree species (Pallet and Sale, 2004). Based on the findings of Binkley *et al.*, (2004) and Stape *et al.*, (2004) this suggests that these interventions may already have inadvertently improved WUE in introduced tree plantations in South Africa.

### **The South African Experience**

Prior to this study, all South African tree-related WUE studies had been conducted on introduced plantation species, particularly eucalypts (Olbrich *et al.*, 1993; Olbrich and Olbrich, 1995; Le Roux *et al.*, 1996; Olbrich *et al.*, 1996; Dye *et al.*, 1997a; Dye *et al.*, 2001). The work developed out of the very successful tree improvement programme, in which genetic improvement of plant material focused primarily on increasing productivity within plantations, but also addressed aspects such as wood quality, tree form and resistance to pests and diseases (Verryn, 2000). With the success of this programme as a foundation, together with increasing attention on the water-use impacts associated with commercial plantations, it was hypothesized that improvements in the WUE of introduced tree species were possible through tree improvement programmes (Dye, 2000).

The exploratory studies cited above evaluated the range of WUE possible within existing genetic material. Results showed that differences in WUE (defined as water transpired per unit of utilizable stem produced) exist in a range of tree species and clones, suggesting that improvements in WUE could be made through tree improvement programmes. From these studies it was also concluded that WUE could vary over time and from site to site, especially in response to changes in Vapour Pressure Deficit (VPD), as well as to changes in carbon partitioning (above vs. below ground) brought about by soil water and nutrient availability. There was also evidence that WUE declined with increasing water deficits. Olbrich *et al.* (1993) found that variable growth rates were more influential than transpiration in determining WUE,

illustrating the importance of a minimum measurement period of 12 months to cover all seasonal growth cycles in the year. The potential to improve yields and optimise WUE within introduced and indigenous tree species in South Africa requires a thorough understanding of key physiological processes underlying how trees function (Dye, 2000).

### **Growth rates of indigenous tree species**

Indigenous tree trials established at Knysna in the late 19<sup>th</sup> century were remeasured some 55 years later together with other experimental efforts to ascertain growth rates of indigenous species (Stapleton, 1955). Using these data it was possible to estimate Mean Annual Increment (MAI) for these species by first calculating average stem volume for each trial, then multiplying by the stocking rate (stems per hectare), and dividing by the tree age at each site (Table 3.1). Stem volume was calculated by assuming that the stem is essentially cone shaped. The volumes of individual cones  $V$  (m<sup>3</sup>) were calculated using (Eq. 3.1):

$$V = (\pi r^2 h) / 3. \quad (3.1)$$

where  $r$  is radius of the base of the cone (m), and  $h$  is height of the cone (m). Tree heights are provided by Stapleton (1955) and the basal radius was assumed to be half the Diameter at Breast Height (DBH). Estimated MAI values range from 0.35 m<sup>3</sup>.ha<sup>-1</sup>.yr<sup>-1</sup> (*Apodytes dimidiata*) to 3.28 m<sup>3</sup>.ha<sup>-1</sup>.yr<sup>-1</sup> (*Podocarpus falcatus*), with an average over all plots of 1.17 m<sup>3</sup>.ha<sup>-1</sup>.yr<sup>-1</sup>.

**Table 3.1 Growth rates of selected indigenous tree species planted under controlled conditions in Knysna, southern Cape (after Stapleton, 1955), with an independent estimate of mean annual increment (MAI).**

Plot No.	Species	Stems / ha	Age	Mean Height (m)	Mean DBH (cm)	Estimated MAI (m <sup>3</sup> .ha <sup>-1</sup> .yr <sup>-1</sup> )
73	Podocarpus latifolius	2298	54	6.40	8.38	0.501
73	Podocarpus falcatus	2298	54	11.89	15.75	3.284
74	Podocarpus latifolius	3237	54	5.18	7.62	0.472
74	Podocarpus falcatus	3237	54	5.18	7.62	0.472
75	Curtisia dentata	988	57	14.02	14.73	1.381
75	Ocotea bullata	988	57	11.58	16.76	1.478
76	Apodytes dimidiata	1048	54	8.23	9.14	0.350
76	Curtisia dentata	1048	55	14.02	16.51	1.906
78	Podocarpus latifolius	1334	45	7.32	10.92	0.677
<b>Average</b>						<b>1.169</b>

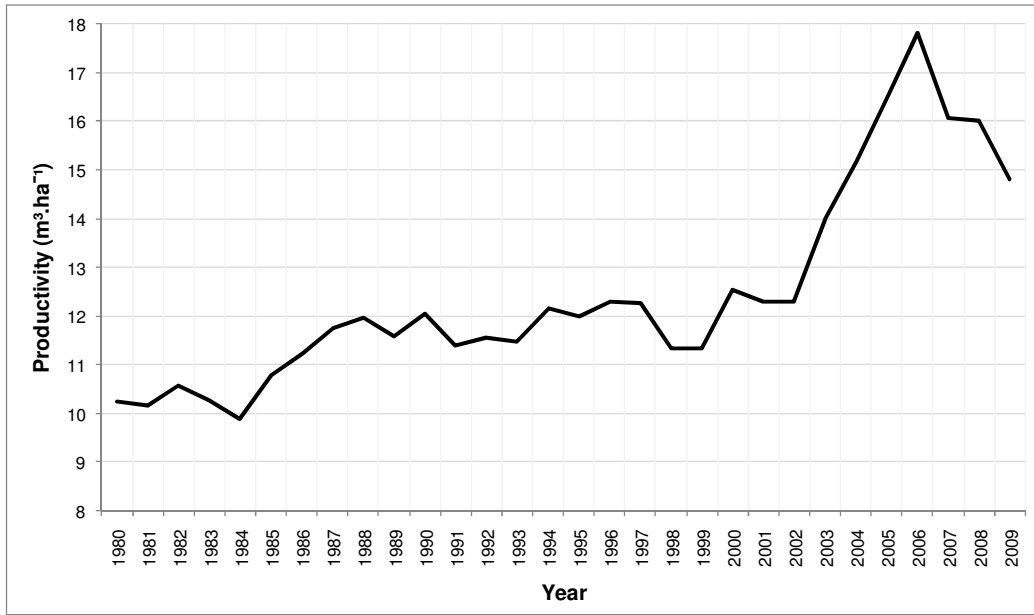
Van Daalen (1991) also reported measurements of growth, mortality and recruitment between 1972 and 1987 in plots within natural stands in the Diepwalle forest, Knysna. The species studied were selected to cover the assumed spectrum of successional tree species, namely light-demanding, pioneer species such as *Olinia ventosa* (L.) Cufod. (Hard Pear) and *Cunonia capensis* (L.) (Butterspoon tree), shade-tolerant, later successional species such as *Elaeodendron croceum* (Thunb.) DC. (Saffron) and *Podocarpus latifolius*, emergent species such as *Olea capensis* subsp. *macrocarpa* (L.) (Black Ironwood), subcanopy species such as *Gonioma kamassi* (E. Meyer) (Boxwood) and valuable timber species such as *Ocotea bullata* (Burch.) Baill. (Black Stinkwood). He found that gross volume growth rate between 1972 and 1987 was 2.065 m<sup>3</sup>/ha/yr, however the net increment (after accounting for recruitment and mortality) was only half that, i.e. 1.124 m<sup>3</sup>/ha/yr (Table 3.2), similar to the 1.169 m<sup>3</sup>/ha/yr estimated from data by Stapleton (1955) above.

**Table 3.2 Timber volume increments between 1972 and 1987 for selected indigenous tree species within the Diepwalle natural forest, Western Cape, South Africa (van Daalen, 1991)**

Species	True Growth (m <sup>3</sup> /ha/yr)	Net Growth (m <sup>3</sup> /ha/yr)
<i>Olinia ventosa</i>	0.017	0.014
<i>Ocotea bullata</i>	0.038	-0.011
<i>Olea capensis (macrocarpa)</i>	0.845	0.360
<i>Apodytes dimidiata</i>	0.117	0.049
<i>Curtisia dentata</i>	0.121	0.078
<i>Gonioma kamassi</i>	0.050	0.071
<i>Pterocelastrus tricuspidatus</i>	0.225	0.194
<i>Cassine papillosa</i>	0.033	0.030
<i>Podocarpus latifolius</i>	0.411	0.274
<b>All Species</b>	<b>2.065</b>	<b>1.124</b>

van Daalen (1991) concluded that the forest could be close to its maximum timber carrying capacity, and that a yield of approximately 2 m<sup>3</sup>/ha/yr appeared to be the universal timber production potential for unlogged, mixed, evergreen tropical and sub-tropical forests. However, he suggested that selective thinning treatments could increase this figure to 6 m<sup>3</sup>/ha/yr. Keet (1962) reported on experimental plantings of *Trema orientalis* (L.) Blume (Pigeonwood) instigated by Dr. Hans Merensky in 1945 at the Westfalia Estate near Tzaneen. Best reported Mean Annual Volume Increment (MAI) from this trial was 15m<sup>3</sup>/ha/yr (for 11-year old trees, exclusive of yield from the first thinning), which is encouraging for an indigenous tree species. However, on account of its lack of adaptability to poor sites and difficulties involved in its silvicultural treatment, afforestation on commercial lines was not deemed to be viable (Keet, 1962).

Yields for indigenous forests may be contrasted against productivity data for introduced commercial plantation tree species in South Africa (Fig. 3.2).



**Figure 3.1 Time series of average annual productivity (m<sup>3</sup>·ha<sup>-1</sup>) from plantations of introduced tree species in South Africa between 1980 and 2009 (FSA, 2010).**

By 2006 average productivity within plantations of introduced tree species in South Africa had increased by 70% since 1980, and peaked at nearly 18 m<sup>3</sup>/ha/yr. However, devastating fires and significant damage from pests and diseases subsequently reduced productivity, and plantations currently yield a Mean Annual volume Increment (MAI) of around 15 m<sup>3</sup>/ha/yr (FSA, 2010). Compared to these figures, growth rates of indigenous trees are slow and have consequently been considered not to be commercially viable. However some evidence suggests that growth performance may be improved through genetic selection, better site/species matching, tree breeding and improved management (Geldenhuys and von dem Bussche, 1997).

### **Water-use of indigenous tree species**

While a body of knowledge exists and is being developed on the growth rates of a range of indigenous tree species in South Africa, surprisingly little is known of their water-use characteristics. The scarcity of information on water-use rates of indigenous tree species and systems limits the extent to which WUE can be evaluated within the South African forest biome, and provides

strong motivation for studies incorporating measurements of both water-use and growth. Several case studies undertaken to address this knowledge gap are presented in the following chapters.

# Chapter 4

## **THE WATER-USE EFFICIENCY OF AN INDIGENOUS AFRO-TEMPERATE FOREST**

### **Introduction**

South Africa has never had abundant resources of indigenous timber-producing forests. The country is more often characterised by open savanna than closed-canopy forest. There are patches of indigenous evergreen forest, which are now carefully conserved and/or sustainably harvested after their protection was necessitated by heavy and uncontrolled exploitation between the 17<sup>th</sup> and early 20<sup>th</sup> centuries (Sim, 1907). A subsequent series of historical events (the 1914-1918 and 1939-1945 World Wars, the 1936 Great Depression and subsequent industrial development) resulted in the demand for timber exceeding supply, and forced South Africa to accelerate the expansion of its own introduced plantation forest industry (van der Zel, 1987). Plantation forests of fast-growing introduced genera such as *Eucalyptus* and *Pinus* spp. were subsequently established in the high-rainfall regions of the country (Olivier, 2009).

As the area under introduced plantations grew, so did concerns about the impacts of these plantations on water resources (Water Matters Committee, 1970). The higher water-use of introduced tree plantations relative to shorter, seasonally dormant vegetation (e.g. grasslands and Fynbos) that they usually replace has been clearly demonstrated by paired catchment afforestation experiments and process studies (Bosch and Hewlett, 1982; van Wyk, 1987; Bosch and von Gadow, 1990; Scott and Lesch, 1997; Scott and Smith, 1997; Zhang, 1999; Dye and Bosch, 2000; le Maitre *et al.*, 2000; Scott *et al.*, 2000; Dye and Jarman, 2004; Brown *et al.*, 2005; Calder, 2005; Farley *et al.*, 2005; Dye and Versfeld, 2007; Scott and Prinsloo, 2008; Silveira and Alonso, 2009).

In comparison, very little work has been undertaken on the water-use of indigenous forests and woodlands. There is a general perception that indigenous trees use water more conservatively than plantations of introduced trees, resulting in a comparatively lower impact on catchment water yields; however this evidence is largely anecdotal (Wilson, 1982; Cooper, 1985; Cawe and McKenzie, 1989). Some transpiration measurements were performed by Henrici (1945) on selected indigenous and introduced trees in the Cathkin Peak area of the KwaZulu-Natal Drakensberg. Water loss per sample leaf mass was determined using Huber's (1927) rapid weighing technique for detached leaves, where individual leaves are excised from the tree and repeatedly weighed to determine rates of water loss. Henrici (1945) concluded that the rate of transpiration as such, calculated on a fresh mass basis, did not support the idea that introduced trees use more water than indigenous varieties. However, several other factors required consideration such as the size of the trees, espacement, requirements for light and position in the forest (margin or interior). Consequently, the results have to be treated with caution, since this technique by itself cannot provide a basis for species comparisons of transpiration rates. Firstly, the total leaf area of the tree must be known to extrapolate the shoot readings to the entire tree canopy. Secondly, it is very difficult to sample sufficient shoots to adequately describe the microclimate variation (and therefore leaf stomatal conductance variation) within the tree canopy.

Paired catchment experiments on the Westfalia Estate near Tzaneen in the Limpopo Province of South Africa provided some data to support the hypothesis that indigenous forests may be relatively conservative users of water (Bosch and Smith, 1989). A small catchment under indigenous scrub forest dominated by *Nuxia floribunda* Benth., *Rapanea melanophloeos* (L.) Mez., *Syzgium cordatum* Hochst. and *Trichelia dregeana* Sonder. (Bosch and Versfeld, 1984) was treated by removing the natural vegetation from 83% of the catchment, prior to the establishment of a plantation of introduced *Eucalyptus grandis* (Hill) ex Maiden (Rose gum). While the catchment was still bare there was a small increase in measured streamflow of about 20 mm per year. However, subsequent establishment of the *Eucalyptus* plantation within

the catchment caused a decrease in streamflow of 200 mm per year within three years after planting. In another study, Licata *et al.* (2008) found that an introduced pine species (*Pinus ponderosa* Doug. ex. Laws) growing in Patagonia, Argentina used significantly more water than native cypress trees (*Austrocedrus chilensis* (D. Don) Pic. Serm. et Bizzarri).

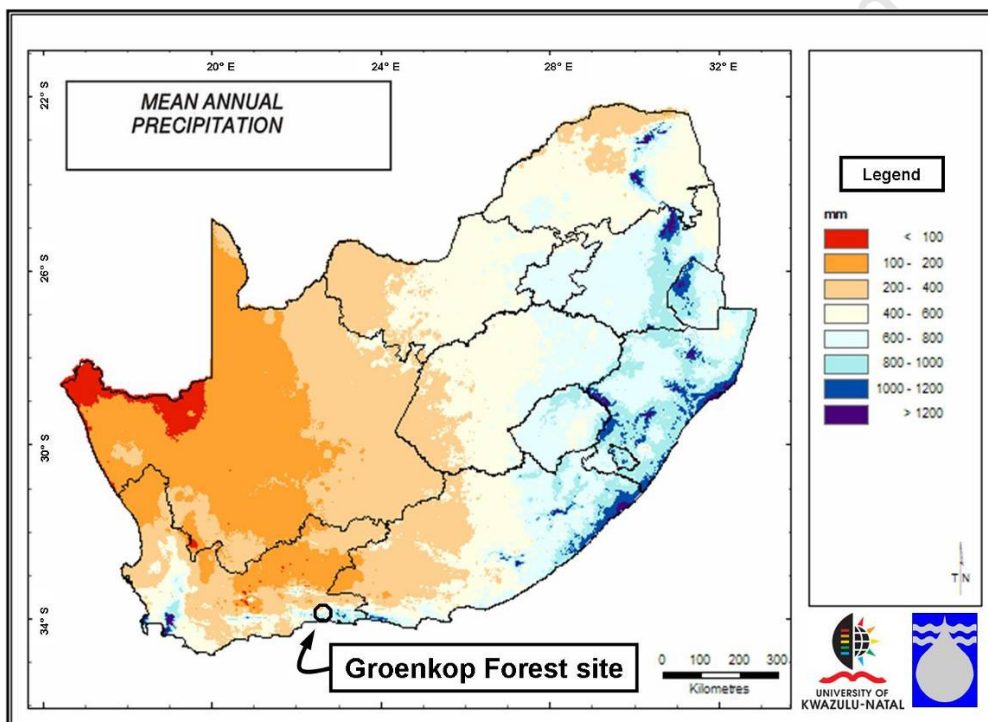
There is little conclusive evidence from South Africa to substantiate the claim that indigenous tree species and indigenous forests utilise less water than plantations of introduced tree species. In this chapter I address this question through a study incorporating short-term seasonal measurements of the water-use of a typical mixed species, mixed age indigenous evergreen forest in the southern Cape of South Africa. I then verify a model against the total evaporation measured from the forest canopy, and subsequently apply it over a 26-year period to simulate longer-term trends in forest water-use. Using a combination of long-term data on tree growth collected by Geldenhuys (2005) and water-use results derived from the model, I then develop an estimate of the water-use efficiency (WUE) of the forest, and compare this result against historical data for introduced tree species in South Africa, measured under a wide range of site and climatic conditions.

## **Methods**

### **Study area**

Of the forest types occurring in South Africa, the southern Cape Afro-temperate forests (von Maltitz *et al.*, 2003) are the most extensive, and are estimated to be approximately 60 560 ha in extent (Geldenhuys, 1991). These are tall (~24 m average canopy height), multilayered forests dominated by *Podocarpus falcatus* (Thunb.) R.Br. ex Mirb. (Outeniqua Yellowwood), *Podocarpus latifolius* (Thunb.) R.Br. ex Mirb. (Real Yellowwood), *Ocotea bullata* (Burch.) Baill. (Black Stinkwood), *Olea capensis* subsp. *macrocarpa* (L.) (Black Ironwood), *Pterocelastrus tricuspidatus* (Lam.) Sond. (Candlewood) and *Platylophus trifolius* (L.f.) D.Don (White Alder) (Mucina

and Geldenhuys, 2006). The Groenkop forest, situated outside the town of George (Fig. 4.1), forms part of this forest type. The area receives rainfall throughout the year, with a peak between September and April. Mean annual precipitation is 920 mm (Lynch and Schulze, 2006). Mean daily maximum temperatures range from a mild 23.9 °C in February to 18.6 °C in July, while mean daily minimum temperatures range from 15.6 °C in February down to 7.7 °C in July (Schulze and Maharaj, 2007). Strong, dry and warm winds (locally referred to as “Berg winds”) occasionally blow from the north during winter and may fan intense and destructive fires (Geldenhuys, 1994a).



**Figure 4.1** Location of the mixed species, mixed aged indigenous forest study site relative to the distribution of Mean Annual Precipitation across South Africa (from Lynch and Schulze, 2006).

The Groenkop forest lies between 190 and 300 m above sea level, at the western end of the belt of mixed evergreen forest on the coastal platform of the southern Cape (Geldenhuys 1991). The study area comprised an area of forest to the north-east of the Saasveld campus of the Nelson Mandela Metropolitan University (S 33° 56.5', E 22° 33'). The soils of the forest are generally acid, leached, low in nutrients and shallow, with poor buffering

capacity and internal drainage (Geldenhuys, 1993). These soils are derived from the underlying Table Mountain Group sandstones and shales of the Cape Super group (Mucina and Rutherford, 2006). The topsoil is 350 to 450 mm deep, overlying poorly-drained clayey subsoil comprising Kroonstad<sup>‡</sup> and Westleigh soil forms on level terrain, and better drained sub-soils of the Clovelly soil form on the slopes (Geldenhuys, 1998).

A total of 87 tree species have been recorded in the forest, and species composition is relatively stable with *Podocarpus latifolius*, *Curtisia dentata* and *Burchellia bubalina* (L.f) Sims (Wild Pomegranate), being the most common (Geldenhuys, 1993). Mean basal area of the forest is approximately 44.6 m<sup>2</sup>.ha<sup>-1</sup> (Geldenhuys, 1998). Leaf Area Index (LAI) of the forest, measured using an LAI-2000 Canopy Analyser (LI-COR Inc, Lincoln, Nebraska, USA), was consistently high, peaking (~6-7) in the wetter summer months (February), and lowest (~4-5) during the drier spring months (September). The over-storey canopy does however contain gaps that allow sunlight to penetrate to well-developed under-storey vegetation, which may be dominated by a dense layer of *Rumohra adiantiformis* (G. Forester) Ching (Seven-weeks Fern).

### **Total evaporation measurements**

Total evaporation (ET) from the forest was measured using the Scintillometry technique on three separate occasions (20-23 February, 4-10 June and 28 September to 4 October) of 2004 resulting in 18 complete days of ET observations. The shortened energy balance approach (Eq. 4.1), as described by Thom (1975) was applied in order to determine ET. This approach requires measures of three separate energy fluxes (net radiation, soil heat flux and sensible heat flux) in order to determine total evaporation (ET) by subtraction (Eq. 4.2). The shortened energy balance equation neglects advection (horizontal transport of energy and water vapour into or out of the area under

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<sup>‡</sup> According to Fey (2010) USDA classification of these South African soil forms is Eluvic (Kroonstad), Soft (Westleigh) and Xanthic (Clovelly).

consideration), as well as physically and bio-chemically (photosynthetically) stored heat flux densities in the canopy as they are considered negligible (Thom, 1975). Total evaporation (ET) is a function of the residual term  $LE$  (the energy used to evaporate water), which closes the shortened energy balance equation:

$$R_n - G - LE - H = 0 \quad (4.1)$$

where:  $R_n$  is the net (incoming minus reflected) irradiance (both short- and long-wave components) above the canopy surface,  $G$  is the energy required to heat soil – referred to as net soil heat flux,  $LE$  is the energy required to evaporate water – referred to as latent energy and is the product of the specific latent heat of vaporisation,  $L$  (in  $\text{J kg}^{-1}$ ) and the water vapour flux density  $E$  ( $\text{kg s}^{-1} \text{m}^{-2}$ ), while  $H$  is the energy required to heat the atmosphere above the soil – referred to as the sensible heat flux. The equation may be re-arranged in the following way to solve for  $LE$ :

$$LE = R_n - G - H \quad (4.2)$$

Knowing the latent energy of vaporisation  $L$  to be equivalent to  $2.453 \text{ MJ kg}^{-1}$ , total evaporation ( $E$ ) may consequently be derived from measurements of  $R_n$ ,  $G$  and  $H$ .

In this study net radiation ( $R_n$ ) measurements were obtained using an NR-Lite net radiometer (Kipp & Zonen, Delft, The Netherlands) mounted on a 30m tall Clark WT8 pneumatic telescopic mast erected in a clearing in the forest. When the mast was fully extended the net radiometer projected above the forest canopy. Soil heat flux ( $G$ ) was simultaneously measured in the middle of the forest, using HFT-S soil heat flux plates (REBS, Seattle, Washington, USA) buried 80 mm below the soil surface, TCAV-L soil temperature averaging probes (Campbell Scientific Inc., Logan, Utah, USA) set at 20 mm and 60 mm below the soil surface, and CS616 time domain reflectometer water content sensors (Campbell Scientific Inc., Logan, Utah, USA) in the upper 100 mm of the soil. These sensors were connected to a CR23X

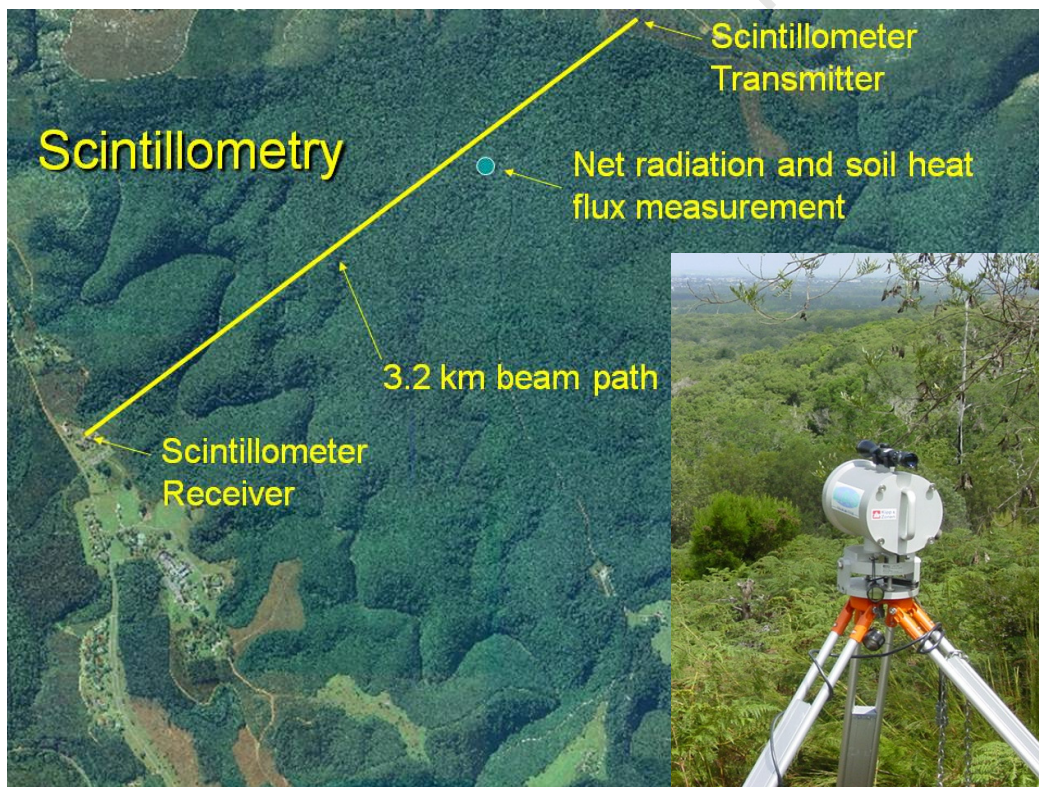
(Campbell Scientific, Logan, Utah) datalogger recoding every ten seconds and averaging every ten minutes. A Campbell Scientific automatic weather station (AWS) measuring rainfall, solar radiation, temperature, humidity, wind speed and wind direction on an hourly basis was installed in an open area of short fynbos vegetation well removed from the edge of the forest. Scintillometry, together with supporting data on wind speed, solar radiation, relative humidity, air temperature and air pressure, was used to determine estimates of mean surface sensible heat flux ( $H$ ) above the forest canopy. The latent heat fraction ( $LE$ ) that equates to total evaporation rate (water-use) was derived as the residual in the energy balance calculation as described above.

Scintillometry (Hill, 1992) is a fairly new technique, having been applied mainly within the last decade or so to estimate sensible heat fluxes, and resultant water-use rates, above vegetated surfaces (see for example Meijninger *et al.*, 2002; Savage, 2009). Various types of scintillometer are available, including a surface layer scintillometer (SLS), a large aperture scintillometer (LAS), a boundary-layer scintillometer or an extra-large aperture scintillometer (XLAS), with respective operating distances, strengths and weaknesses (Savage *et al.*, 2004; Jarman *et al.*, 2008). A Large Aperture Scintillometer (LAS) system (Kipp and Zonen, Delft, Netherlands) was selected for this study as it provides spatially-averaged total evaporation estimates over distances of up to 5 km, which suited the forest size. The system consists of a transmitter that beams a light source towards an accurately aligned receiver.

The technique conducts measurements of the path-averaged structure parameter of the refractive index of air  $C_n^2$  (Thiermann and Grassl, 1992), and is based on the propagation statistics of electromagnetic radiation through the turbulent atmosphere. When an electromagnetic beam of radiation propagates through the atmosphere, it is distorted by a number of processes that remove energy from the beam, leading to signal attenuation. The most dominant of these are small fluctuations in the refractive index of air ( $n$ ) caused by small temperature and humidity fluctuations. These refractive index fluctuations lead to signal intensity fluctuations that are known as scintillations (Hill *et al.*,

1980). Using Monin-Obukov Similarity Theory (MOST) together with supporting data on wind speed, air temperature and air pressure, scintillometer measurements allow the calculation of mean surface sensible heat flux (H) along the light path.

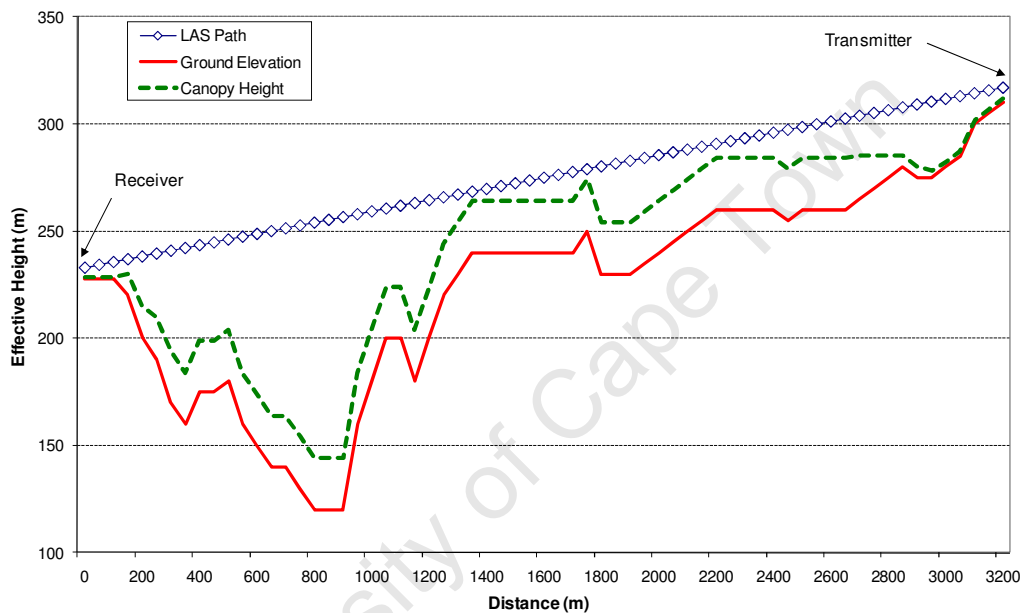
For the purposes of this study the LAS transmitter was positioned on a south-facing slope just above the forest edge, while the receiver was mounted 3.2km away on the opposite slope (Fig. 4.2). A rifle telescope mounted on both the transmitter and receiver allowed for the accurate initial alignment of the beam. With the help of a two-way radio system, team members at the transmitter and receiver stations communicated to further align the instruments to achieve maximum signal strength at the receiver.



**Figure 4.2 Aerial photograph of the 3.2 km scintillometry beam path from transmitter (inset) to receiver. The position of the mast, where net radiation and soil heat flux measurements were taken, is also indicated.**

The final calculation of sensible heat also requires a careful analysis of the height of the transmitted beam in relation to the vegetation canopy height

along the entire path length. Measurement of the topographic profile between the scintillometer transmitter and receiver were obtained using orthographic photographs of the locality with superimposed 10 m contours to estimate the ground elevation along the path at 50 m intervals. Canopy heights at the start and end of the transect as well as in the middle of the beam path were measured, and these canopy heights were added to the ground elevation data to obtain the resultant profile of beam height to canopy height (Fig 4.3).



**Figure 4.3 Profile of elevation and canopy height variation relative to the 3.2 km scintillometry beam path from transmitter to receiver.**

### **Total evaporation modelling**

A model derived from a combination of the Penman-Monteith (Monteith, 1965) and Granier (Granier *et al.*, 2000) models was applied to determine canopy total evaporation. The model was initially tested against the data collected during the three field campaigns, and thereafter applied over a longer time period (1972 to 1997). The original Penman-Monteith equation (Monteith, 1965) may be expressed as (Eq. 4.3):

$$\lambda_v E = \frac{\text{Energy flux rate}}{\Delta + \gamma (1 + g_a/g_s)} \quad (4.3)$$

where:

- $\lambda_v$  = Latent heat of vaporisation. Energy required per unit mass of water vaporised (= 2.453 MJ kg<sup>-1</sup>)
- $E$  = Total evaporation rate (g s<sup>-1</sup> m<sup>-2</sup>)
- $\Delta$  = slope of the vapour pressure curve [kPa °C<sup>-1</sup>]
- $R_n$  = Net irradiance (W m<sup>-2</sup>), the external source of energy flux
- $c_p$  = Specific heat capacity of air (= 1010 J kg<sup>-1</sup> K<sup>-1</sup>)
- $\rho_a$  = dry air density (= 1.204 kg m<sup>-3</sup>)
- $\delta q$  = vapour pressure deficit, or specific humidity (Pa)
- $g_a$  = Aerodynamic (or boundary layer) conductance (m s<sup>-1</sup>) \*
- $g_s$  = Stomatal (or canopy  $g_c$ ) conductance (m s<sup>-1</sup>)
- $\gamma$  = psychrometric constant [kPa °C<sup>-1</sup>].

Daily weather data are required by the model in order to calculate certain parameters (e.g. net radiation from solar radiation data, or vapour pressure deficit from temperature and relative humidity data). 26 years of daily temperature, relative humidity and solar radiation data for this location were obtained from the South African Atlas of Climatology and Agrohydrology database (Schulze and Chapman, 2007; Schulze and Maharaj, 2007; Schulze, Chapman and Maharaj, 2007). The altitude and latitude of the site, together with the Day-of-year (or Julian Day) were used to convert daily solar radiation data to net radiation values, and to derive the psychrometric constant and slope of the saturated VPD curve, according to the FAO56 methods described by Allen *et al.* (1998). The latent heat of vaporisation, specific heat capacity of air and dry air density were kept constant, although they are known to show some dependency upon changes in air temperature and / or pressure. Based on the work of Jarvis (1981) who showed that the

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\* Note: Often resistances are used rather than conductances, and they are inversely related to each other, e.g. for aerodynamic conductance  $g_a = r_a^{-1}$ , and for canopy conductance  $g_c = r_c^{-1}$

aerodynamic conductance ( $g_a$ ) of tall forests with high surface roughness and resultant turbulent mixing of air is typically in the range of 0.1 to 0.3  $\text{m s}^{-1}$ , a value of 0.2  $\text{m s}^{-1}$  was used in the model.

In order to determine  $g_c$  the canopy conductance sub-model approach used by Granier *et al.* (2000) was applied utilising equations proposed by Jarvis (1976) and Stewart (1988) (Eq. 4.4); and by Lohammer *et al.* (1980) (Eq. 4.5):

$$g_c = g_{cmax} * f1(R,VPD) * f2(LAI) * f3(I_s) * f4(T_i) \quad (4.4)$$

$$g_c = g_{cmax} * R/(R+R_0) * (1/(1+b*VPD)) \quad (4.5)$$

The Jarvis and Stewart equation is a multiplicative function relating variation in  $g_c$  to environmental factors, while the Lohammer-type equation is used to account for the relationship between canopy conductance, solar radiation and VPD, where stomatal conductance increases with increasing solar radiation, but decreases with increasing VPD. By combining the above equations (Eq. 4.6),  $g_c$  was determined in the following way:

$$g_c = g_{cmax} * f1(R/(R+R_0) * (1/(1+b*VPD))) * f2(LAI) * f3(I_s) * f4(T_i) \quad (4.6)$$

where:

$g_{cmax}$  = a hypothetical maximum canopy conductance

R = solar radiation ( $\text{W m}^{-2}$ )

VPD = air vapour pressure deficit (kPa)

LAI = leaf area index

$I_s$  = water stress index

$T_i$  = air temperature index

f1-4 = multiplier functions<sup>§</sup>

$R_0$  = a parameter altering the magnitude and shape of the curve (100)

b = a coefficient (2.0615)

VPD = air vapour pressure deficit (kPa)

<sup>§</sup> Functions 1-4 all range from 0-1, and are multiplicative in their effects on reducing the maximum  $g_c$ . No interactions are assumed.

The value of  $g_{cmax}$  is hypothetical and can be used to calibrate the model. Working in tropical rain forests, Granier *et al.* (2000) suggest a value of  $4.047m.s^{-1}$  for  $g_{cmax}$  in forests with high (>5.7) Leaf Area Index. However, for this study a value of 9 for  $g_{cmax}$  was found to yield the best results when calibrated against the 18 observed daily ET totals. The water stress and air temperature indices were not included as these were assumed not to be limiting at this site. The forest also maintains a high and relatively constant leaf area index, although a degree of variation was incorporated into the function to reflect seasonal changes. For this study a value of 0.16 for the f4 LAI multiplier was used, as suggested by Granier *et al.* (2000). Inputs of solar radiation and VPD were determined from the weather data, and combined with the other parameters to derive daily estimates of canopy conductance.

The observed ET data from the Scintillometer were used to calibrate the  $g_c$  values within the Penman-Monteith equation. Calibrated daily  $g_c$  values calculated using equation 4.6 were then utilised in the Penman-Monteith equation to model daily ET over a twenty-six year period (1972 to 1997). This time period was selected as it coincided with the period over which growth measurements for the Groenkop forest had been calculated.

### **Tree growth measurements and water-use efficiency**

Geldenhuys (2005) estimated increments in utilisable stem volume within the forest between 1972 and 1997. Average growth rates in utilisable stem volume were calculated for individual species and for the forest over time. The information was also used to develop relationships between stem diameter and utilisable timber volume (van Laar & Geldenhuys 1975). For this study, the average annual increment in utilisable timber volume for the forest was divided by the average annual ET modelled between 1972 and 1997 to derive an estimate of water-use efficiency for this particular forest.

## **Results**

### **Weather**

A wide range of evaporative conditions were encountered during the measurement periods, ranging from sunny and warm days with dry berg winds, to wet, overcast and cool days (Table 4.1). The sample days are therefore considered to be a reasonable reflection of the range of meteorological conditions experienced by the forest.

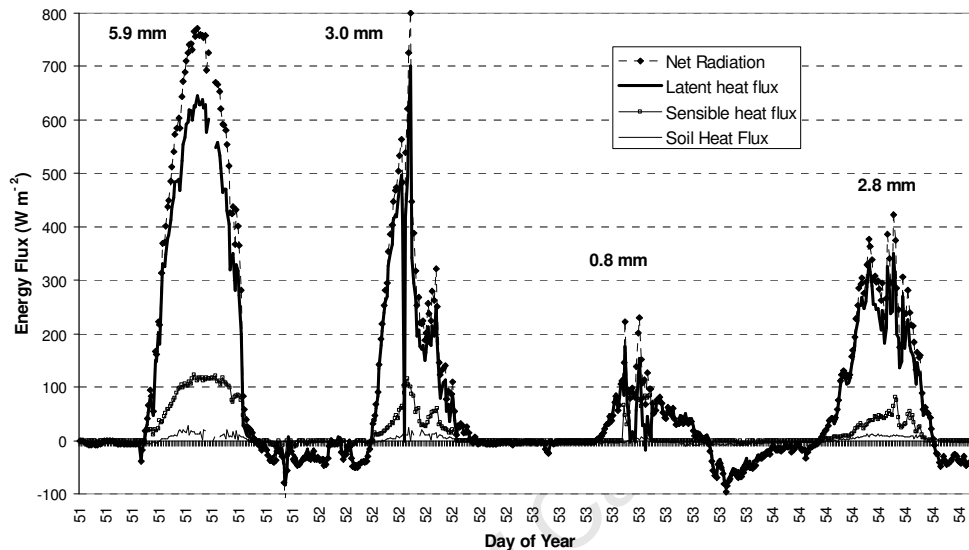
**Table 4.1 Daily meteorological variables measured at the forest site during the three field campaigns.**

<b>Date</b>	<b>Day Of Year</b>	<b>Temp Max (°C)</b>	<b>Temp Min (°C)</b>	<b>RH Max (%)</b>	<b>RH Min (%)</b>	<b>Wind (m s<sup>-1</sup>)</b>	<b>Solar Rad. (MJ m<sup>-2</sup> day<sup>-1</sup>)</b>	<b>VPD (kPa)</b>	<b>Rain (mm)</b>
20-Feb-04	51	26.5	17.1	98.6	66.0	0.96	23.2	0.756	1.4
21-Feb-04	52	27.11	19.23	98.6	62.1	1.06	11.1	0.680	3.8
22-Feb-04	53	21.14	16.7	98.8	87.7	0.89	3.67	0.304	10.4
23-Feb-04	54	22.95	17.04	98.3	76.7	0.79	9.72	0.429	0
04-Jun-04	156	25.47	14.71	89.2	19.7	2.74	11.04	0.792	0
05-Jun-04	157	24.28	13.27	96.3	23.4	1.64	8.5	0.755	4.8
06-Jun-04	158	14.42	10.52	97.4	66.8	1.22	3.34	0.186	2.8
07-Jun-04	159	11.65	9.89	98.5	60.1	1.50	1.73	0.076	25.7
08-Jun-04	160	15.84	8.71	93.7	46.3	2.71	10.41	0.337	0
09-Jun-04	161	16.84	9.98	82.3	44.7	2.40	11.58	0.346	0
10-Jun-04	162	22.28	13.54	67.8	23.2	1.62	10.23	0.569	0
29-Sep-04	272	20.25	11.48	93.2	42.5	1.28	23.94	0.510	0
30-Sep-04	273	23.13	11.48	88.2	44.7	0.83	24.4	0.738	0
01-Oct-04	274	24.02	15.12	92.5	35.8	0.74	20.26	0.634	0
02-Oct-04	275	20.87	15.28	96.8	77.8	0.76	8.02	0.365	0
03-Oct-04	276	30.01	14.61	90.6	32.2	0.90	23.34	1.291	0
04-Oct-04	277	20.83	13.58	91.8	40.8	0.84	7.13	0.453	0
05-Oct-04	278	22.16	13.16	96.0	56.9	0.90	13.22	0.578	0

## Observed total evaporation

*Summer (20-23 February 2004)*

The scintillometer data collected in February 2004 were typical of warm and wet conditions (Fig. 4.4).



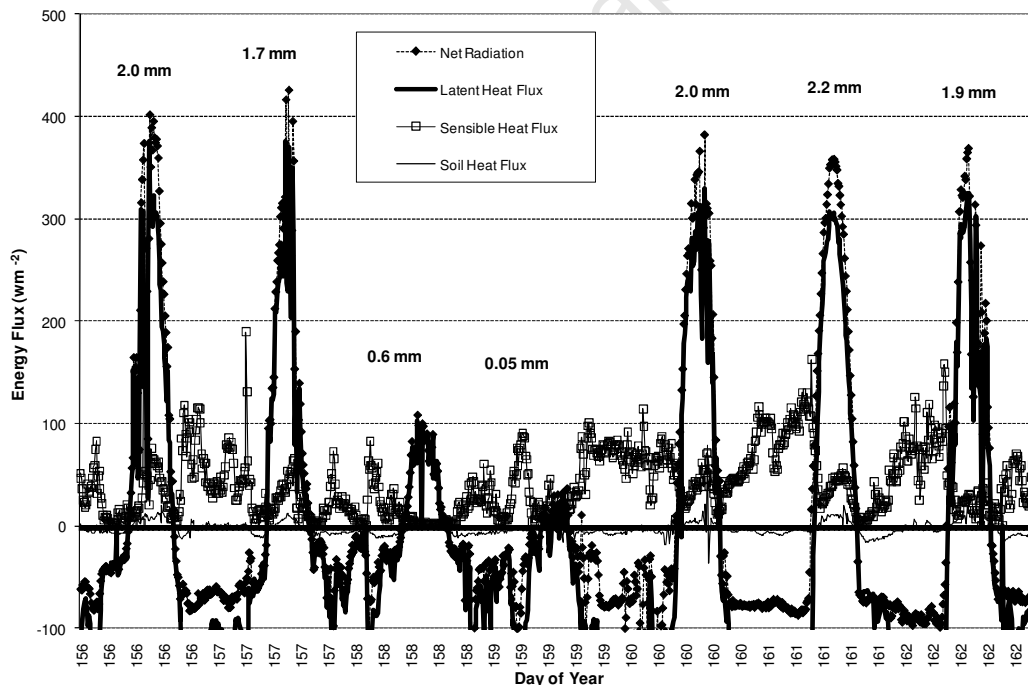
**Figure 4.4 Diurnal variations in 10-minute measurements of energy balance components above the Groenkop forest for the period 20-23 February 2004. Calculated daily total evaporation values are annotated on the figure.**

Although 1.4 mm of rainfall was recorded (during the night), cloudless warm weather (max temp. 26.5 °C, solar radiation 23.2 MJ m<sup>-2</sup> day<sup>-1</sup>) during Day of Year (DOY) 51 (Table 4.1) resulted in high and characteristically bell-shaped net radiation values, with corresponding high latent heat flux (equivalent to 5.9 mm total evaporation). A partly cloudy day (max temp. 27.1 °C, solar radiation 11.1 MJ m<sup>-2</sup> day<sup>-1</sup>) on DOY 52 showed similar peak values of net radiation, but with considerably more variation due to periods of cloud cover, which increased with the approach of a frontal weather system during the afternoon of that day. The net result on the calculation of latent heat flux and the corresponding estimate of total evaporation was a reduction to approximately half of the previous cloudless day (3 mm). Continual overcast conditions (max temp. 21.14 °C, solar radiation 3.67 MJ m<sup>-2</sup> day<sup>-1</sup>) and a precipitation event totalling 10.4 mm on the following day (DOY 53) resulted in very low net

radiation values for that day, and daily total evaporation amounted to just 0.8 mm. Brighter and slightly warmer weather (max temp. 22.95 °C, solar radiation 9.72 MJ m<sup>-2</sup> day<sup>-1</sup>) on the following day (DOY 54) increased total evaporation from the forest to 2.8 mm. Soil heat flux values remained consistently low throughout, as would be expected under these conditions of high leaf area and shading of the forest floor.

*Winter (4-10 June 2004)*

A day of warm and windy weather (max temp. 25.47 °C, average wind speed 2.74 m s<sup>-1</sup>), characteristic of winter ‘berg wind’ conditions, was experienced (DOY 156) before two frontal systems passed over the southern Cape (DOY 158 and 159) during this measurement period (Fig. 4.5). The following three days (DOY 160 to 162) were dry, fine and mild (Table 4.1).

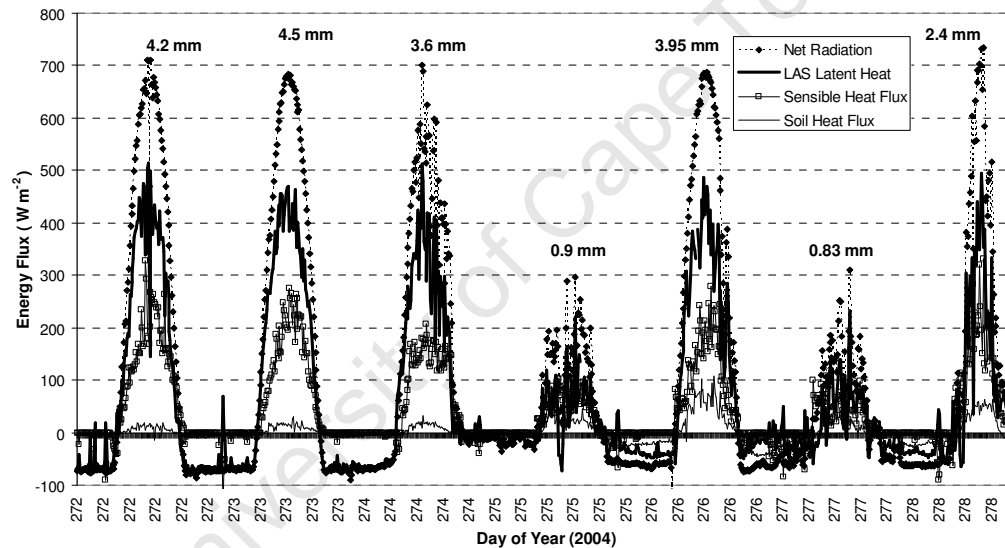


**Figure 4.5 Diurnal variations in 10-minute measurements of energy balance components above the Groenkop forest for the period 4-10 June 2004. The decline in net radiation on DOY 158 & 159 is associated with a passing frontal system. Calculated daily total evaporation values are annotated on the figure.**

Clear days resulted in smooth diurnal curves of net radiation data, sometimes punctuated by occasional passing clouds. Peak net radiation values were approximately half of those measured during the summer season due to lower solar elevations, while shorter day lengths further reduced total energy inputs. The result was significantly lower total evaporation estimates for the forest during this season, averaging approximately 2 mm per day.

*Spring (28 September – 4 October 2004)*

The spring weather experienced during this period was consistently warm and dry, with partly cloudy conditions on DOY 275 and 277 (Fig. 4.6).

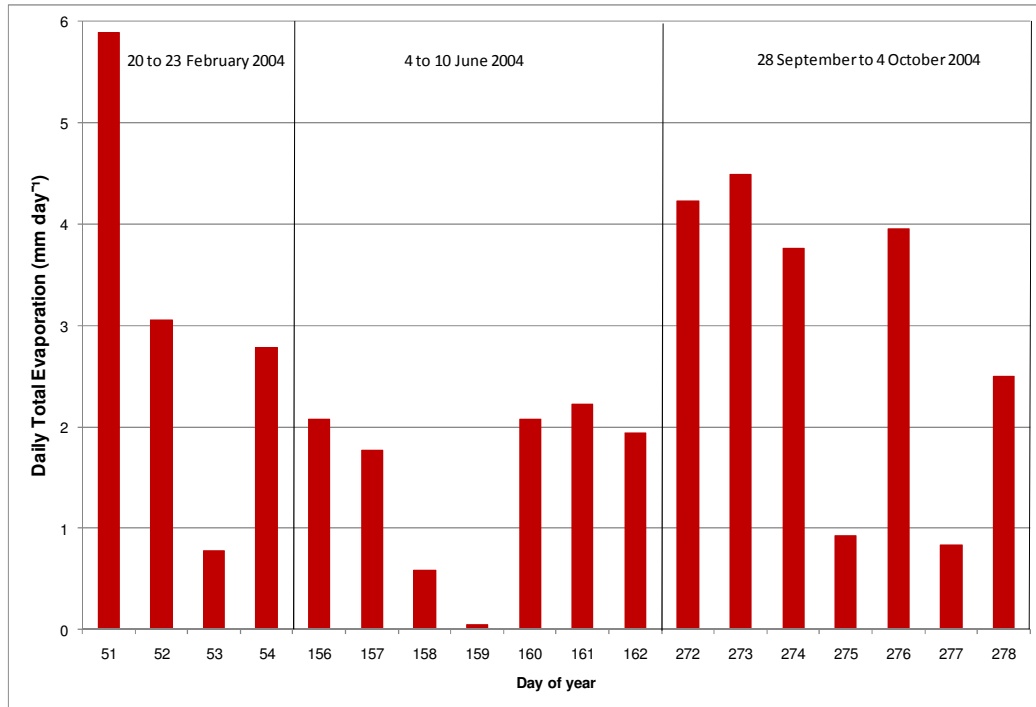


**Figure 4.6** Diurnal variations in 10-minute measurements of energy balance components above the Groenkop forest for the period 28 September to 4 October 2004. Calculated daily total evaporation values are annotated on the figure.

Net radiation peaks were only slightly lower than the summer values ( $700 \text{ W m}^{-2}$ ). However, significantly higher sensible heat flux values, compared to the summer and winter data, resulted in corresponding lower latent heat flux estimates and resultant daily total evaporation rates of approximately 4 mm. The cloudy and humid conditions experienced on two of the days, resulted in daily total evaporation being reduced to less than 1 mm. Soil heat flux values were higher than those measured in previous seasons, which may have

resulted from some thinning in the leaf area of the forest canopy, characteristic of this time of year, which would have allowed more light to penetrate to the forest floor.

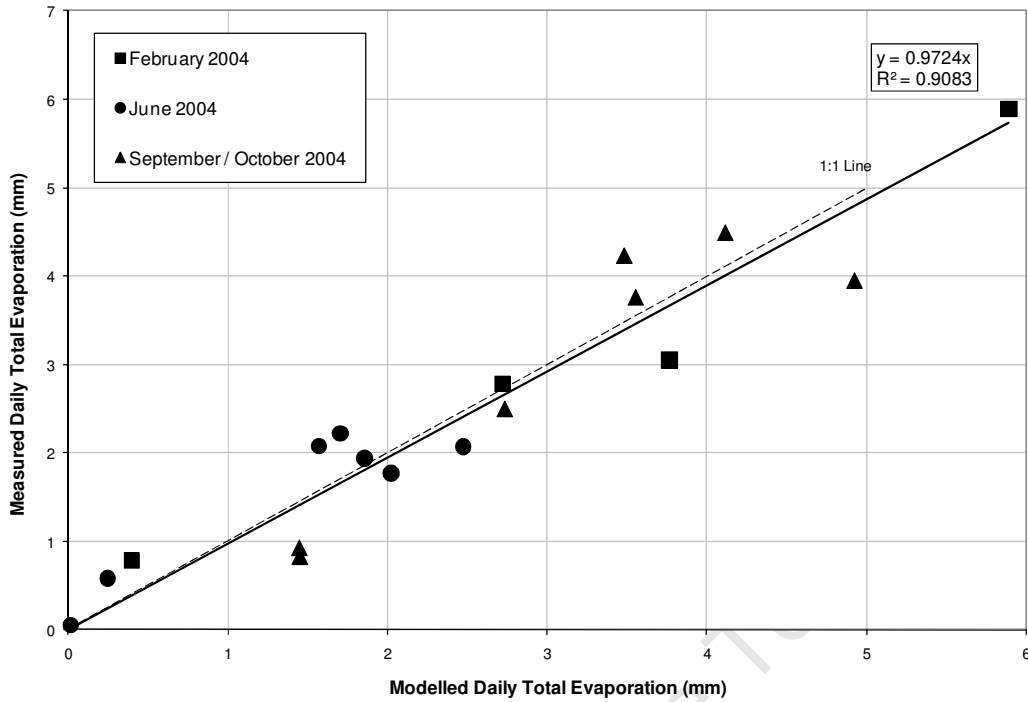
For the purposes of verifying the modelling exercise the most important data to be collected were the daily total evaporation values for the forest, measured using the scintillometer (Fig. 4.7).



**Figure 4.7** Daily total evaporation measured over the forest using scintillometry during three separate field campaigns in 2004.

**Modelled total evaporation**

The modelled results correlate well (slope = 0.9724 and  $R^2 = 0.9083$ ) with observed values (Fig. 4.8).



**Figure 4.8 Relationship between measured and modelled daily ET during 18 sample days in February 2004 (■), June 2004 (●) and September / October 2004 (▲).**

This result lends confidence to the application of the model over a longer time-period. Modelled annual total evaporation, rainfall and the difference between the two, for a 26-year period are given in Table 4.2.

**Table 4.2 A comparison of modelled annual total evaporation and annual rainfall for the Groenkop forest, from 1972 to 1997.**

<b>Year</b>	<b>ET (mm)</b>	<b>Rainfall (mm)</b>	<b>Difference (mm)</b>
1972	1037.2	779.4	257.8
1973	986.3	643.2	343.1
1974	913.4	713.3	200.1
1975	910.0	897.0	13.0
1976	934.1	915.0	19.1
1977	895.7	1014.3	-118.6
1978	957.7	726.2	231.5
1979	941.5	969.3	-27.8
1980	980.3	791.8	188.5
1981	869.2	1656.1	-786.9
1982	960.1	960.0	0.1
1983	964.6	892.4	72.2
1984	996.0	711.0	285.0
1985	944.4	834.3	110.1
1986	969.3	717.6	251.7
1987	958.1	739.3	218.8
1988	931.2	695.3	235.9
1989	925.3	751.4	173.9
1990	940.3	753.1	187.2
1991	905.5	726.9	178.6
1992	918.2	845.3	72.9
1993	957.9	994.2	-36.3
1994	943.8	940.7	3.1
1995	844.4	973.9	-129.5
1996	926.5	953.8	-27.3
1997	949.2	794.1	155.1
<b>Average</b>	<b>940.8</b>	<b>861.1</b>	<b>79.7</b>

Year-on-year total evaporation modelled for the forest remained consistent, never varying by more than 100 mm from the mean, while rainfall varied by up to 800 mm. This suggests that the forest is not water-limited in terms of total evaporation, and that maximum total evaporation rates plateau at approximately 1000 mm irrespective of available water. Mean annual rainfall for the site (860 mm) is, on average, less than the average annual total

evaporation simulated for the forest (958 mm). This may be attributed to a number of factors. Firstly, higher rainfall falling over the forest (MAP 920 mm according to Lynch and Schulze, (2006)) compared to the weather station from which meteorological data were sourced for the model (MAP of 860 mm) would result in underestimates of rainfall. The calculated long-term difference between mean annual rainfall and mean annual ET may therefore only be in the region of 20 mm. Furthermore, there is evidence of the importance of fog drip in augmenting the store of soil water in these forests. Phillips (1931) provided the first observations of a significant contribution by fog / low-cloud to the water balance of these forests in particular, and recent work by Bruijnzeel *et al.* (2011) has highlighted the importance of fog interception in forests across tropical and sub-tropical Africa.

Moist evergreen indigenous forests mostly occur in riparian situations and other localities where a degree of soil water augmentation is likely, and where the forest is thus unlikely to be water-limited. At this site it is probable that soil moisture levels are being augmented by lateral flow from upslope sources. Soils in this area are characterised by a 35-45 cm sandy-loam topsoil layer which overlies a dense clay layer, and lateral movement of water occurs above this layer (Geldenhuys and Theron, 1994). Evidence of this is suggested by observations within a soil pit at the experimental site within the forest which was found to continually be full of water as a result of the pronounced clay layer (Coert Geldenhuys, pers. comm.). Additional water is likely to enter the forest from the higher mountain slopes, where lateral flow of water would be promoted by higher rainfall, cooler temperatures, higher air humidity, more frequent low-cloud events, steeper slopes, and a covering of fire prone sclerophyllous vegetation (Fynbos) (Scott, 1993).

### **Tree growth and water-use efficiency**

Results from the tree growth analysis of Geldenhuys (2005) showed that in 1972, when the original measurements were carried out, the initial growing stock of utilisable timber volume was 220.93 m<sup>3</sup> ha<sup>-1</sup>. A mean annual

increment (MAI) of  $4.22 \text{ m}^3 \text{ ha}^{-1}$  ( $\pm 1.025 \text{ m}^3 \text{ ha}^{-1}$ ) was calculated based on tree growth increments measured in subsequent surveys conducted in 1972 (van Laar & Lewark 1973), 1987 (van Daalen, 1991) and 1997 (Geldenhuys, 1998).

Average annual total evaporation of the forest simulated over 26 years (957.9 mm) was directly converted to volumetric ( $9579 \text{ m}^3 \text{ ha}^{-1}$ ) and mass-based ( $9579000 \text{ kg ha}^{-1}$ ) units of water-use. This was compared against the average annual stem volume increment ( $4.22 \text{ m}^3 \text{ ha}^{-1}$ ) which was also converted to appropriate mass-based units ( $2532000 \text{ g ha}^{-1}$ ) using a wood density of  $0.6 \text{ g cm}^{-3}$ , being an average of values provided by Goldsmith and Carter (1981) for the most common species in the forest. The resultant water-use efficiency (g stem wood produced per kg water used) of 0.264 was calculated for the forest (Table 4.3).

**Table 4.3** Calculation of water-use efficiency for the Groenkop forest, based on modelled total evaporation and tree growth estimates between 1972 and 1997.

Mean Annual Precipitation (mm)	Mean Annual Water-use ( $\text{kg} \cdot \text{ha}^{-1}$ )	Mean Annual Increment ( $\text{m}^3 \cdot \text{ha}^{-1}$ )	Estimated Ave. Wood Density ( $\text{g} \cdot \text{cm}^{-3}$ )	Stem Mass Increment ( $\text{g} \cdot \text{ha}^{-1}$ )	Water-use Efficiency (g stem wood)/(kg water)
860	9579000	4.22	0.6	2532000	0.264

## Discussion

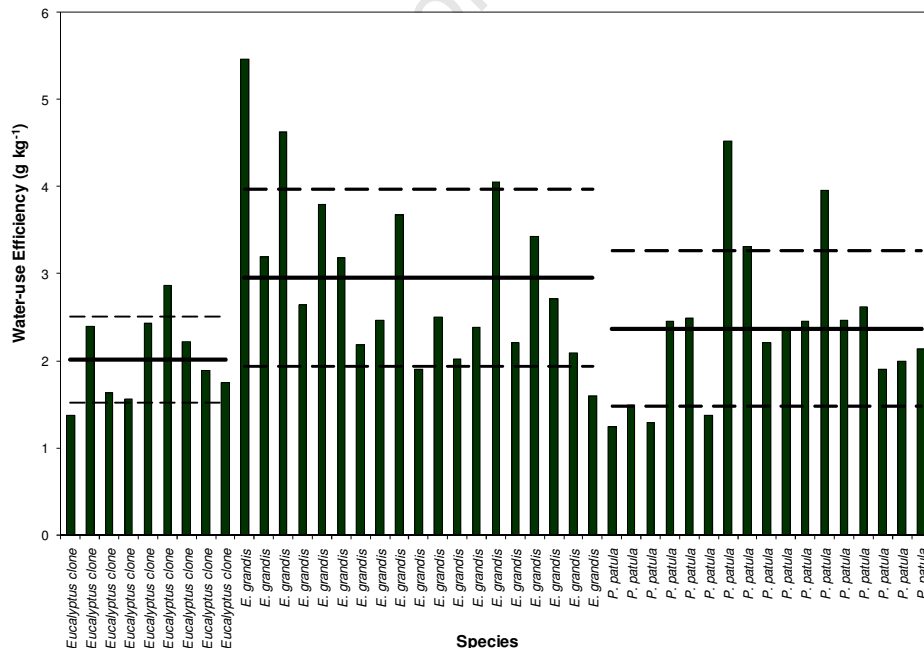
The objective of this study was to determine the water-use efficiency of an indigenous evergreen Afro-temperate forest, through a combination of water-use and growth measurements. The method chosen to quantify the water-use of the forest, namely scintillometry, proved to be a suitable technique. It was a relatively simple and robust instrument to use, which provided good, spatially integrated, estimates of sensible heat. The simultaneous use of an automatic weather station and sensors attached to a telescopic mast extended to above the forest canopy effectively provided data on the remaining components of the energy balance, from which total evaporation (water-use) could be

derived. The use of short-term seasonal measurements resulted in a relatively small, although highly varied and representative, data set of water-use measurements. Reproduction of the observed data through the application of a Penman-Monteith-Granier combination model was satisfactory. However, the fact that  $g_{\max}$  needed to be raised in the model by more than twice that recommended in the literature to match the observed (scintillometer) values of ET suggests that sensible heat flux (H) may have been underestimated by the scintillometry technique, resulting in an overestimate of latent heat flux (LE) and resultant ET.

In terms of overall water-use, the indigenous forest in this study was not water-constrained and was found to use equivalent amounts of water relative to what was available from rainfall. Total evaporation from established introduced tree plantations (e.g. *Pinus radiata*) is commonly in the range of 1100–1200 mm, and is usually limited by the rainfall available on the site (Dye and Versfeld, 2007). However, evidence is emerging that introduced plantations are able to “mine” deeper groundwater reserves and use water in excess of amounts supplied by rainfall (Jarmain and Everson, 2002; Clulow *et al.*, 2010). Clulow *et al.* (2010) measured annual total evaporation values of 1156 mm and 1171 mm in a plantation of *Acacia mearnsii* (de Wild) (Black Wattle) trees growing in the KwaZulu-Natal province of South Africa, where the long-term MAP is just 853 mm. Measurements were conducted continually over two hydrological years (October 2006 to September 2008) using scintillometry, and the corresponding annual rainfall totals were 689 mm and 819 mm respectively. Their data showed that over the study period as a whole total evaporation from the plantation exceeded rainfall by 46 %. Similarly, Jarmain and Everson (2002) measured total evaporation from a young *Eucalyptus dunii* (Maiden) (Dunn’s White Gum) / *Eucalyptus macarthurii* (Deane & Maiden) (Camden Woollybutt) plantation at the same site, using the Bowen Ratio energy balance technique, and found that total evaporation from the introduced plantation averaged 1470 mm per annum over 4 years, exceeding rainfall over that period by 75%. In comparison, the estimated annual water-use of the Southern Cape Afro-temperate indigenous forest in this study averaged 941 mm, at a site where the MAP is in the region of 860-

920 mm. This indigenous forest is also comprised primarily of mature trees at an ecological equilibrium, supporting a high standing biomass. Consequently, direct comparisons cannot be made with Pine and Eucalyptus plantations normally harvested before maturity when growth rates and water-use are at a maximum.

The period selected for modelling ET in this forest coincided with historical forest growth measurements over a period of 26 years that provided an estimate of mean annual timber increment. The resultant estimate of WUE is the first recorded for an indigenous forest system in South Africa, and permits some comparison against water-use and WUE estimates for introduced tree plantations. Results from several South African studies using sap flow and growth measurements on *Eucalyptus* and *Pinus* spp. have been reported by Olbrich *et al.*, (1996) and Dye *et al.*, (2001). In these investigations, 12-month transpiration totals (measured using the heat pulse velocity technique) were compared to annual stem growth increments (g stem mass per kg water transpired) to derive estimates of WUE (Fig. 4.9).



**Figure 4.9** Water-use efficiency (g utilizable stem mass per kg of water transpired) recorded in a variety of *E. grandis* and *P. patula* plantations in South Africa (after Olbrich *et al.*, 1996 and Dye *et al.*, 2001). The mean (—) and standard deviation (---) for species are indicated.

The calculated water-use efficiency value 0.264 (g stem wood produced per kg water used) for the indigenous forest in this study is very low compared to the results of Olbrich *et al.*, (1996) and Dye *et al.*, (2001) for introduced plantations. However, the WUE estimates for the introduced trees are based on transpiration alone and not total evaporation including water-use by the under-storey and soil evaporation. The total evaporation measurements for the indigenous forest recorded water used, not only by the trees, but also by the shrub under-storey and herb layer, which is extremely well developed in these forests (Geldenhuys, 1993). This could comprise a significant proportion of total ET and would also reduce WUE. Commenting on growth of the southern Cape indigenous forests, Phillips (1931) noted that exploited and tended trees yielded the greatest girth increments due to the extra light penetration afforded by regular harvesting, as well as the eradication of competing undergrowth. This has not been the management strategy for the Groenkop forest and, according to Geldenhuys (1998) timber was last harvested from the site in 1971. Consequently, the age of many of the trees, as well as competition for resources by the undergrowth would significantly reduce over-storey productivity and contribute to lowering the WUE of the forest.

In conclusion, the hypothesis that the water-use of the indigenous forest in this study is less than that of an introduced plantation growing under similar conditions can not be conclusively supported by the results. Growth rates of utilisable timber are significantly less than for introduced plantations, and consequently the resultant WUE of the indigenous forest is also lower. Nevertheless, the potential economic and environmental benefits of the goods and services from indigenous forests such as these warrant further attention, together with comparative WUE studies of other indigenous tree species and systems.

# Chapter 5

## THE WATER-USE OF A SEMI-ARID SAVANNA WOODLAND

### Introduction

In arid and semi-arid regions water availability and use play a critical role in determining dominance by one or other vegetation type, particularly in combination with other influences such as fire or herbivory (Scholes and Archer, 1997; van der Waal *et al.*, 2009). While many studies have been conducted on the effect of resource availability (e.g. water) on tree / grass interactions and competition in savanna landscapes (Walker and Noy-Meier, 1982; Scholes and Archer, 1997; Sankaran *et al.*, 2005; Sankaran *et al.*, 2008), few studies exist on the impacts of landuse change on water resources in this biome. For example, the question of whether we understand the causes of bush encroachment or not may be considered from the alternative perspective of 'do we understand the implications of bush encroachment, particularly on water resources?' So, while there is evidence that changes in vegetation may result *from* differences in water availability, it is also probable that changes in vegetation may result *in* changes in water availability. Knowledge of the water-use of savanna tree systems can assist in interpreting such questions, and improving our understanding of the delicate balance between grasses and trees in these landscapes.

Catchments receiving lower rainfall are often large by virtue of their relatively flat topography, and widespread land use changes such as bush encroachment, invasion by alien plants, or over-utilisation of woody species and bush clearing have the potential to significantly impact water resources (Wilcox, 2002; Huxman *et al.*, 2005). It is therefore important that information on water-use and plant growth within savanna woodlands be available to help clarify the consequences of land use change on ecosystem processes (Scott *et al.*, 2006). Information of this kind is useful for promoting the interdisciplinary approach of ecohydrology (linking hydrology and ecology),

and to assist in the development of strategic plans to meet long term demands for water and ensure the sustainability of existing land and water resources (Newman *et al.*, 2006). This is particularly important considering that water-limited environments occupy about half of the earth's land surface and contain some of the fastest growing population centres in the world (Newman *et al.*, 2006), and a real need for research in this field has been identified (Malmer and Nyberg, 2008).

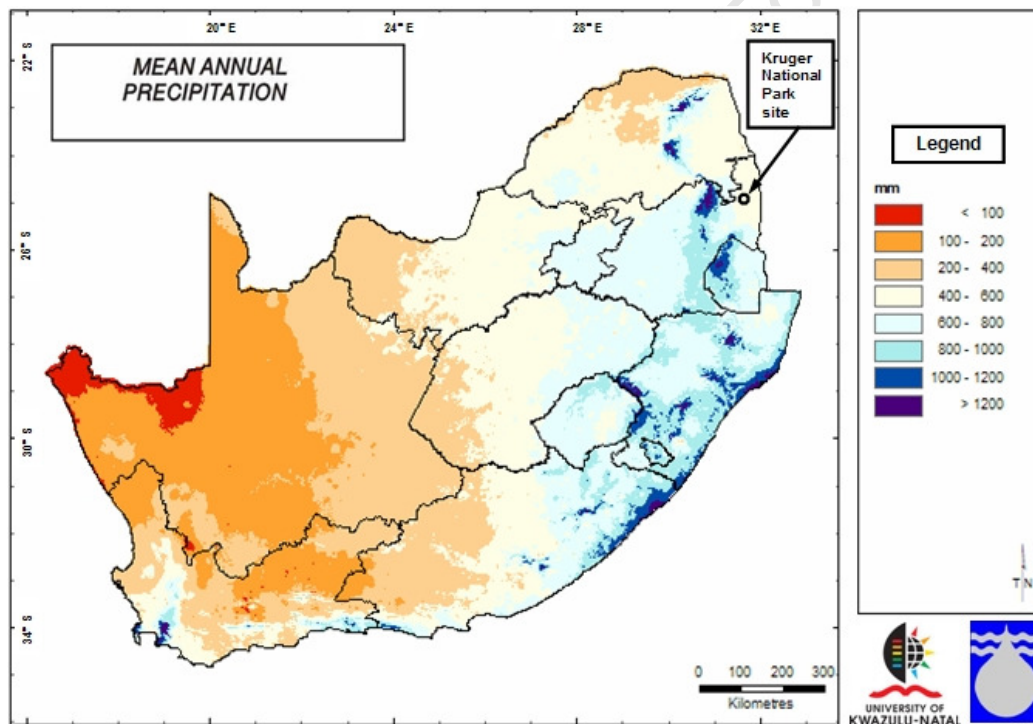
In this chapter I determine the water-use of savanna vegetation in the Mpumalanga Province of South Africa. Short-term seasonal measurements of total evaporation (ET) above the savanna are compared against two years of continuous sap flow (transpiration) measurements from a selection of individual trees within the woodland. These results are used to gauge the relative proportions of tree transpiration to total evaporation, and to derive estimates of the water-use of the tree component of the savanna vegetation, as well as of the savanna vegetation as a whole (trees, shrubs and grass). The results are discussed in the light of their potential to influence land and water resources management decisions, particularly given evidence that woody biomass is on the increase in this biome (Wigley *et al.*, 2010).

## **Methods**

### **Study area**

The study area is located south of Skukuza in the Kruger National Park (25° 01.184' S, 31° 29.813' E) at an altitude of 370 metres above sea level (Fig. 5.1). A full description of the environment and vegetation of this area is provided by Scholes *et al.* (2001) and Archibald *et al.* (2008). It is semi-arid sub-tropical, with a Mean Annual Precipitation (MAP) of 550 ±160 mm. The area experiences hot wet summers (Mean Maximum Temperature Dec to Jan = 32°C) and warm dry winters (Mean Maximum Temperature Jun to Aug = 26°C MAT). Soils are shallow (<0.8m deep) and sandy, represented by

Clovelly<sup>\*\*</sup>, Hutton and Glenrosa forms, overlying granite and gneiss (Venter *et al.*, 2003). The vegetation is classified by Mucina and Rutherford (2006) as Granite Lowveld, representing approximately 7% of the total savannah biome. The dominant tree species are *Combretum apiculatum* (Sond.) subsp. *apiculatum* (Red Bush Willow), *Acacia nigrescens* (Oliv.) (Knob Thorn) and *Sclerocarya birrea* (A.Rich.) Hochst. subsp. *caffra* (Sond.) Kokwaro (Marula). Grasses common in the area are characterised by un-palatable species such as *Pogonarthia squarosa* (Roem. & Schult.) Pilg. (Herringbone Grass) and *Perotis patens* (Gand.) (Cat's Tail Grass), and palatable species such as *Panicum maximum* (Jacq.) (Guinea Grass) and *Urochloa mossambicensis* (Hack.) Dandy (White Buffalo Grass) (Scholes *et al.*, 2001).

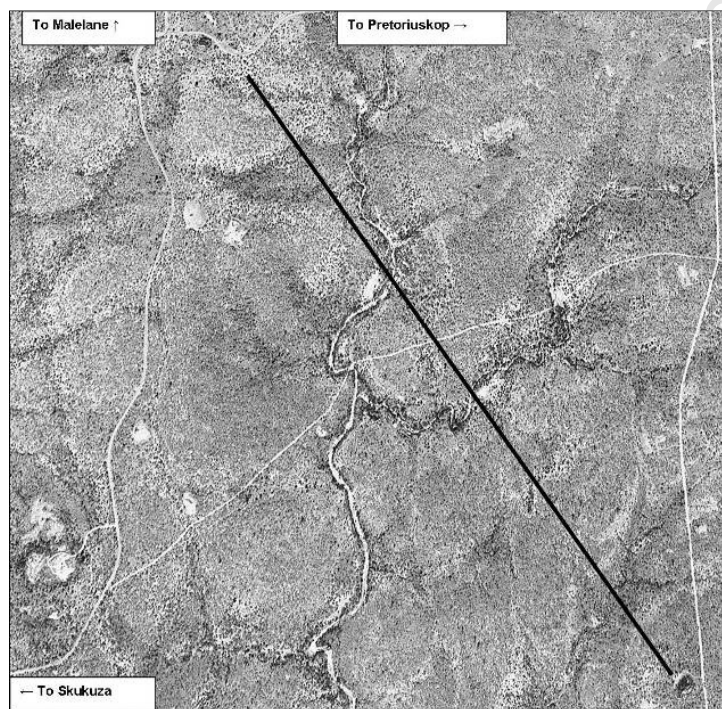


**Figure 5.1** Location of the woodland savanna study site in relation to the distribution of Mean Annual Precipitation in South Africa (from Lynch and Schulze, 2006).

Within this study area two separate sites were selected for monitoring transpiration (sap flow system), and total evaporation (scintillometry system)

<sup>\*\*</sup> According to Fey (2010) USDA classification of these South African soil forms is Xanthic (Clovelly), Rhodic (Hutton) and Glossic (Glenrosa).

respectively. The sap flow site was situated amongst a predominance of *Combretum apiculatum* trees within a few hundred metres of the SAFARI-2000 flux tower experiment (Scholes *et al.*, 2001). The scintillometry site was established approximately 5 kms to the south-east thereof. The Large Aperture Scintillometer (LAS) needs to be positioned above the vegetation so that there is an un-obstructed line-of-sight path between the transmitter and the receiver. Consequently the LAS transmitter was installed near the summit of a small hill, while the receiver was deployed near the summit of another hill 4.25km away (Fig. 5.2).



**Figure 5.2 Aerial photograph of the Scintillometry sites showing the 4.25km beam path between hills. The receiver site is at the lower right side of the image.**

### **Sap flow measurements**

Continuous hourly measurements of sap velocities using the Heat Pulse Velocity (HPV) technique were conducted at the site to determine transpiration of the tree component of the landscape. Three tree species typical of these woodlands were selected for HPV measurements (Table 5.1),

namely a cluster of three *Combretum apiculatum* trees, an isolated *Sclerocarya birrea* and an isolated *Lannea schweinfurthii* (Engl.) Engl. (False Marula). Individual trees deemed visually to be representative of average mature specimens for the respective species were selected for measurement.

**Table 5.1** Some physical attributes of the sample trees selected for sap flow measurements. Leaf area index (LAI) measurements recorded with a Li-COR LI-2000 Plant Canopy Analyser show seasonal changes.

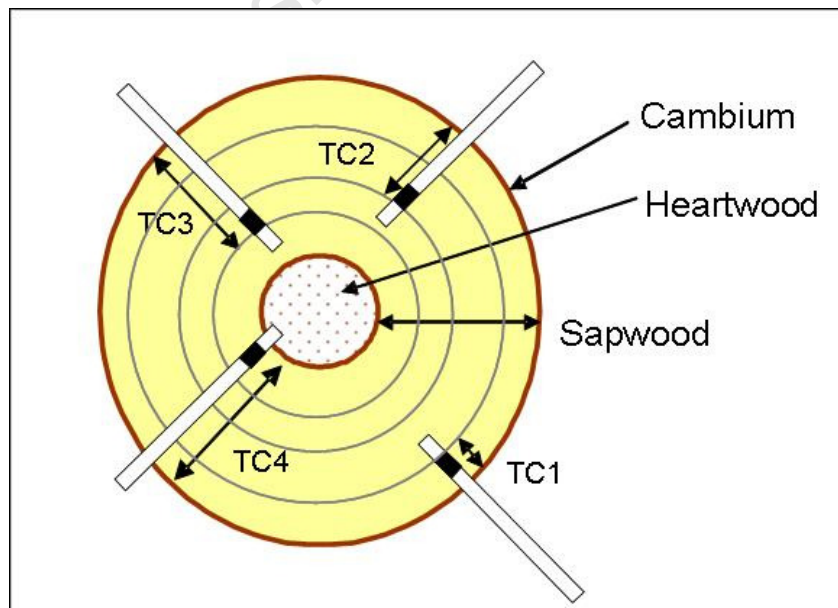
Species	Diameter at breast height (DBH) (cm)	Tree height (m)	Crown diameter (m)	LAI Sep 2004	LAI Feb 2005	LAI May 2005
<i>S. birrea</i>	38.99	11.23	12.03	0.31	1.45	0.53
<i>L. schweinfurthii</i>	19.74	7.97	6.81	0.50	1.15	0.84
<i>C. apiculatum</i>	17.51	9.44	4.77	0.56	1.83	0.80
<i>C. apiculatum</i>	10.95	6.64	2.74	0.71	0.97	0.80
<i>C. apiculatum</i>	18.88	7.92	5.57	0.58	1.35	0.80

The HPV technique is essentially a tracer method which measures the rate of flux with which heat pulses applied to the conductive xylem portion of woody stems are transmitted vertically by the flow of sap through the stem. It is recognized internationally as an accepted method for the measurement of sap flow in woody plants and has been extensively applied in South Africa (Dye and Olbrich, 1993; Dye, 1996; Dye, Soko and Poulter, 1996; Dye, Poulter *et al.*, 1996; Gush, 2008; Gush and Dye, 2009). The heat ratio method (HRM) of the HPV technique was selected for this study because of its ability to accurately measure low rates of sap flow (Burgess *et al.*, 2001). The HRM requires a line-heater, which is typically 60 mm long and made from 1.8 mm outside-diameter stainless steel tubing enclosing a constantan filament, to be inserted into the xylem of the selected tree at the vertical midpoint (commonly 5 mm) between two temperature sensors (thermocouples), which are 2 mm in diameter (Fig. 5.3). The velocity of the heat pulse (Eq. 5.1) is determined by recording the ratio of the increase in temperature measured by the upstream and downstream thermocouples, following the release of a pulse of heat by the line heater (Marshall, 1958), calculated as:

$$V_h = \frac{k}{x} \ln(v_1 / v_2) 3600 \quad (5.1)$$

where  $V_h$  is the heat pulse velocity ( $\text{cm hr}^{-1}$ ),  $k$  is thermal diffusivity of the wood,  $x$  is distance (cm) between the heater and either temperature probe, and  $v_1$  and  $v_2$  are increases in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively. Thermal diffusivity ( $k$ ) is assigned a nominal value of  $2.5 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$  (Marshall 1958).

The thermocouple (TC) probes were inserted to different depths below the cambium (Table 5.2) to sample different regions of the sapwood, as sap flow velocities are known to vary laterally across the xylem. The TC insertion depths were determined by sampling the sapwood depth using an increment borer (Haglöf, Sweden), and then arranging the measurement positions accordingly (Fig. 5.3), although there was a limitation to the depth that TC probes could be inserted due to their design. Sap velocities in the sapwood beyond the deepest probe depth were assumed to equal velocities measured at the deepest probe. All drilling was performed with a battery-operated drill using a drill guide strapped to the tree, to ensure that the holes were as close to parallel as possible.



**Figure 5.3** Illustration of a typical sampling pattern of thermocouples within the sapwood, and the associated sapwood areas represented by each thermocouple.

A CR10X data-logger connected to two AM16/32 multiplexers (Campbell Scientific, Logan, UT) was programmed to initiate the hourly heat pulses and record data from the respective thermocouple pairs. Cellular phone modems allowed remote access to the logger. Additional automatic weather station sensors connected to the HPV system were used to monitor hourly changes in air temperature and relative humidity in the vicinity of the trees. Net radiation data were sourced from the nearby flux tower. Instrumentation at the study site was protected from disturbance by large herbivores such as elephants and rhino by means of pole and weld-mesh structures angled against the trees. Shade-cloth was used on the structures to provide some shading to the instrumentation, and all data-loggers, multiplexers, modems, relay-control modules and batteries were housed in sealed boxes.

Heat pulse systems were installed during August 2004, and maintained continuously over the 2004/5 and 2005/6 summer growing seasons. To extend the life-span of some of the HPV heater units the HPV probes were temporarily removed from the *S. birrea* and *L. schweinfurthii* sample trees at the end of the growing season (May 2005). Very little relevant data was lost since sap flow rates had dropped to undetectable levels, and most of the leaves were either already shed or in a state of senescence. The probes in the *C. appiculatum* trees were left in place, since functional leaves were still in evidence. Low sap flow rates in these trees were monitored throughout the dry season. Probes were reinstalled in the *S. birrea* and *L. schweinfurthii* trees in newly drilled holes at the start of the following wet season (September 2005) and monitoring continued through to May 2006 when all the HPV systems were dismantled.

Heat pulse velocity data require correction for sapwood wounding caused by the drilling procedure, using wound correction coefficients described by Swanson and Whitfield (1981). The corrected heat pulse velocities are then converted to sap flux densities by accounting for wood density and sapwood moisture content (Marshall, 1958). Finally, the sap flux densities are converted to whole-tree total sap flow by calculating the sum of the products of sap flux

density and cross-sectional area for individual tree stem annuli (determined by below-bark TC insertion depths and sapwood depth). Consequently at the conclusion of the monitoring period 3 X 7 X 2 cm wood samples incorporating the thermocouple and heater probe insertion holes were chiselled out of the trees to determine the width of wounded (non-functional) xylem around the thermocouple holes. Sapwood moisture content and wood density values were also determined from these samples according to the Archimedes Principle using oven-dried mass and volume measurements (TAPPI, 1994).

**Table 5.2 Physical characteristics of the five savannah woodland sample trees used in this study.**

Sample Tree	Stem diam. at probes (cm)	Sapwood depth (cm)	TC insertion depths (mm)	Wound width (mm)	Bark depth (mm)	Wood density (g.cm <sup>-3</sup> )	Sapwood moisture content (%)
<i>Sclerocarya birrea</i>	40.62	15.0	28, 36, 45, 60	3	25	0.597	49.19
<i>Lannea schweinfurthii</i>	20.24	7.8	19, 24, 31, 40	4	15	0.569	44.89
<i>Combretum apiculatum</i> 1	21.20	9.7	7, 11, 16, 24	3	3	0.769	30.35
<i>Combretum apiculatum</i> 2	11.84	5.4	7, 11, 16, 24	3	3	0.735	31.93
<i>Combretum apiculatum</i> 3	18.91	8.6	7, 11, 16, 24	3	3	0.752	31.1

To scale up the sap flow measurements from the single trees I used aerial photographs to determine the proportion of trees in the landscape. 1:50 000 aerial photos were obtained from Scientific Services of the KNP. The transect covered by the scintillometer was overlaid on the aerial photographs and the proportional representation of trees, grass and shrubs was determined through visual interpretation of the canopy cover at 25m intervals along the 4.25km transect.

### **Total evaporation measurements**

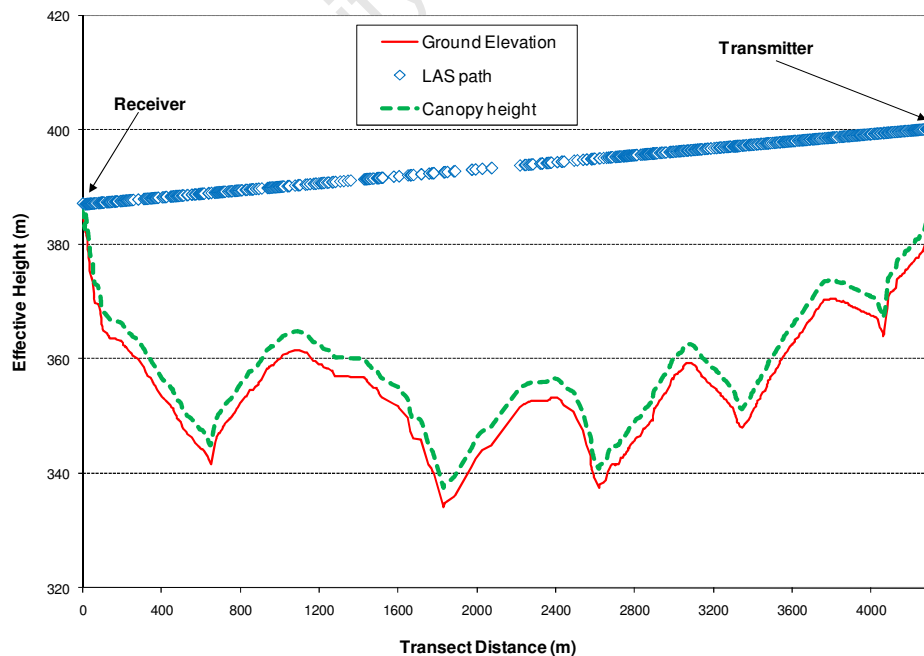
Scintillometry was used to determine the total evaporation (ET) of the savanna vegetation (i.e. water-use of trees, shrubs and grass combined). This technique has been explained in detail in Chapter 4, but essentially entails measurements of fluctuations in the refractive index of air, caused by small temperature and humidity fluctuations (scintillations). These are measured in the form of signal intensity fluctuations of light beamed between a transmitter and an accurately aligned receiver. Together with supporting data on wind speed, solar radiation, relative humidity, air temperature and air pressure, the scintillometry technique measures mean surface sensible heat flux ( $H$ ) above the savanna woodland. These data are combined with additional measurements of variables comprising the shortened energy balance equation, namely  $R_n$  which is net (incoming minus reflected) irradiance (both short- and long-wave components) above the canopy surface,  $G$  which is the energy required to heat soil – referred to as net soil heat flux,  $LE$  which is the energy required to evaporate water – referred to as latent energy and is the product of the specific latent heat of vaporisation,  $L$  (in  $\text{J kg}^{-1}$ ) and the water vapour flux density  $E$  ( $\text{kg s}^{-1} \text{m}^{-2}$ ), and  $H$  which is the energy required to heat the atmosphere above the soil – referred to as the sensible heat flux. Total evaporation (ET) is then a function of the residual term  $LE$  (the energy required to evaporate water), which closes the shortened energy balance equation (see Eq. 4.2).

Net radiation ( $R_n$ ) measurements were obtained using NR-Lite net radiometers (Kipp & Zonen, Delft, The Netherlands) mounted above a *Combretum apiculatum* and an area of grassland respectively, so as to be representative of the vegetation as a whole. Data from these two sites were simply averaged to integrate them. Similarly, average soil heat flux ( $G$ ) was determined from measurements beneath trees and grass respectively, using soil heat flux plates (model HFT-S, REBS, Seattle, Washington, USA) buried 80 mm below the soil surface, TCAV-L soil temperature averaging probes (Campbell Scientific Inc., Logan, Utah, USA) set at 20 mm and 60 mm below

the soil surface, and time domain reflectometer water content sensors (CS616, Campbell Scientific Inc., Logan, Utah, USA) in the upper 100 mm of the soil. These sensors were connected to a CR23X (Campbell Scientific) datalogger recording every ten seconds and averaging every ten minutes.

A Campbell Scientific automatic weather station (AWS) measuring rainfall, solar radiation, temperature, humidity, wind speed and wind direction on an hourly basis was installed on the hill alongside the scintillometer receiver during periods of ET measurement. These data were supplemented with continuous long-term weather data available for the duration of the study from the flux tower and sap flow monitoring systems.

Scintillometer data analysis requires the calculation of the weighted mean height of the beam relative to the height of the vegetation. This was achieved by determining the topographic profile between the scintillometer transmitter and receiver using GPS altitude data collected along a transect between the transmitter and the receiver, relative to the average vegetation height along the transect determined using height-rods (Fig. 5.4).



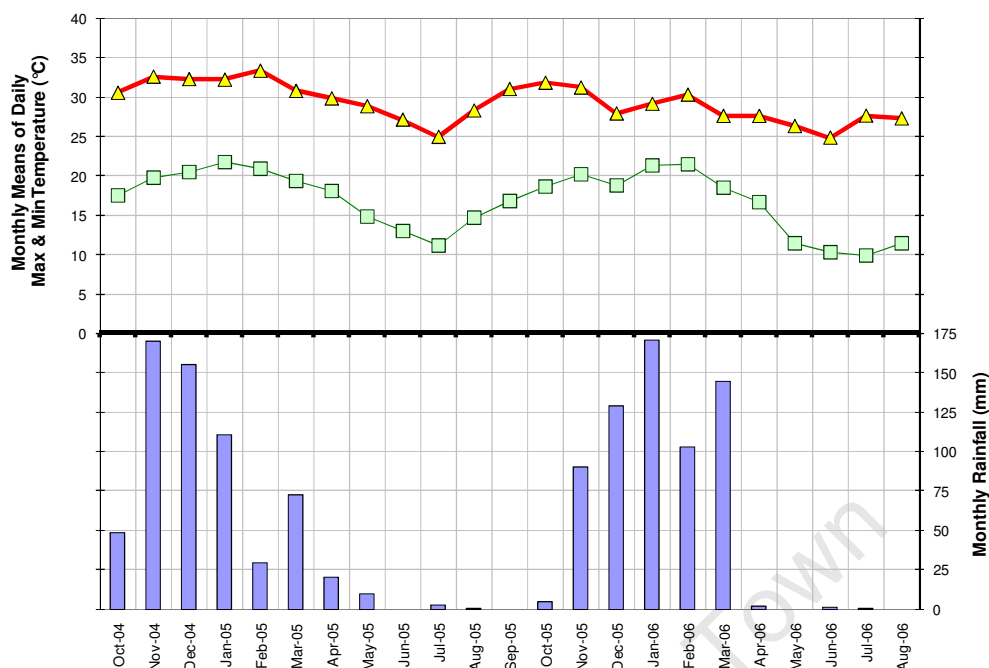
**Figure 5.4** Profile of elevation and canopy height variation relative to the 4.25 km scintillometry beam path from transmitter to receiver.

Two visits to the site took place to record total evaporation and energy balance information under varying climatic and vegetation conditions, namely: in the wet season (2<sup>nd</sup> to 8<sup>th</sup> February, 2005 (DOY 33 to 39)) and in the early dry season (11<sup>th</sup> to 18<sup>th</sup> May 2005 (DOY 131 to 138)). Based on a comparison between tree-only transpiration totals estimated using sap flow measurements, and whole-vegetation total evaporation values calculated from scintillometry measurements, the transpiration fraction (trees only) of total ET was estimated. This result was based on the days when the sap flow and scintillometry measurements were obtained simultaneously. The transpiration measurements, combined with scaled up tree densities for the individual sample trees, provided water-use totals for the tree component of the vegetation over two consecutive years. Utilising the T:ET partitioning ratio determined by this study, resultant estimates of total annual savanna ET (trees, grass and shrubs) were calculated.

## **Results**

### **Weather**

Distinct seasonal trends in rainfall and temperature over the study period (October 2004 to August 2006) were evident from the weather data collected over this period (Fig. 5.5). Rainfall totalled 618.6 mm in the 2004/2005 hydrological year (Oct – Sep), and 646.7 mm in 2005/2006. ET sampling during the wet and dry seasons of the year ensured that measurements were conducted under a range of vegetative growth phases and climatic (evaporative) conditions (Table 5.3). No particular climatic anomalies were encountered during the two sampling periods, and the weather was generally characterised by warm, dry conditions, with no rain. Wind speeds were accentuated by the situation of the AWS on the top of the hill. Varying intensities of solar radiation and vapour pressure deficit were the principal differentiators between seasons, both of these being relatively higher in the wet season (February) compared to the early dry season (May).



**Figure 5.5** Season variation in monthly rainfall (■) and mean daily maximum (▲) and minimum (■) temperatures from October 2004 to August 2006 at the study site.

**Table 5.3** Daily meteorological variables recorded in February 2005 and May 2005.

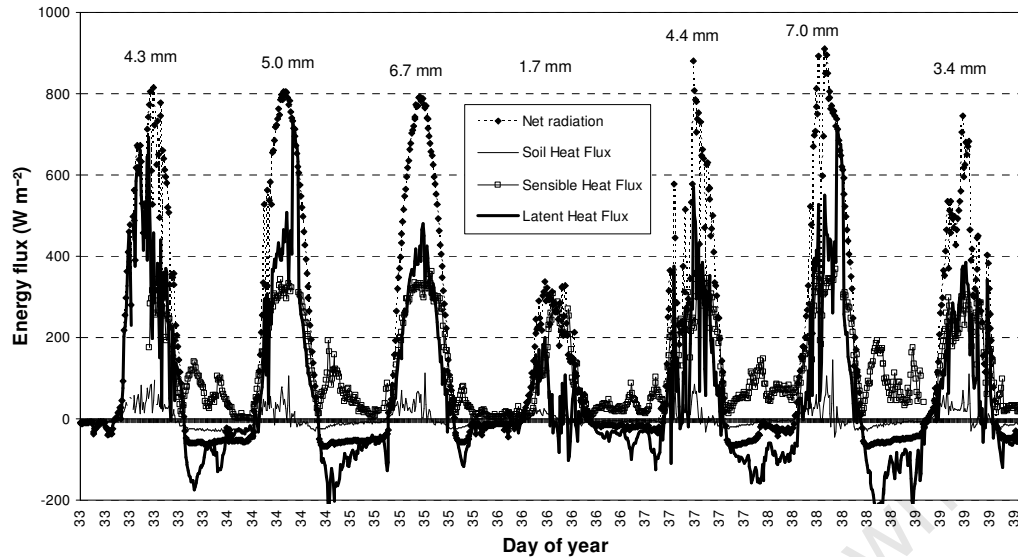
Date	Day Of Year	Temp Max (°C)	Temp Min (°C)	RH Max (%)	RH Min (%)	Wind (m s <sup>-1</sup> )	Solar Rad. (MJ m <sup>-2</sup> day <sup>-1</sup> )	VPD (kPa)	Rain (mm)
02-Feb-05	33	31.3	21.6	86.1	42.9	2.92	27.68	2.03	0.0
03-Feb-05	34	32.8	21.5	88.7	34.8	1.30	29.28	2.07	0.0
04-Feb-05	35	33.6	20.0	87.7	40.2	3.19	29.80	2.20	0.0
05-Feb-05	36	25.8	21.8	78.2	56.5	4.83	13.85	1.98	0.0
06-Feb-05	37	29.1	20.2	80.0	32.9	3.82	23.64	1.70	0.0
07-Feb-05	38	32.4	20.3	80.3	29.8	1.60	27.40	1.67	0.0
08-Feb-05	39	33.7	20.0	86.9	35.5	2.07	21.78	2.03	0.0
10-May-05	131	29.1	15.3	83.5	28.8	1.87	17.41	1.35	0.0
11-May-05	132	29.3	16.0	72.4	28.2	1.64	14.30	1.31	0.0
12-May-05	133	32.5	14.7	72.2	17.5	1.49	17.00	1.09	0.0
13-May-05	134	27.1	16.2	92.6	35.7	3.03	12.92	1.52	0.0
14-May-05	135	29.4	18.0	93.4	30.3	1.94	15.52	1.57	0.0
15-May-05	136	30.1	17.6	86.3	31.3	1.97	15.86	1.55	0.0
16-May-05	137	32.2	18.5	88.6	30.3	1.90	14.74	1.63	0.0
17-May-05	138	34.5	16.8	78.1	16.9	1.79	15.99	1.24	0.0

### **Observed total evaporation**

Observations of total evaporation (ET) above the savanna woodland using the scintillometry technique provided a measure of the water-use of the vegetation as a whole (trees, grass and shrubs).

#### *Wet season (2-8 February 2005)*

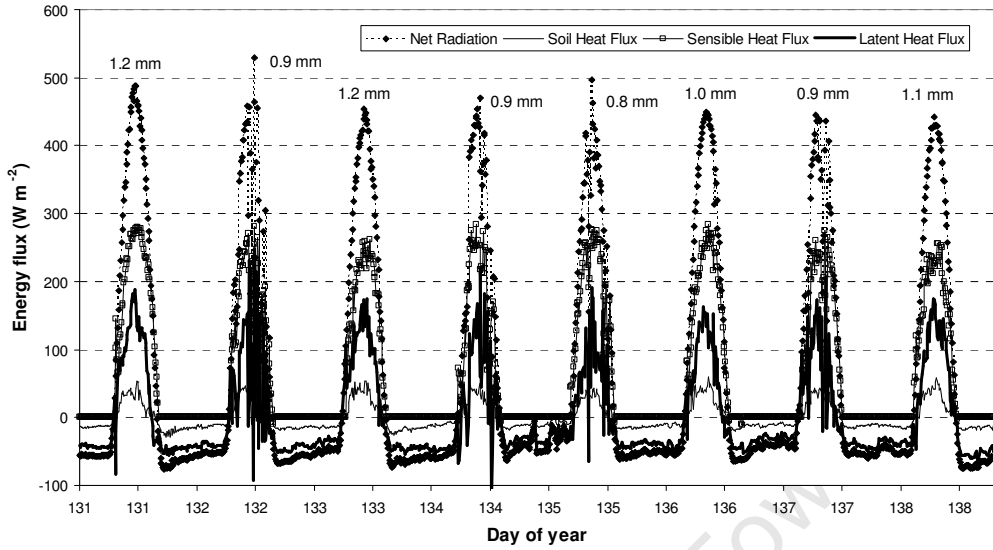
Cloudless warm weather (max temp. 33.6 °C, solar radiation 29.8 MJ m<sup>-2</sup> day<sup>-1</sup>) on the third day of measurement (DOY 35) resulted in high net radiation values (peaking at 800 W m<sup>-2</sup>) with correspondingly high latent heat fluxes (equivalent to 6.7 mm total evaporation). A subsequent cloudy day (max temp. 25.8 °C, solar radiation 13.85 MJ m<sup>-2</sup> day<sup>-1</sup>) on DOY 36 showed substantially reduced values of net radiation (peaking at 300 W m<sup>-2</sup>), and correspondingly low latent heat flux values (equivalent to 1.7 mm total evaporation). However, the highest daily total evaporation value (7 mm) was recorded on DOY 38, when particularly high values of net radiation (peaking at over 900 W m<sup>-2</sup>) combined with lower sensible and soil heat fluxes resulted in the highest latent heat flux values recorded at this site. Soil heat flux values were generally lower and more variable compared to in the late dry season (Fig. 5.6).



**Figure 5.6** Diurnal variations in 10-minute energy balance data measured above savanna vegetation for the period 2-8 February 2005. Calculated daily total evaporation values are annotated on the figure.

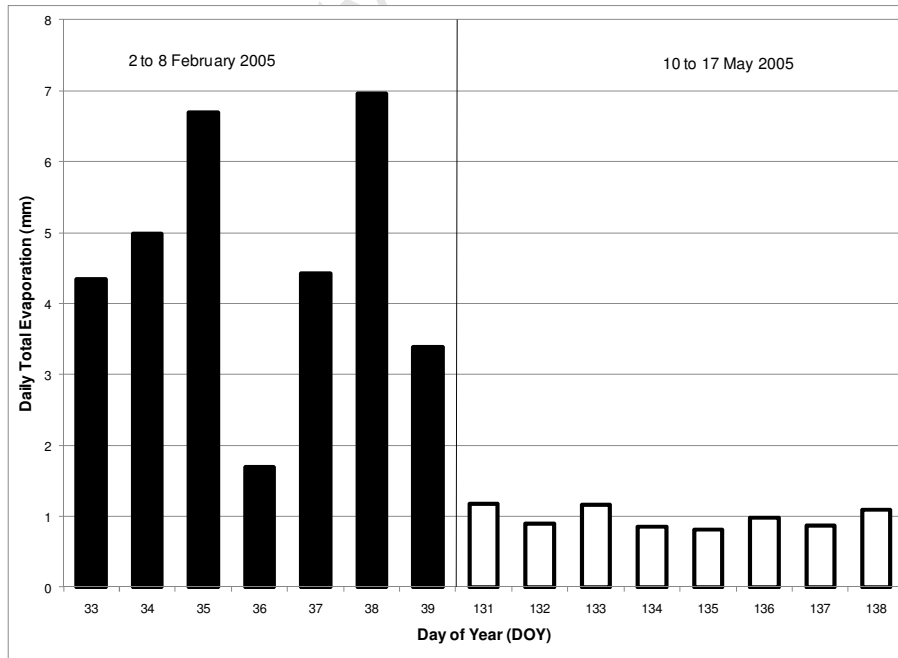
*Early dry season (10-17 May 2005)*

This period incorporated a series of consistently clear, warm and dry days. Maximum temperatures were high, ranging from 27.1 °C (DOY 134) to 34.5 °C (DOY 138), however solar radiation values were limited to between 12.92 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 134) and 17.41 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 131). Mid-day net irradiances were the lowest measured in the various seasons, only peaking at between 400 and 500 W m<sup>-2</sup>. As in the late dry season soil heat flux values peaked at approximately 50 W m<sup>-2</sup>. In contrast to the previous two seasonal measurement periods latent heat fluxes were approximately half of the sensible heat flux values, resulting in low daily total evaporation rates consistently in the region of 1 mm (Fig. 5.7).



**Figure 5.7** Diurnal variations in 10-minute energy balance data measured above savanna vegetation for the period 10-17 May 2005. Calculated daily total evaporation values are annotated on the figure.

Daily ET and energy balance data were recorded over a total of 15 days (Fig. 5.8).



**Figure 5.8** The range of daily total evaporation (ET) estimated with the scintillometer for 15 days over a wet (■) (February) and dry (□) (May) season in 2005.

During February 2005, moisture availability and green leaf area within the savanna vegetation would have been at their peak, resulting in maximum daily ET reaching 7 mm under conditions of high evaporative demand, but dropping to 1.7 mm during particularly overcast days. The variability in daily ET during this period is attributable to changing temperature, humidity and solar radiation levels. During May, conditions were dry and the bulk of the vegetation was senescing (grasses and deciduous trees), leading to substantially lower daily ET totals in the region of 1 mm.

### **Observed transpiration**

Observed sap flow data provided a measure of the water used by the tree component of the vegetation. Results of the vegetation composition analysis using aerial photographs revealed that trees made up approximately 22% of the canopy cover, with grass accounting for 30% and the remaining 48% being under shrubs. Using the assumption that the sample trees in which sap flow was observed were of average dimensions, and that they comprised 22% tree cover per hectare, it was possible to derive hypothetical trees densities. This was done by dividing the crown area of each sample tree into a hectare (10000 m<sup>2</sup>), and then assuming that only 22% of the resultant tree number was present. Hypothetical tree densities in stems per hectare (spha) were thus calculated for the individual species and for the landscape as a whole, based on canopy dimensions and average tree cover across the site (Table 5.4). These were used to convert transpiration in litres per tree, to mm.

**Table 5.4** Relative tree density in stems per hectare (spha) for the respective sample trees based on canopy dimensions and average tree cover within this vegetation type.

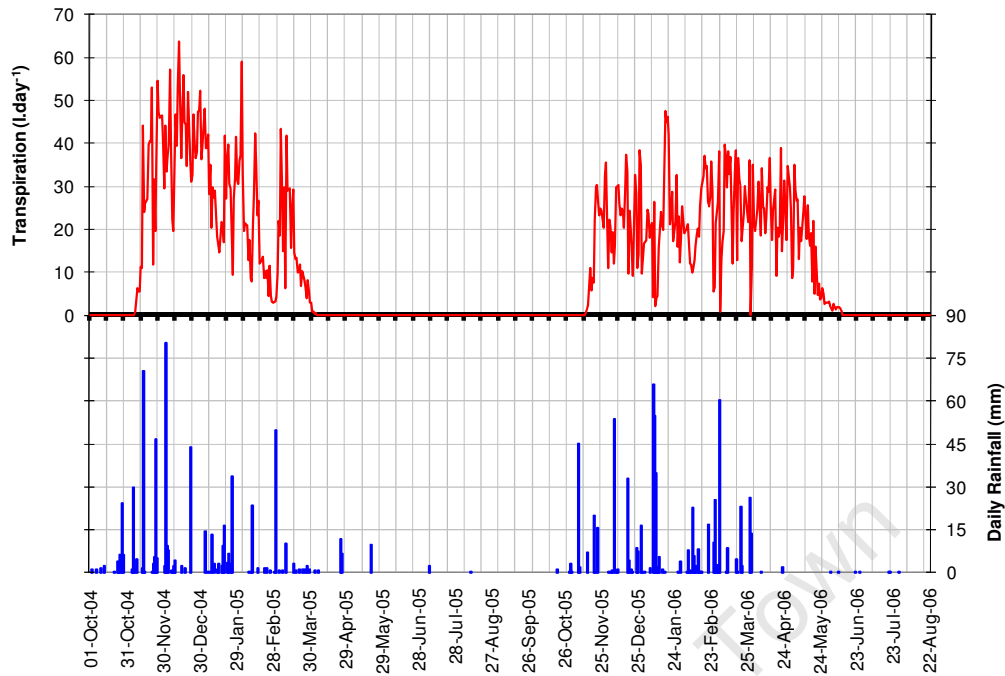
Species	Crown diam. (m)	Crown area (m <sup>2</sup> )	spha (full cover)	spha (22% cover)
<i>S. birrea</i>	11.1	97.5	102.6	22.6
<i>L. schweinfurthii</i>	6.4	31.8	314.2	69.1
<i>C. apiculatum 1</i>	3.8	11.5	872.7	192.0
<i>C. apiculatum 2</i>	2.5	5.1	1963.5	432.0
<i>C. apiculatum 3</i>	5.1	20.4	490.9	108.0
<b>average</b>		<b>33.2</b>	<b>300.8</b>	<b>66.2</b>

As an example of long-term fluctuations in transpiration observed using the HPV measurements in the sample trees, water-use volumes for the smaller *Lannea schweinfurthii* sample tree in litres.day<sup>-1</sup> (Fig. 5.9) and mm.month<sup>-1</sup> calculated using hypothetical tree densities (Fig. 5.10) are illustrated. The data show clearly how this species rapidly builds up to peak transpiration rates, but also how water-use trends in this deciduous species are distinctly seasonal, controlled by changes in leaf area, rainfall and hence soil water availability. A significant amount of variability in daily transpiration totals was also evident, with rates often being particularly low on days of rainfall (due to limited available solar energy, low vapour pressure deficits and a fully wetted canopy), but increasing rapidly thereafter as the trees utilised newly available soil water. The onset of sap flow in this species appears to be remarkably consistent from one year to the next, with the date of first detectable transpiration after the dry season corresponding virtually to the day (~7 November) between the 2004/2005 and 2005/2006 monitoring periods. The seasonal correlation between transpiration and rainfall is especially marked when monthly transpiration and rainfall totals are compared (Fig. 5.10).

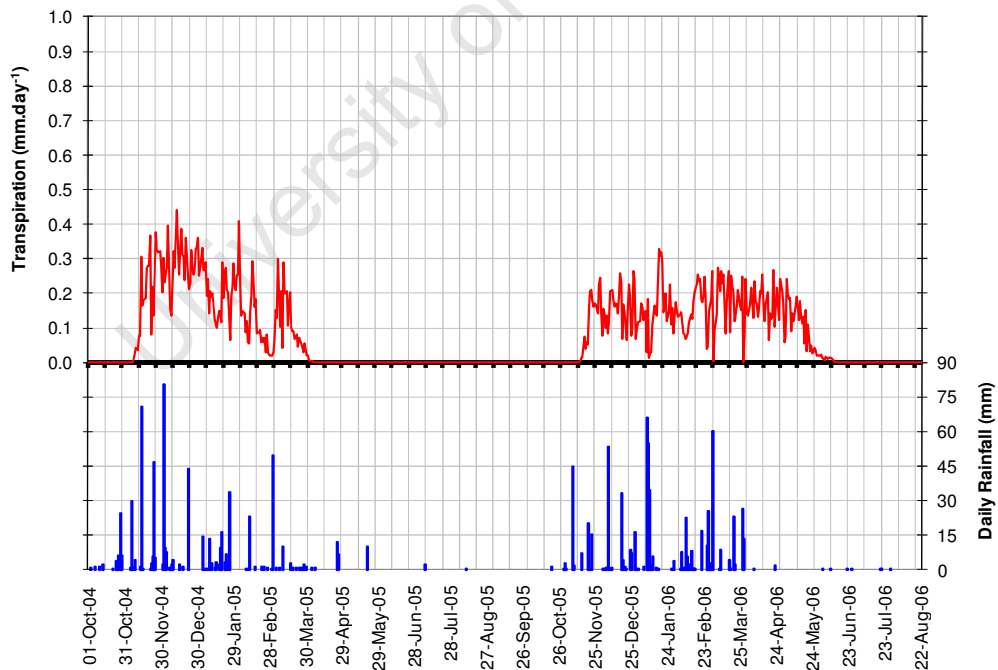
From comparable data for one of the *Combretum apiculatum* sample trees at the same site (Fig. 5.11 and 5.12) it is noticeable that transpiration persists significantly later into the dry season in this species, compared to the *L. schweinfurthii* (Fig. 5.9) and the *S. birrea* (Fig. 5.13). This reflects the fact that this species was observed to retain its leaves for longer than the other two

species. Transpiration continued into the dry winter months, particularly in the second year of measurement when heavy rains in February and March (250 mm) presumably replenished soil-water reserves to the point where they could provide moisture longer into the dry season.

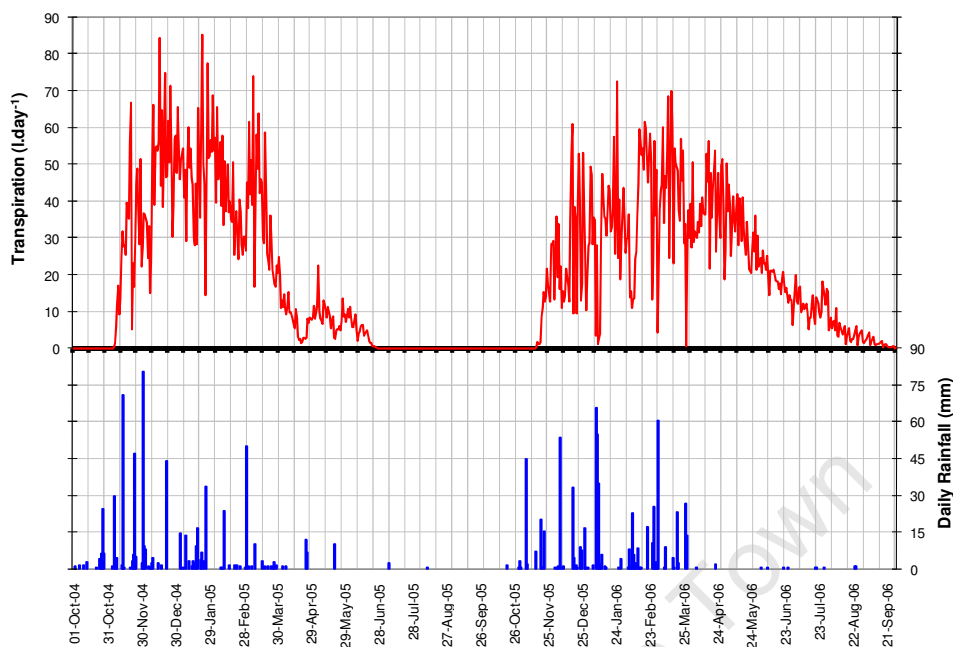
Comparable data for one of the *Sclerocarya birrea* trees (Fig. 5.13 and 5.14) illustrate that seasonal transpiration patterns in this species were very highly correlated with rainfall, and the increase and decrease in sap flow activity at the start and end of the wet season is very pronounced. In terms of absolute values of water transpired by the respective tree species, greatest volumes were recorded in the stem of the *S. birrea* tree (up to 187 litres.day<sup>-1</sup>), followed by the *C. apiculatum* (up to 85 litres.day<sup>-1</sup>) and lastly the *L. schweinfurthii* (up to 63 litres.day<sup>-1</sup>). To a certain extent this was influenced by the stem diameters of the respective trees as sap flow volumes are a product of sap velocity and sapwood cross-sectional area. However the *C. apiculatum* had a smaller stem diameter than the *L. schweinfurthii* and yet transpired greater volumes of water due to significantly higher rates of sap flow in the former species. At a landscape scale, however, water-use is a product of single-tree transpiration volumes and tree densities. Consequently, while the *S. birrea* exhibited the greatest individual tree transpiration volume (litres.tree<sup>-1</sup>), at a landscape scale (mm) it was the lowest due to the relatively low hypothetical tree density.



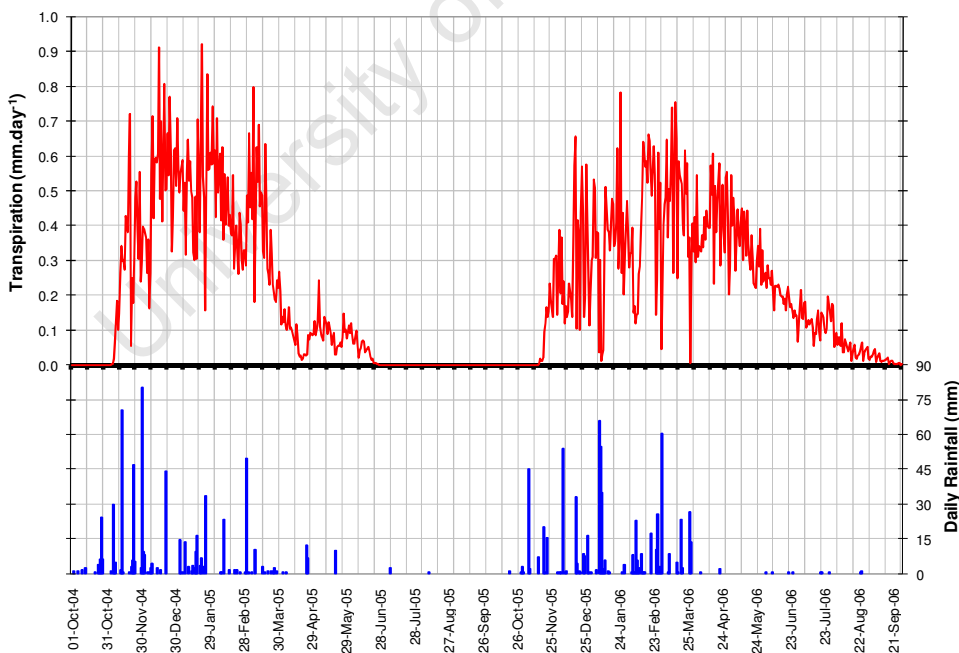
**Figure 5.9** Daily transpiration (—) (litres) observed in a *Lanena schweinfurthii* tree using sap flow measurements, with daily rainfall (■) (mm) over two growing seasons at the sap flow monitoring site in the Kruger National Park.



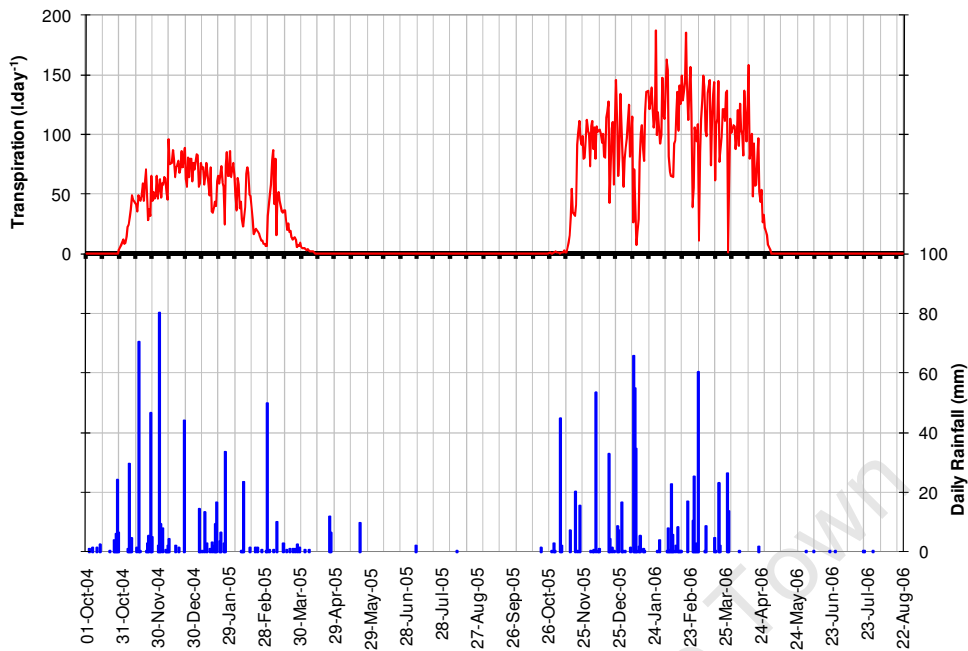
**Figure 5.10** Daily transpiration (—) (mm) for a *Lanena schweinfurthii* tree, calculated from sap flow measurements and hypothetical tree densities, with daily rainfall (■) (mm) over two growing seasons at the sap flow monitoring site in the Kruger National Park.



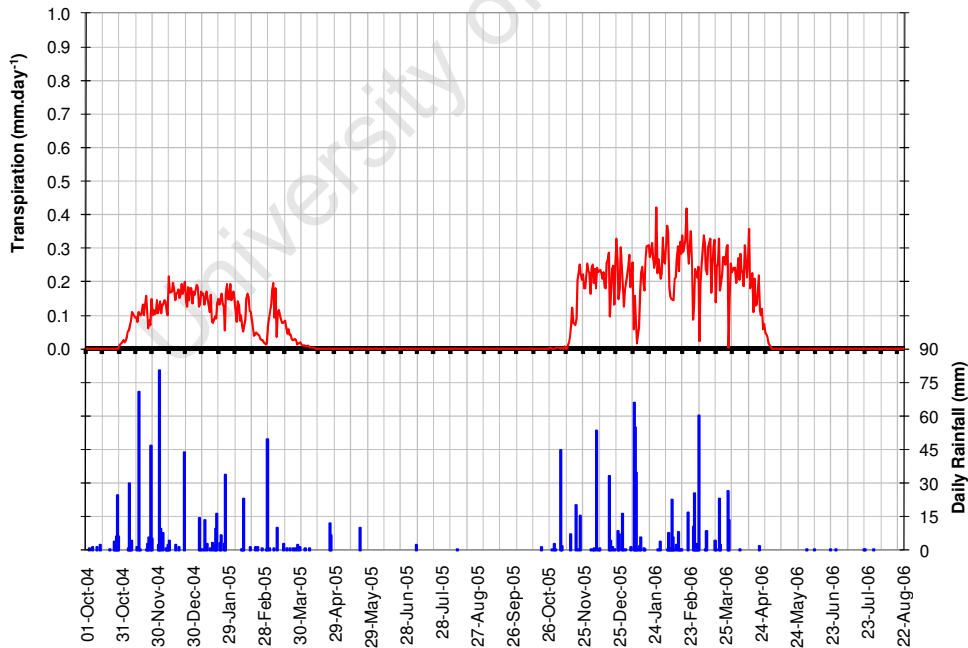
**Figure 5.11** Daily transpiration (—) (litres) observed in a *Combretum apiculatum* tree using sap flow measurements, daily rainfall (■) (mm) over two growing seasons at the sap flow monitoring site in the Kruger National Park.



**Figure 5.12** Daily transpiration (—) (mm) in a *Combretum apiculatum*, calculated from sap flow measurements and hypothetical tree densities, with daily rainfall (■) (mm) over two growing seasons at the sap flow monitoring site in the Kruger National Park.



**Figure 5.13** Daily transpiration (—) (litres) observed in a *Sclerocarya birrea* tree using sap flow measurements, with daily rainfall (■) (mm) over two growing seasons at the sap flow monitoring site in the Kruger National Park.



**Figure 5.14** Daily transpiration (—) (mm) for a *Sclerocarya birrea* tree, calculated from sap flow measurements and hypothetical tree densities, with daily rainfall (■) (mm) over two growing seasons at the sap flow monitoring site in the Kruger National Park.

The annual water-use (mm) of an “average tree” within this environment, determined by converting transpiration totals from litres.tree<sup>-1</sup>.month<sup>-1</sup> to mm.month<sup>-1</sup> using hypothetical tree densities from Table 5.4, is tabulated below (Table 5.5).

**Table 5.5 Monthly transpiration totals in the sample trees (mm.month<sup>-1</sup>) between October 2004 and September 2006, calculated from sap flow observations and hypothetical tree densities. Corresponding monthly rainfall totals are included.**

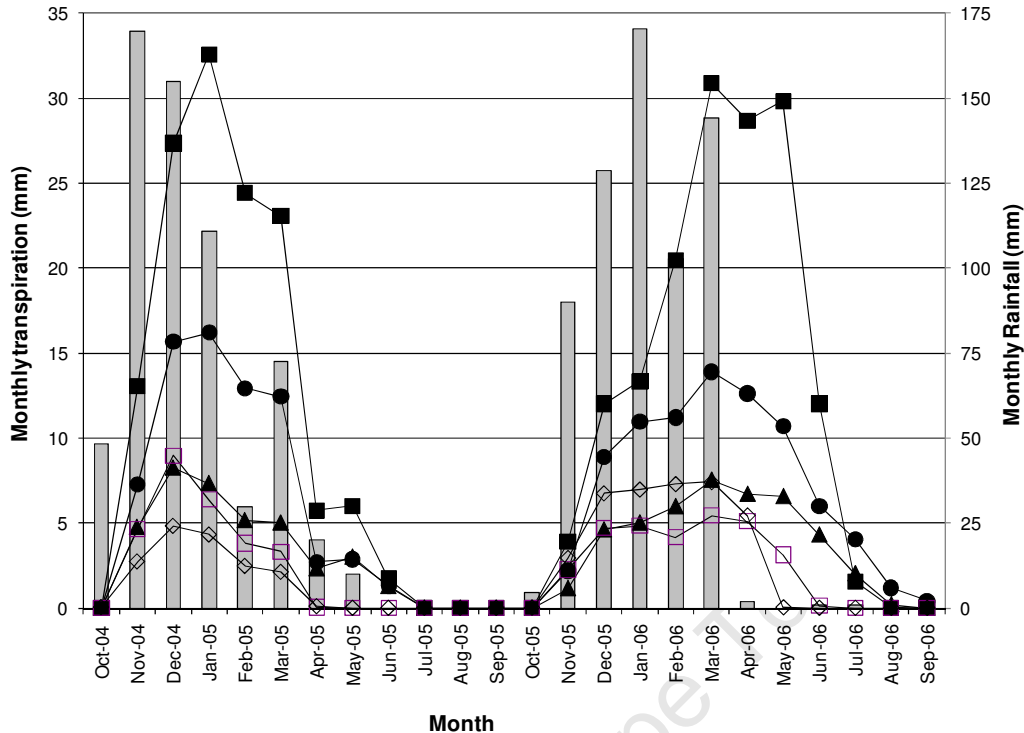
Month	Rain (mm)	Transpiration (mm)					Average
		<i>S. birrea</i>	<i>L. schwein.</i>	<i>C. apic.</i> 1	<i>C. apic.</i> 2	<i>C. apic.</i> 3	
Oct-04	48.3	0.0	0	0.0	0	0	0.0
Nov-04	169.9	2.7	4.7	13.1	4.8	7.3	6.5
Dec-04	155.1	4.8	9.0	27.4	8.3	15.7	13.0
Jan-05	110.7	4.3	6.4	32.6	7.3	16.2	13.4
Feb-05	29.7	2.5	3.8	24.4	5.2	12.9	9.8
Mar-05	72.4	2.1	3.3	23.1	5.0	12.5	9.2
Apr-05	20.1	0.1	0.0	5.7	2.3	2.7	2.2
May-05	9.9	0.0	0.0	6.0	3.0	2.9	2.4
Jun-05	0.0	0.0	0.0	1.8	1.3	1.3	0.9
Jul-05	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Aug-05	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Sep-05	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Totals (04/05)</b>	<b>618.6</b>	<b>16.6</b>	<b>27.2</b>	<b>134.0</b>	<b>37.1</b>	<b>71.5</b>	<b>57.3</b>
Oct-05	4.6	0.0	0.0	0.0	0.0	0.0	0.0
Nov-05	90.2	2.9	2.3	3.9	1.2	2.2	2.5
Dec-05	128.8	6.8	4.7	12.0	4.6	8.9	7.4
Jan-06	170.4	7.0	4.8	13.4	5.0	11.0	8.2
Feb-06	102.9	7.3	4.2	20.5	6.0	11.2	9.8
Mar-06	144.3	7.4	5.5	30.9	7.5	13.9	13.0
Apr-06	2.0	5.5	5.1	28.7	6.7	12.6	11.7
May-06	0.0	0.0	3.1	29.8	6.6	10.7	10.1
Jun-06	1.0	0	0.1	12.0	4.3	6.0	4.5
Jul-06	0.8	0	0	1.6	2.0	4.1	1.5
Aug-06	1.8	0	0	0.0	0.2	1.2	0.3
Sep-06	0	0	0.0	0	0	0.4	0.1
<b>Totals (05/06)</b>	<b>646.7</b>	<b>36.9</b>	<b>29.8</b>	<b>152.8</b>	<b>44.1</b>	<b>82.2</b>	<b>69.2</b>

Estimated average annual transpiration from the trees amounted to 57.3 mm and 69.2 mm in 2004/5 and 2005/6, respectively, comprising 9.3% of rainfall in 2004/5 and 10.7% in 2005/6. Water-use by the individual sample trees (litres.tree<sup>-1</sup>.year<sup>-1</sup>) over the two years of measurement were totalled and converted to spatial estimates of water use (mm) using the tree density (spha) calculations (Table 5.6).

**Table 5.6 Annual transpiration totals (in litres and mm) for the respective sample trees over two consecutive years, obtained from sap flow measurements and scaled up hypothetical tree density estimates.**

Year	Species	1-yr Rainfall (mm)	1-yr Water-use (litres/tree)	Spha	Transpiration (mm)
2004/2005	<i>S. birrea</i>	618.6	7377.4	22.6	16.6
	<i>L. schweinfurthii</i>		3934.5	69.1	27.2
	<i>C. apiculatum 1</i>		6980.7	192.0	134.0
	<i>C. apiculatum 2</i>		859.5	432.0	37.1
	<i>C. apiculatum 3</i>		6616.7	108.0	71.5
	<b>Average</b>		<b>5153.8</b>	<b>66.2</b>	<b>57.3</b>
2005/2006	<i>S. birrea</i>	646.7	16367.1	22.6	36.9
	<i>L. schweinfurthii</i>		4317.5	69.1	29.8
	<i>C. apiculatum 1</i>		7957.1	192.0	152.8
	<i>C. apiculatum 2</i>		1021.3	432.0	44.1
	<i>C. apiculatum 3</i>		7569.7	108.0	82.2
	<b>Average</b>		<b>7446.5</b>	<b>66.2</b>	<b>69.2</b>

Monthly transpiration totals (mm) observed for all the species, relative to monthly rainfall totals over the entire monitoring period are illustrated (Fig. 5.15). All species show growing season changes due to an early wet season build-up in leaf area, and an early dry season decline as conditions become drier and the leaves senesce.



**Figure 5.15 Monthly transpiration totals (mm) from 3 *Combretum apiculatum* trees (■▲●), 1 *Lannea schweinfurthii* tree (□) and 1 *Sclerocarya birrea* tree (◇), with monthly rainfall totals (■) (mm) over two growing seasons in the Kruger National Park.**

Based on a comparison between tree-only transpiration totals estimated using sap flow measurements, and whole-vegetation total evaporation values calculated from scintillometry measurements, the transpiration fraction (trees only) of total ET was estimated to be 9.81% (Table 5.7), with the remaining 90.19% of ET at the site being attributable to grass and shrub water-use. This result was based on the days when the sap flow and scintillometry measurements were obtained simultaneously. The transpiration fraction varied seasonally, being slightly higher in February (avg. 12%) than in May (avg. 8%). This was attributed to the deciduous nature of the trees, with their increased green leaf area and ability to utilise readily available soil water during the wet summer months (February). In May, these deciduous trees were already losing their leaves, and while the grass was also entering senescence, the transpiration fraction of the trees declined relative to the ET contribution of grass and evergreen shrubs.

**Table 5.7 Partitioning of total evaporation (ET, of trees, grass and shrubs) and transpiration (T, of trees only) fluxes within woodland savanna for several days in the wet season (February) and early dry season (May). The relative proportion (%) comprising transpiration is also shown.**

Date	DOY	ET (mm)	T (mm)	Diff. (mm)	T (%)
02-Feb-05	33	4.33	0.53	3.81	12.14%
03-Feb-05	34	4.98	0.50	4.48	10.08%
04-Feb-05	35	6.69	0.50	6.18	7.50%
05-Feb-05	36	1.69	0.40	1.29	23.88%
06-Feb-05	37	4.41	0.52	3.89	11.73%
07-Feb-05	38	6.96	0.49	6.47	6.99%
08-Feb-05	39	3.39	0.43	2.96	12.55%
11-May-05	131	1.18	0.09	1.08	7.92%
12-May-05	132	0.90	0.09	0.81	9.46%
13-May-05	133	1.16	0.09	1.08	7.53%
14-May-05	134	0.85	0.07	0.78	8.21%
15-May-05	135	0.81	0.08	0.73	9.39%
16-May-05	136	0.99	0.07	0.92	7.16%
17-May-05	137	0.86	0.05	0.81	5.94%
18-May-05	138	1.10	0.06	1.04	5.14%
<b>Totals</b>		<b>40.30</b>	<b>3.95</b>	<b>36.34</b>	<b>9.81%</b>

The transpiration measurements, combined with scaled up tree densities for the individual sample trees, provided water-use totals for the tree component of the vegetation of 57.3 mm for the 2004/2005 hydrological year, and 69.2 mm for the 2005/2006 hydrological year - an average of 63.25 mm. Utilising an approximate 1:10 T:ET partitioning ratio as determined by this study, resultant estimates of total annual savanna ET (trees, grass and shrubs) suggest water-use volumes of approximately 630 mm (Table 5.8). This value is very similar to the annual rainfall totals of 618.6 mm and 646.7 mm measured over the 2-year study period, and confirms that the vegetation in this semi-arid site is likely to use virtually all the available water that is supplied by rainfall.

**Table 5.8** The water-use of the savanna woodland as a whole (trees, grass and shrubs), estimated from the observed ratio between transpiration and total evaporation.

Year	1-yr Rainfall (mm)	Transpiration (mm)	T:ET ratio	Equivalent ET estimate (mm)	1-yr Water-use (kg.ha <sup>-1</sup> )
2004/2005	618.6	57.3	1:10	573	5730000
2005/2006	646.7	69.2	1:10	692	6920000
Average	632.65	63.25	1:10	632.5	6325000

### Discussion

The two seasons over which water-use measurements were conducted exhibited typical weather conditions, albeit with slightly higher rainfall than the MAP for the site. The measurements of transpiration (water-use) for the individual trees showed a wide range between species. In both seasons (2004/2005 and 2005/2006) the *S. birrea* tree emerged as the species with the highest water-use, although it was also observed to have the lowest tree density in the landscape. The *L. schweinfurthii* and the larger *C. apiculatum* trees used similar amounts of water, however the larger crown size of the *L. schweinfurthii* tree meant that its estimated tree density was lower (as crown size was assumed to be inversely proportional to tree density), which resulted in a lower estimate of water-use spatially. The smallest tree sampled, namely the second *C. apiculatum* tree, used considerably less water than the larger individuals of the same species, and this was due to its relatively smaller leaf and sapwood conducting areas. It is speculated that seasonal variations in sap velocity are not only correlated to available soil moisture, but also to climatic stimuli such as changes in temperature and daylength. From field

observations it was concluded that sap flow ceased before all the leaves had dropped from the trees, and only commenced approximately a month after the flush of early wet season leaves.

Estimates of water-use were relatively consistent within the individual sample trees over the two study years, with the exception of the *S. birrea*. While all trees used more water in the second year (attributed to the increased rainfall in that year), this particular tree used more than double the amount of water compared to the first year. Due to the considerable size and large stem diameter of this tree, combined with limitations in terms of probe insertion depths, this could be related to some uncertainty about the extent of the sapwood conducting area of this tree.

My results show that only 10% of the total evaporation (ET) taking place from this savanna woodland site may be attributed to transpiration from the tree component of the vegetation. This is due to the low tree density and the predominantly deciduous nature of the dominant trees in the area. A 10:90 T/ET contribution ratio is supported by Archibald and Scholes (2007) who estimated the respective contributions to Leaf Area Index (LAI) in the peak growing season to be 10% from trees and 90% from grass/shrubs. Other studies on the partitioning of ecosystem ET within African savannas are rare; however the 1:10 transpiration/ET partitioning ratio found in this study appears to be lower than for other forms of savanna, in which similar studies have been conducted. Using a combination of sap flow and Eddy Covariance techniques over an 11-month period, Paço *et al* (2009) found that tree transpiration represented 56% of total ecosystem ET within an evergreen Mediterranean Oak savanna in Portugal, despite a low tree crown cover fraction (21%). Using a similar approach within Eucalyptus savanna in northern Australia, Hutley *et al* (2000) concluded that transpiration accounted for approximately 33% (313 mm) of annual total evaporation (958 mm) at that site. In another study, Yopez *et al* (2003) used stable isotope measurements of atmospheric water vapour (verified with Eddy Covariance measurements) to partition overstorey and understorey total evaporation within semi-arid savanna woodland comprising deeply rooted *Prosopis velutina* ("mesquite")

trees, and perennial grass, *Sporobolus wrightii*. They found that transpiration by the trees accounted for approximately 70% of total ecosystem ET.

The T:ET ratio estimated in this study emphasises the hydrological importance of the shrub component of the vegetation given its high proportion (48%) in the landscape compared to the remaining 52% comprising trees (22%) and grass (30%), and the fact that it appears to be increasing through the process of bush encroachment both locally and internationally (Wigley *et al.*, 2010). It is not surprising therefore, that there is growing interest in the eco-hydrological consequences of bush encroachment (Huxman *et al.*, 2005, Wilcox, 2010). It has been suggested that augmentation of streamflow through shrub removal is not viable in environments receiving mean annual rainfall of 450-500 mm or less (Wilcox, 2002). This particular site, with a MAP of approximately 550 mm thus has limited potential for streamflow alteration from that respect. However, in areas in which precipitation is sufficient, indicators of the potential for increasing streamflow through shrub control may include the presence of high density stands of shrubs with high rainfall interception potential, underlying shallow permeable soils, and the dominance of baseflow / groundwater recharge events as opposed to stormflow / Hortonian overland flow events (Wilcox, 2002). Under such conditions, reducing shrub cover may increase streamflows because water that would normally have been lost through transpiration by the shrubs now moves into the soil, and rapidly passes beyond the root zone to deeper groundwater supplies, augmenting streamflow as a result. More studies of this nature are required to quantify the potential hydrological benefits associated with bush clearing.

# Chapter 6

## **THE WATER-USE EFFICIENCY OF AN INDIGENOUS *Podocarpus falcatus* PLANTATION**

### **Introduction**

Historically, the paired catchment approach has been the basis for determining the hydrological impacts of changes in vegetation cover and land-use (Hibbert, 1967; Bosch and Hewlett, 1982; Brown *et al.*, 2005). While this approach has its merits, international interest in direct measurements of the water-use of different tree species, plantations and natural forests worldwide has increased over the last 15 years (Wullschleger *et al.*, 2001; Asbjornsen *et al.*, 2011). This is primarily a result of the increased availability, accuracy and use of micrometeorological and heat dissipation techniques for measuring total evaporation and transpiration from forests, plantations and individual trees (Smith and Allen, 1996; Wullschleger *et al.*, 1998; Rana and Katerji, 2000; Wilson *et al.*, 2001). This interest has also developed from an increasing need to understand the role of trees in catchment hydrology and to resolve issues of water resource management resulting from deforestation, afforestation and reforestation (Bruijnzeel, 2004; Farley *et al.*, 2005; Dye and Versfeld, 2007; Scott and Prinsloo, 2008). In the past, the majority of tree water-use studies in South Africa focused on single-species commercial plantations of the genera *Pinus*, *Eucalyptus* and *Acacia* (Gush *et al.*, 2002; Dye and Versfeld, 2007; Scott and Prinsloo, 2008; Clulow *et al.*, 2010). However, there is growing international interest in both the water-use (Fetene and Beck, 2004; McJannet *et al.*, 2007; Licata *et al.*, 2008; Whitley *et al.*, 2008; Dierick and Hölscher, 2009; Kagawa *et al.*, 2009; Cavaleri and Sack, 2010), and water-use efficiency (Dye *et al.*, 2008; Gyenge *et al.*, 2008) of indigenous tree species.

There are very few plantations of indigenous tree species in South Africa, primarily due to the slow growth rates of desirable species (van Daalen, 1991; Geldenhuys and von dem Bussche, 1997) when compared with growth rates of introduced species (FSA, 2010). The only strong historical motivation for the establishment of indigenous plantations in the past was a policy, adopted by the commercial forestry industry in South Africa, excluding the planting of introduced timber species in riparian zones (FIEC, 1995). The rationale for this was the disproportionately high water-use of evergreen woody vegetation growing in riparian zones, when compared to other parts of the catchment (Wicht, 1941; Rowe, 1963; DeBano and Schmidt, 1990; Scott, 1999; Everson *et al.*, 2007). These studies showed that clearing evergreen woody vegetation within riparian zones measurably increased streamflow from catchments, even after the cleared areas were re-colonised by herbaceous vegetation. Interestingly, no limitations have ever been imposed on planting indigenous tree species in South African catchments. There is a general perception that indigenous trees use water more conservatively than plantations of introduced trees, resulting in a comparatively lower impact on catchment water yields; however this evidence is largely anecdotal (Wilson, 1982; Cooper, 1985; Cawe and McKenzie, 1989). There have however been no studies done on plantations of South African indigenous tree species, or comparisons made against introduced plantation water-use, to justify this perception. In this chapter I address this paucity of research through a determination of the water-use and growth of an indigenous *Podocarpus falcatus* (Thunb.) R.Br. ex Mirb. (Outeniqua Yellowwood) plantation in the Limpopo Province of South Africa.

A number of previous studies have combined eddy covariance (EC) and sap flow measurements to determine plantation and individual plant water-use (Granier *et al.*, 1996; Wilson *et al.*, 2001; Williams *et al.*, 2004, Bovard *et al.*, 2005, Paço *et al.*, 2009). The EC measurements quantify total evaporation (ET) from the plantation (trees, soil and understory vegetation), while the sap flow measurements determine transpiration rates (water-use) of the individual trees. Combining these techniques makes it possible to partition the above and below canopy components of total evaporation by quantifying the

fractions of evaporation and transpiration contributing to total evaporation (ET).

I verify a Penman-Monteith-Granier model against short-term seasonal ET measurements from the plantation canopy, and extrapolate these over a 12-month period corresponding to a period of continuous sap flow measurements. Using a combination of water-use data derived from these measurements and the model, and tree growth data for this particular plantation reported by Geldenhuys and von dem Bussche (1997), I then estimate the water-use efficiency (utilisable stem wood produced per unit of water used) of both the plantation as a whole (trees and understorey vegetation) as well as individual trees. Finally, I compare the results against existing data for introduced commercial forestry species. The primary objective is to test the hypothesis that plantations of indigenous *Podocarpus falcatus* trees use less water than introduced tree plantations (*Eucalyptus* and *Pinus* spp.). I do this to explore the possibility of expanding indigenous plantation forestry in South Africa without incurring negative water resource impacts.

## **Methods**

### **Site and species selection**

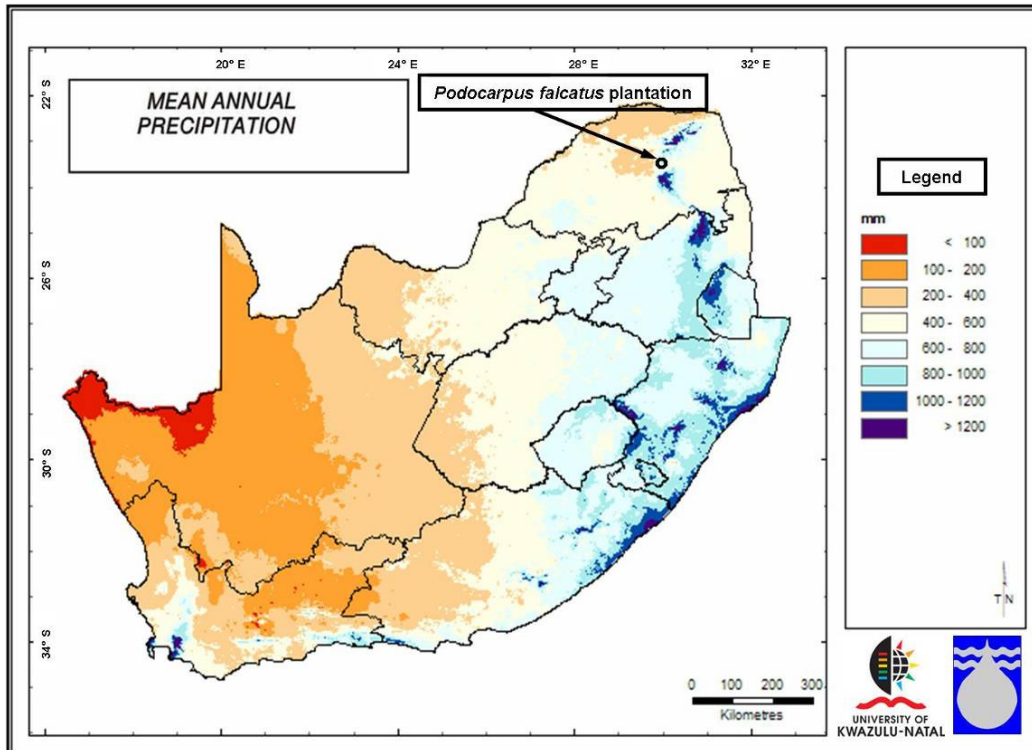
Of the few commercial plantings of indigenous tree species in South Africa, plantations of *Podocarpus falcatus* are the most common in view of the species' growth form and the commercial value of the timber. Trial plantings of indigenous yellowwood trees are known to have been established at sites in the southern Cape (Witfontein), Mpumalanga (Frankfort) and Limpopo provinces (De Hoek) in the early 1980's (Geldenhuys and von dem Bussche, 1997). The site selected for this study comprised a 7.8ha stand of 24-year old *P. falcatus* trees situated on the Woodbush-De Hoek Forest Plantation (23° 49' 50.4" S, 30° 02' 31.2" E, altitude 857 m.a.s.l) in the Limpopo Province of South Africa (Fig. 6.1).

The stand was originally established as a provenance trial to test growth rates of seed collected from various locations across South Africa (Geldenhuys and von dem Bussche, 1997). Planting took place between October 1982 and December 1983, and tree spacing is 3 m by 3 m (1111 spha). Blanking (replacing of dead trees with new seedlings) took place over the first three years. No thinning was performed. The average height of the trees was 10m. An under-storey cover of mixed grasses, including *Setaria megaphylla* (Steud) Dur. & Schinz (Ribbon Grass), and invasive *Lantana camara* (L.) was present during this study, varying in leaf area from sparse during the cold dry winter months to dense during the warm wet summer months. Changes in leaf area index (LAI) over the study period for the trees only and trees+undergrowth were measured seasonally (spring, summer and late winter) using an LAI-2000 Canopy Analyser (LI-COR Inc, Lincoln, Nebraska, USA). Soils consist of red sandy-clay-loams of the Oakleaf<sup>1</sup> form to a depth of 110 cm, above a shallow ground water table due to the riparian nature of the site (Willem Hollestein, pers. comm.).

Mean annual precipitation at the plantation is 1257 mm, falling predominantly in the summer, with a peak between December and March (Lynch and Schulze, 2006). Mean daily maximum temperatures range from 26.7 °C in February to 20.2 °C in July, while mean daily minimum temperatures range from 17.4 °C in February down to 8.2 °C in July (Schulze and Maharaj, 2007).

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<sup>1</sup> According to Fey (2010) USDA classification of this South African soil forms is Neocutanic (Oakleaf).



**Figure 6.1** Location of the *Podocarpus falcatus* study site relative to the distribution of Mean Annual Precipitation across South Africa (from Lynch and Schulze, 2006).

### **Total evaporation measurements**

The Eddy Covariance (EC) technique (Savage *et al.*, 1997; Savage *et al.*, 2004) was used to determine total evaporation (ET) from the plantation. The technique measures turbulent eddies of air above the canopy, which are important drivers of water vapour exchange (total evaporation) from the underlying vegetation. As such, the EC instrumentation needs to be positioned above the canopy of the plantation, and for this study a Clark WT8 pneumatic telescopic mast erected in the plantation was used for this purpose. The EC technique is reliant on the shortened energy balance approach (Thom, 1975), which requires estimates of all the components of the energy balance equation (Eq. 6.1) in order to close the equation:

$$R_n - G - LE - H = 0 \quad (6.1)$$

where  $R_n$  ( $W\ m^{-2}$ ) is the net (incoming minus reflected) solar irradiance (both short- and long-wave components) above the canopy surface,  $G$  ( $W\ m^{-2}$ ) is the energy required to heat soil – referred to as soil heat flux,  $LE$  ( $W\ m^{-2}$ ) is the energy required to evaporate water – referred to as latent energy flux, and  $H$  ( $W\ m^{-2}$ ) is the energy required to heat the atmosphere above the soil – referred to as sensible heat flux.  $R_n$  was measured using a net radiometer (Model 240-110 NR-Lite, Kipp & Zonen, Delft, The Netherlands) mounted on the telescopic mast at a height of 12.5 m above the ground.  $G$  was measured in the plantation floor using HFT-S soil heat flux plates (REBS, Seattle, Washington, USA) buried 80 mm below the soil surface, together with TCAV-L soil temperature averaging probes (Campbell Scientific Inc., Logan, Utah, USA) set at 20 mm and 60 mm below the soil surface and time domain reflectometer water content sensors (CS616, Campbell Scientific Inc., Logan, Utah, USA) in the upper 100 mm of the soil.  $H$  was measured with a 3-D ultrasonic anemometer (Model 81000, R.M. Young, Traverse city, Michigan, USA) mounted at 12.2 m above the ground. This instrument provided measurements of the three directions of wind velocity ( $u$ ,  $v$  and  $w$ ) caused by the air eddies above the plantation, as well as high frequency measurements of air temperature using sonic temperature ( $T_{sonic}$ ), from which sensible heat ( $H_{EC}$ ) was calculated (Eq. 6.2) as follows:

$$H_{EC} = \rho_a c_p \sum (w - \bar{w})(T_{sonic} - \bar{T}_{sonic}) \quad (6.2)$$

where  $\rho_a$  is the density of air (approximately  $1.12\ kg\ m^{-3}$ ),  $c_p$  is the specific heat capacity of air at constant pressure (approximately  $1040\ J\ kg^{-1}\ K^{-1}$ ),  $w$  is the vertical wind velocity,  $T_{sonic}$  is the air temperature using sonic temperature, and the over bar denotes the average value during a time period of suitable length. All measurements were averaged and stored every 30 minutes, and sonic coordinate rotations were performed post the data collection period using a Fortran program. Energy Balance closure at this site was independently tested (Jarman *et al.*, 2008), and found to be generally around 1, meaning that energy balance closure was achieved at this site, and hence

no additional source of energy contributed to the energy balance. Once these components of the energy balance equation had been derived Equation 6.1 was re-arranged in the following way (Eq. 6.3) to solve for the residual term  $LE$ .

$$LE = R_n - G - H \quad (6.3)$$

$LE$  is the product of the specific latent energy of vaporisation ( $L$ ) and the water vapour flux density ( $E$ ). Knowing  $L$  to be  $2.454 \times 10^6 \text{ J kg}^{-1}$ , total evaporation (ET) was consequently derived by subtraction, from measurements of  $R_n$ ,  $G$  and  $H$ , and converted from  $\text{W m}^{-2}$  to  $\text{mm}^1$ .

Measurements were conducted in a 130m X 600m stand of trees comprising a N-S orientated flat valley-bottom riparian strip. The tower was positioned in the centre of the plantation to maximise fetch. The site is bordered by a stream on the west and surrounded by stands of introduced timber genera such as *Pinus spp.* and *Khaya anthotheca* (Welw.) C.DC. (East African Mahogany). Total evaporation (ET) was determined on three separate occasions; namely in the late dry season (22-28 September, 2005), the wet season (9-15 February, 2006) and the dry season (23-30 August, 2006), for a total of 22 complete days of measured total evaporation data.

### **Sap flow measurements**

The heat-pulse velocity (HPV) technique (Swanson, 1994; Smith and Allen, 1996) was used to determine sap flow (i.e. transpiration) of five trees (Table 6.1) representative of the range of tree sizes present in the plantation. The trees were selected after first conducting a stem size survey on 48 trees within the plantation, and then selecting individual trees that represented the respective size-classes. Trees were subsequently assigned to one of 5 stem

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<sup>1</sup>  $\text{W m}^{-2} = \text{J s}^{-1} \text{ m}^{-2}$ . To convert from  $\text{W m}^{-2}$  (i.e. from  $\text{J s}^{-1} \text{ m}^{-2}$ ) to mm, half-hourly averages of  $LE$  were multiplied by the number of seconds (s) in each measurement interval (i.e. 1800 in this case), and divided by the latent energy of vaporisation ( $2.454 \times 10^6 \text{ J kg}^{-1}$ ). Units of J and s cancel and remaining units are  $\text{kg m}^{-2}$  (i.e. mm) of water evaporated.

diameter size classes, with each size class being represented by a sample (HPV) tree on which sap flow measurements were conducted continuously from September 2005 to August 2006.

**Table 6.1** Details of the *Podocarpus falcatus* (Thunb.) Mirb. (Outeniqua Yellowwood) trees selected for sap flow measurements in this study.

Tree No.	Tree Height (m)	Diameter at breast height (cm)	Bark depth (mm)	TC insertion depths (mm below surface)
1	8.85	18.72	5	10, 15, 22 and 31
2	8.6	16.33	5	10, 15, 22 and 31
3	8.15	8.44	5	10, 15, 22 and 31
4	8.32	12.54	5	10, 15, 22 and 31
5	11.05	22.35	5	10, 15, 22 and 31

Once sap-flow monitoring had been completed, additional supplementary information required to complete the HPV data analysis was collected. The trees could not be destructively sampled, so small wood samples and tree cores were taken using an 8 mm inside-diameter increment corer (Haglöf, Sweden) to determine sapwood depth, sapwood moisture content, wood density and the width of wounded (non-functional) xylem around the thermocouples ('wound widths') (Table 6.2). Cores were analysed for sapwood depth by staining with Methyl Orange. However, as no visual distinction between sapwood and heartwood could be observed, even after staining, the sapwood was assumed to extend to within 5mm of the centre of the stem. Subsequent heat pulse velocity data obtained from the deepest insertion depths confirmed this assumption.

**Table 6.2** Physical properties of the *Podocarpus falcatus* trees in this study.

Tree No.	Sapwood depth (cm) & (area) (cm <sup>2</sup> )	Ave. wound width (mm)	Wood Density (g cm <sup>-3</sup> )	Sapwood moisture content (%)
1	7.7 (242.3)	4	0.441	54.44
2	7.1 (183.6)	4	0.439	53.64
3	3.1 (42.2)	4	0.473	51.38
4	5.4 (104.2)	4	0.467	52.36
5	9.6 (354.2)	3	0.431	56.87

Measured heat-pulse velocities were corrected for sapwood wounding caused during the drilling procedure, using wound correction coefficients described by Swanson and Whitfield (1981). The corrected heat-pulse velocities were then converted to sap-flux densities according to the method described by Marshall (1958). Finally, the sap-flux densities were converted to whole-tree total sap flow by calculating the sum of the products of sap-flux density and cross-sectional area for individual tree stem annuli (ring-shaped areas determined by below-bark individual probe insertion depths and sap-wood depth). Hourly sap-flow values were aggregated into daily, monthly and annual totals for each tree. Individual transpiration (i.e. sap flow) totals observed for the 5 sample trees were then weighted according to the number of trees in their size class that they represented (Table 6.3), and a single transpiration rate for the plantation was determined.

**Table 6.3**      **Weighting of observed transpiration rates relative to stem diameter.**

<b>Diam. Size Classes (cm)</b>	<b>No. of trees</b>	<b>HPV tree</b>	<b>DBH (cm)</b>	<b>Weighting (%)</b>
≤11	3	3	8.44	6.25
11 - 14	15	4	12.54	31.25
14 - 17	18	2	16.33	37.50
17 - 20	10	1	18.72	20.83
≥20	2	5	22.35	4.17

### **Total evaporation modelling**

I applied a model derived from a combination of the Penman-Monteith (Monteith, 1965) and Granier (Granier *et al.*, 2000) models (see detailed explanation in Chapter 4) to extrapolate the seasonal canopy total evaporation measurements to a full year. The model was first calibrated against the short-term observed ET values determined by the Eddy Covariance measurements and then extrapolated to a full year coinciding with the sap flow measurements. Using exactly the same approach and assumptions adopted in the modelling exercise for the Southern cape Afro-temperate forest, daily values of total evaporation were modelled from September 2005 to

September 2006. Daily maximum and minimum temperature, relative humidity, windspeed, rainfall and solar radiation at the site over the study period were sourced from the South African Weather Service (station 0679106A8 - Greshoek Tzaneen and station 0678858/4 - Woodbush). Changes in leaf area index over time were estimated from the LAI measurements conducted at the site during field visits and were also used as input into the model. Parameter values of  $0.2 \text{ m s}^{-1}$  for  $g_a$ , 6.6 for  $g_{cmax}$ , 100 for  $R_o$ , and 2.0615 for  $b$  were found to provide the best fit to the data during the calibration exercise, and were subsequently used to extrapolate total evaporation estimates over the same calendar year for which there were sap flow (transpiration) measurements. The resultant time-series of daily total evaporation estimates was then compared against the year-long daily transpiration record determined using sap flow monitoring, as a means of comparing the water-use of the trees only (transpiration) against the water-use of the plantation as a whole (trees and under-storey vegetation).

### **Tree growth measurements and water-use efficiency**

Tree growth rates over a 12-month period corresponding to the water-use measurement period were required for the calculation of WUE. Geldenhuys and von dem Bussche (1997) reported on growth data recorded at the study site during October 1993 (11 years after planting), while additional growth survey data recorded during May 2001 (19 years after planting) were sourced from unpublished records at the holding company (Komatiland Forests). These data were combined with stem diameter and height data measured on 48 trees at the study site in August 2006. Based on a sample of *Podocarpus falcatus* trees in the southern Cape with diameters less than 40 cm, Geldenhuys (1983) derived the following relationship (Eq. 6.4) between single-tree stem diameter and stem volume:

$$V = 0.0000996 * DBH^{2.5} \quad (6.4)$$

where  $V$  is stem volume ( $m^3$ ) and DBH is Diameter at Breast Height (cm). This equation was used to calculate average single-tree stem volumes at the times of the respective surveys, which were scaled up to plantation scale using the planting density. However these were instantaneous estimates of standing stem volume, while an increase in total stand volume over the year of interest (2005/2006) was required. Consequently, growth trajectories were used to calculate changes in Periodic Mean Annual Increment (PMAI) values i.e. the mean annual increment observed between growth surveys. This was necessary because the time between respective growth surveys varied and a growth rate for the year of interest (2005/2006) needed to be interpolated. In conjunction with the sap flow (transpiration) and total evaporation results this allowed the calculation of WUE ( $m^3$  wood produced per  $m^3$  water used) for the trees alone and for the plantation as a whole (trees and under-storey vegetation). Tree volume increments were converted to mass using an average wood density determined for this species using mass and volume measurements (Archimedes Principle) on wood samples from the trees.

## **Results**

### **Observed total evaporation**

A wide range of evaporative conditions were encountered, relating directly to the time of year. Three distinct seasons were represented (Table 6.4), namely a late dry season (September) before the commencement of rains in October, a wet season (February) in the middle of the growing season, and a dry season (August) when there was little activity in the trees. Measured seasonal changes in Leaf Area Index (LAI) of the plantation (trees and undergrowth) are also shown. LAI values for the trees and whole plantation were the same in September 2005, as the understorey of the plantation, comprising primarily the alien invasive plant *Lantana camara*, had recently been slashed and cleared. However, by the time of the summer (February) campaign, the undergrowth had re-established and contributed significantly (37.5%) to the overall LAI, before declining to a 20% contribution in August.

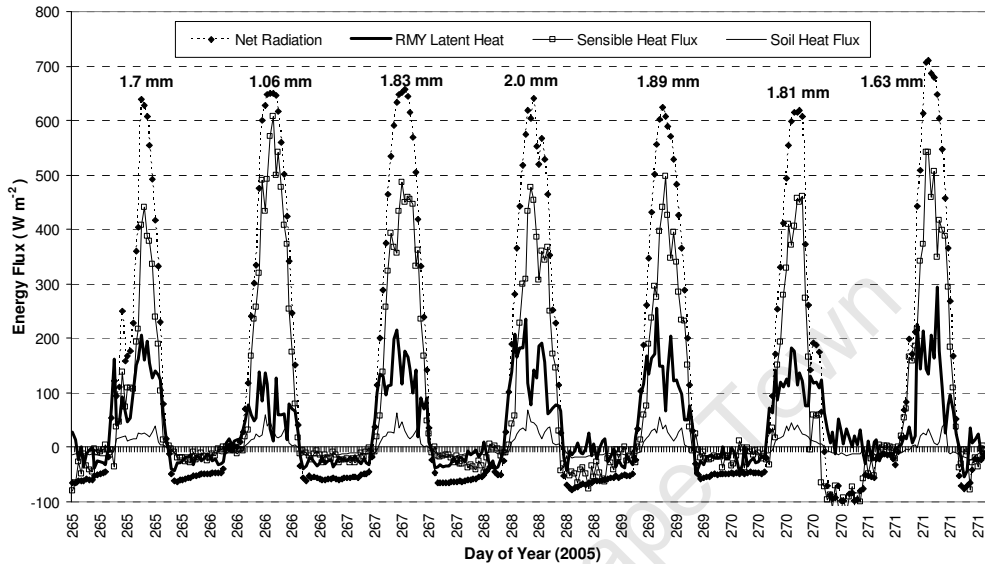
**Table 6.4 Daily meteorological variables and Leaf Area Index (LAI) values recorded in September 2005, February 2006 and August 2006.**

Date	Day Of Year	Temp Max (°C)	Temp Min (°C)	RH Max (%)	RH Min (%)	Wind (m s <sup>-1</sup> )	Solar Rad. (MJ m <sup>-2</sup> day <sup>-1</sup> )	VPD (kPa)	Rain (mm)	LAI (m <sup>2</sup> m <sup>-2</sup> )
22-Sep-05	265	28.2	16.4	82.9	38.2	0.55	14.33	1.529	0.0	2.0 (trees & undergrowth)
23-Sep-05	266	31.2	14.5	92.2	31.1	0.38	19.42	1.628	0.0	
24-Sep-05	267	32.5	15.4	84.9	25.2	0.56	22.54	2.349	0.0	
25-Sep-05	268	37.7	15.6	76.7	13.7	0.50	21.33	3.634	0.0	
26-Sep-05	269	31.8	17.3	74.1	30.7	0.56	20.65	2.269	0.0	
27-Sep-05	270	35.5	16.4	84.5	10.8	1.02	18.36	2.785	0.0	
28-Sep-05	271	25.3	15.4	80.7	17.8	1.45	20.90	1.425	0.0	
09-Feb-06	40	25.6	19.6	97.7	89.7	0.15	12.52	0.501	6.5	4.0 (trees & undergrowth)
10-Feb-06	41	26.6	20.5	97.8	81.4	0.26	9.40	0.535	121.5	
11-Feb-06	42	26.2	19.8	97.7	75.5	0.31	14.17	0.546	4.7	
12-Feb-06	43	27.3	20.2	97.2	80.5	0.27	18.02	0.630	2.7	
13-Feb-06	44	31.6	17.8	97.8	57.2	0.28	23.48	1.305	24.6	
14-Feb-06	45	24.2	19.4	97.4	91.5	0.11	9.67	0.383	31.3	
15-Feb-06	46	28.2	19.8	97.7	74.0	0.46	24.96	0.757	0.0	
23-Aug-06	235	23.2	11.5	87.1	40.4	0.37	4.35	0.743	0.4	2.5 (trees & undergrowth)
24-Aug-06	236	19.8	13.3	96.0	71.0	0.23	4.67	0.389	0.2	
25-Aug-06	237	26.1	11.1	97.2	39.7	0.43	18.39	1.025	1.9	
26-Aug-06	238	24.0	11.2	94.2	30.7	0.69	15.37	0.828	0.0	
27-Aug-06	239	22.7	12.0	96.1	37.8	0.29	15.79	0.675	0.1	
28-Aug-06	240	25.5	8.6	95.9	27.1	0.40	21.65	1.073	0.0	
29-Aug-06	241	30.4	9.0	88.7	14.7	0.64	21.76	1.595	0.0	
30-Aug-06	242	24.5	10.6	83.7	29.7	0.49	18.20	0.898	0.0	

*Late dry season (22 - 28 September 2005)*

This measurement period incorporated mainly clear, hot days, with maximum temperatures ranging from 25.3 °C (DOY 271) to 37.7 °C (DOY 268). Solar radiation values ranged from 14.33 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 265) to 22.54 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 267), and no rain was recorded (Table 6.4). Mid-day net irradiances consistently peaked at between 600 and 700 W m<sup>-2</sup> during this period, while daily maximum soil heat flux values ranged from 40 to 70 W m<sup>-2</sup> (Fig. 6.2). The generally cloudless warm weather resulted in estimates of total

evaporation consistently around 1.8 mm per day, apart from DOY 266 when more energy was partitioned into heating the air (sensible heat) resulting in lower latent heat and a correspondingly low 1.06 mm total evaporation.

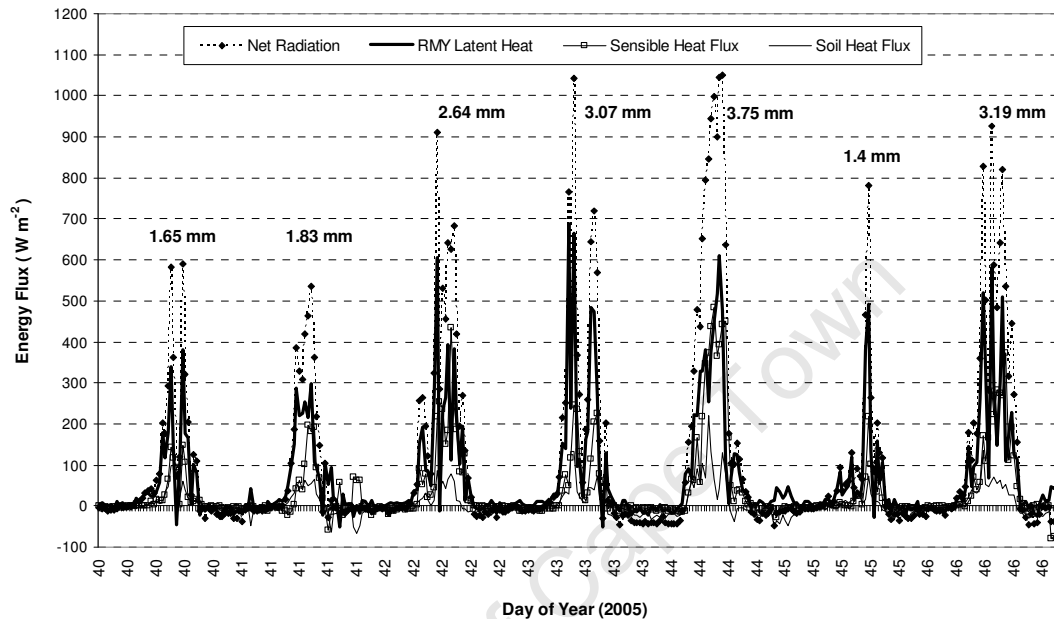


**Figure 6.2** Diurnal variations in 30-minute energy balance data measured above a *Podocarpus falcatus* plantation for the period 22-28 September 2005. Calculated daily total evaporation values are annotated on the figure.

#### *Wet season (9 - 15 February 2006)*

This period was characterised by partly cloudy and extremely wet conditions (Table 6.4). Maximum temperatures ranged from 24.2 °C (DOY 45) to 31.6 °C (DOY 44). Solar radiation values also ranged from a low 9.4 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 41) to 24.96 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 46). Mid-day net irradiances occasionally peaked above 1000 W m<sup>-2</sup> but for the most part were less than 500 W m<sup>-2</sup> during this period. Soil heat flux values occasionally peaked above 200 W m<sup>-2</sup> but were generally lower than 100 W m<sup>-2</sup> (Fig. 6.3). Substantial rainfall was recorded during the measurement period (191.3 mm) which together with the cloudy conditions reduced ET rates to between 1.4 and 1.8 mm on certain days (DOY 40, 41 and 45) although a maximum ET value of 3.75 mm was recorded on DOY 44. On that particular day, the 24.6 mm of rain that were recorded only fell late at night, and the daylight hours were

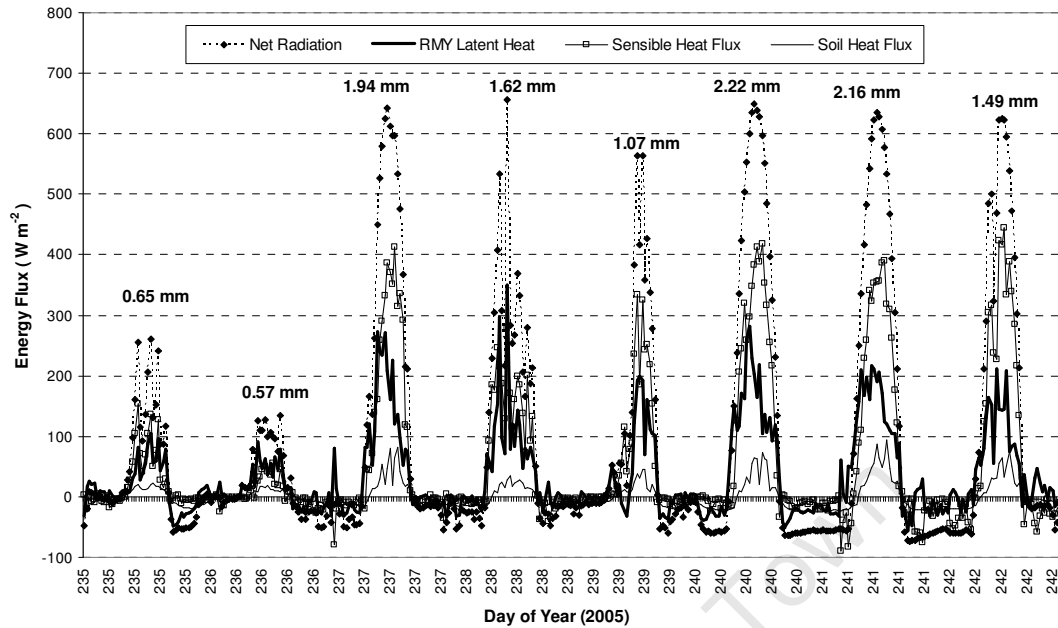
characterised by high net radiation values and high temperatures. This, together with replenished soil moisture reserves from previous rainfall events resulted in the high ET value recorded on this day, and similarly on DOY 46.



**Figure 6.3** Diurnal variations in 30-minute energy balance data measured above a *Podocarpus falcatus* plantation for the period 9-15 February 2006. Calculated daily total evaporation values are annotated on the figure.

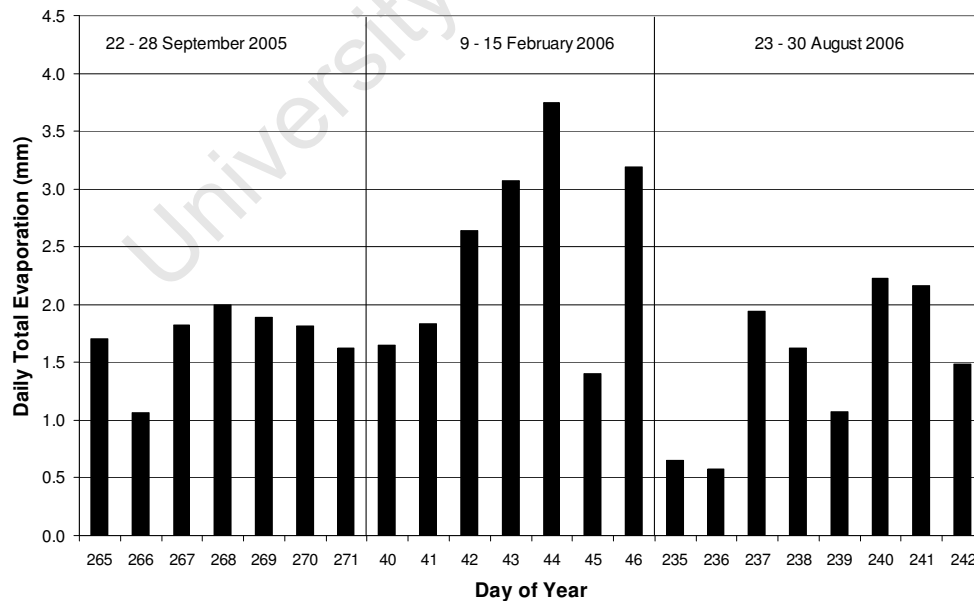
#### *Dry season (23 – 30 August 2006)*

The dry season weather experienced during this period incorporated a combination of cool overcast days with some light rain initially, followed by clear mild days with no rain (Table 6.4). Maximum temperatures consequently ranged from 19.8 °C (DOY 236) to 30.4 °C (DOY 241) and solar radiation values also ranged from a very low 4.35 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 235) to 21.76 MJ m<sup>-2</sup> day<sup>-1</sup> (DOY 241). Mid-day net irradiances were typical of the season peaking at between 600 and 700 W m<sup>-2</sup> on clear days but being limited to less than 150 W m<sup>-2</sup> on DOY 236. Soil heat flux values never exceeded 100 W m<sup>-2</sup> and only peaked at 20 W m<sup>-2</sup> during the cool overcast days (Fig. 6.4). Resultant estimates of total evaporation ranged from 0.57 mm (DOY 236) to a maximum of 2.22 mm (DOY 240).



**Figure 6.4** Diurnal variations in 30-minute energy balance data measured above a *Podocarpus falcatus* plantation for the period 23-30 August 2006. Calculated daily total evaporation values are annotated on the figure.

All the daily total evaporation values recorded for the plantation (Fig. 6.5) were subsequently used to test and parameterise the model.

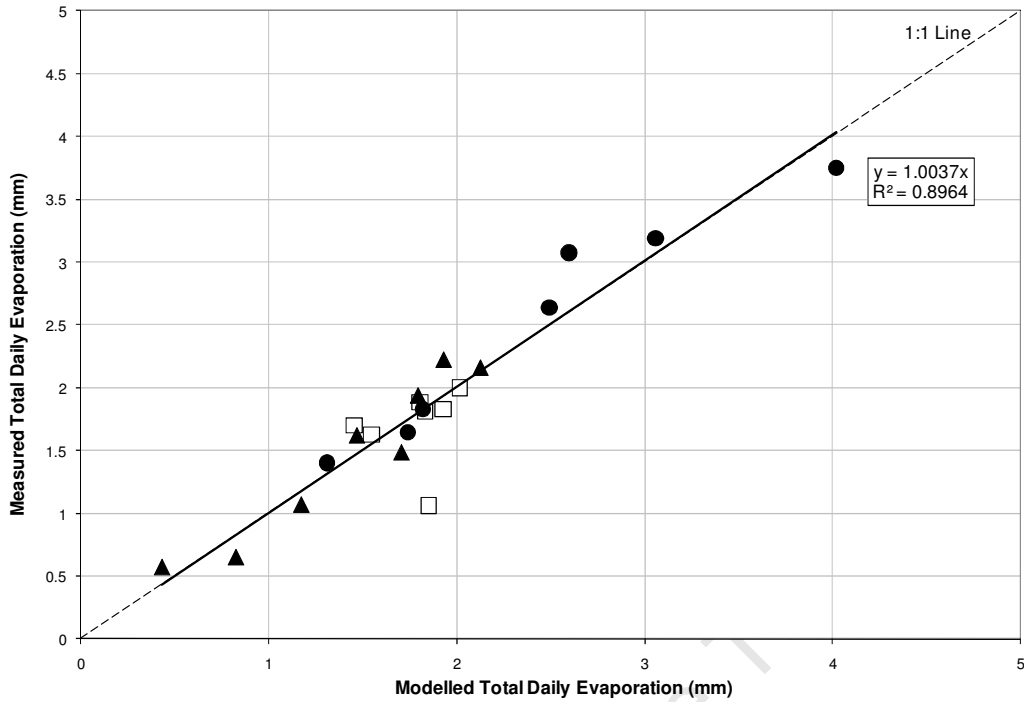


**Figure 6.5** Daily total evaporation rates measured over a *Podocarpus falcatus* plantation using Eddy Covariance in September 2005, February and August 2006.

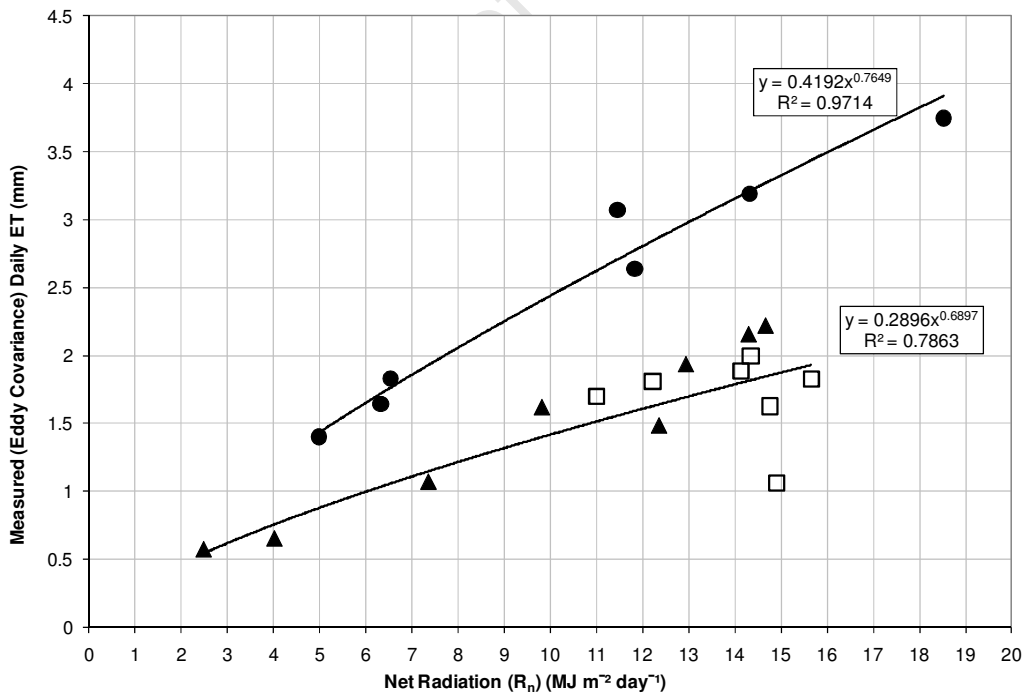
The water-use of this *Podocarpus falcatus* plantation exhibited considerable day-to-day and seasonal variation. While total evaporation rates peaked in the warm and wet summer months and were lowest during the cold and dry winter months, daily variation was greatest in the summer. After the first rains in October and November modelled total evaporation for the plantation climbed steadily from 2 mm day<sup>-1</sup> in September, peaking at up to 4 mm day<sup>-1</sup> in January and February (verified by ET measurements during this period). These increases in ET may be attributable to the increasing vigour and transpiration of the trees and understorey vegetation which was dense and displayed a high green leaf area at this time. Enhanced evaporation from wet foliage and the soil are also likely to have contributed to the high ET rates over this period, since intermittent rainfall was recorded regularly over this wet season. Thereafter, total evaporation from the plantation declined gradually between March and June in response to reductions in available energy and senescence of undergrowth vegetation.

### **Modelled total evaporation**

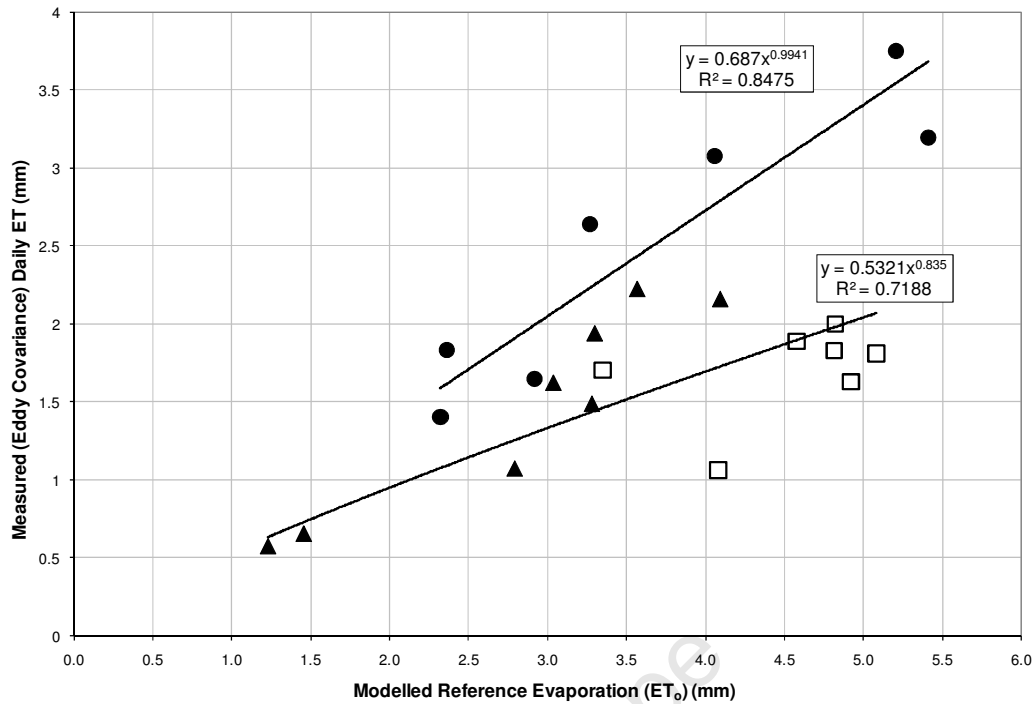
The Penman-Monteith-Granier combination method used to model total evaporation (ET) from the plantation was effective (slope = 1.0037 and R<sup>2</sup> = 0.8964) in replicating the observed values (Fig. 6.6). There were also clear correlations between observed ET and net radiation (R<sub>n</sub>) (Fig 6.7), and observed ET and Reference Evaporation (ET<sub>o</sub>) (Fig. 6.8), calculated according to Allen *et al.* (1998). In both instances there was a clear distinction between data observed in the warm wet summer period (February 2006), and the cool dry spring period (September 2005 and August 2006). The lower and flatter trend lines for the spring measurements in these figures support the conclusion that the site is an energy-limited environment.



**Figure 6.6 Relationship between measured and modelled daily ET during 22 sample days in September 2005 (□), February 2006 (●) and August 2006 (▲).**

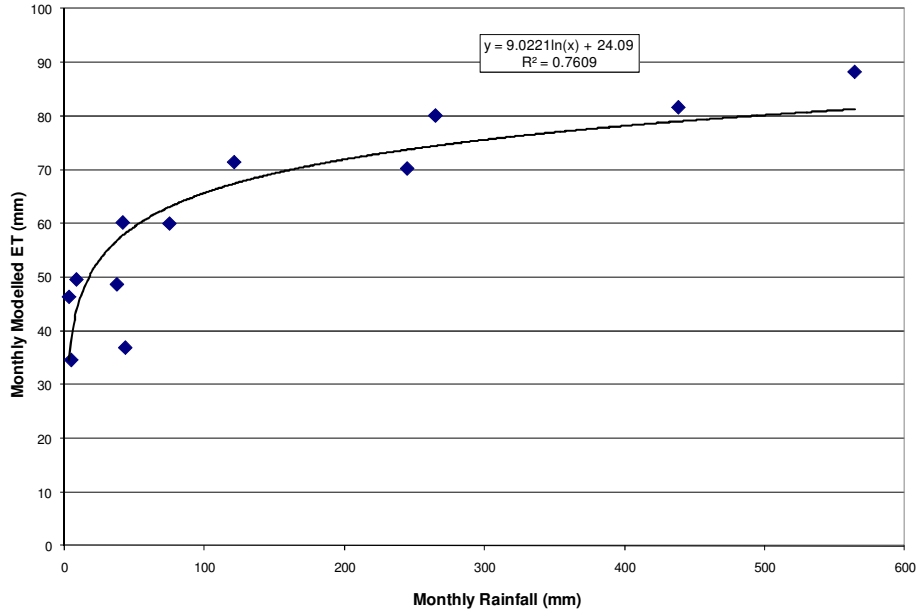


**Figure 6.7 Relationship between measured daily ET and Net Radiation ( $R_n$ ) during 22 sample days in September 2005 (□), February 2006 (●) and August 2006 (▲).**



**Figure 6.8 Relationship between measured daily ET and Reference Evaporation ( $ET_0$ ) during 22 sample days in September 2005 ( $\square$ ), February 2006 ( $\bullet$ ) and August 2006 ( $\blacktriangle$ ).**

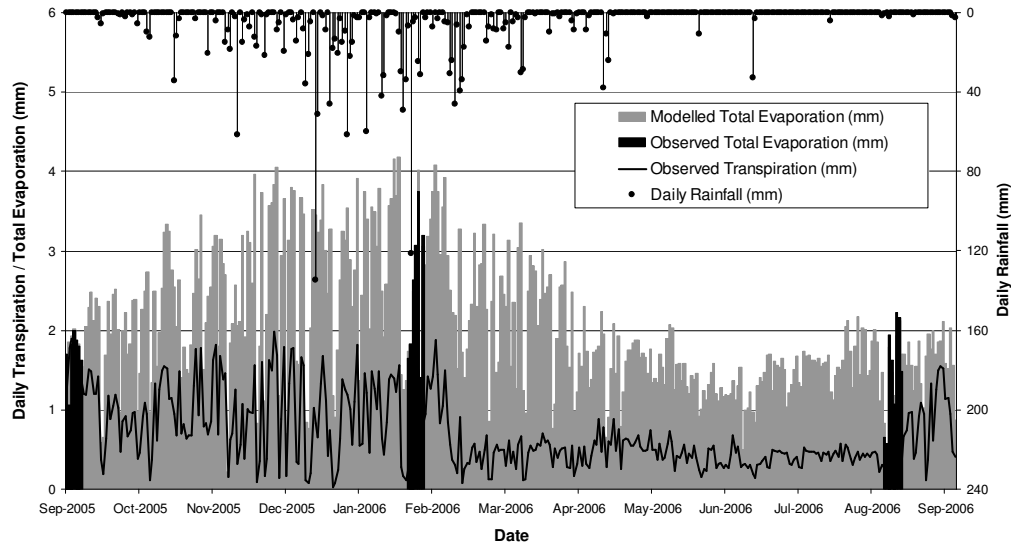
Following the extrapolation exercise modelled ET was found to range from  $0.22 \text{ mm day}^{-1}$  (November 2005) to  $4.18 \text{ mm day}^{-1}$  (February 2006), and averaged  $2.04 \text{ mm day}^{-1}$  for the year. Annual total evaporation (ET) for the *P. falcatus* plantation (trees and undergrowth) modelled in this way amounted to 743 mm, while total rainfall for the corresponding period (sourced from the South African Weather Service, Tzaneen and Woodbush stations) amounted to 1847.6 mm. When daily values of ET and rainfall were aggregated to monthly totals and regressed against each other a logarithmic relationship between the two was observed (Fig. 6.9) reflecting the overall seasonal pattern of water-use by this plantation relative to rainfall distribution through the year. However no significant relationships were observed between daily ET or Transpiration and daily rainfall, presumably as the site is riparian, with trees having access to ground-water reserves, so daily total evaporation is not limited by rainfall.



**Figure 6.9 Relationship between monthly totals of rainfall and modelled ET using the Penman-Monteith-Granier combination method.**

**Observed transpiration**

Sap flow measurements showed that the water-use of one of the larger sample trees (Tree 1) peaked at 34 L day<sup>-1</sup> (February 2006), averaged 10.5 L day<sup>-1</sup> and totalled 3808 L over the year of measurement. Daily average transpiration volumes for all the sample trees (weighted according to tree size) ranged from 0.2 to 18 L tree<sup>-1</sup> day<sup>-1</sup> (0.024 to 2 mm) in the wet growing season (October to March), and from 0.6 to 8 L tree<sup>-1</sup> day<sup>-1</sup> (0.07 to 1 mm) in the dry season (April to September), averaging 6 L tree<sup>-1</sup> day<sup>-1</sup> (0.67 mm) and totalling 2298 L tree<sup>-1</sup> over the year of measurement. Accounting for the planting density of 1111 spha this translated into total annual transpiration for the plantation (trees only) of 255 mm (Fig. 6.10).



**Figure 6.10 Relationship between measured daily ET during 22 sample days, modelled ET using the Penman-Monteith-Granier combination method, and observed daily transpiration rates. Corresponding daily rainfall totals are also illustrated.**

Tree transpiration (T), derived from sap flow measurements in the *P. falcatus* plantation accounted for a seasonally variable fraction of total evaporation (ET) from the whole plantation. The T:ET ratios varied from approximately 90% of ET in September, to approximately 20% of ET in February, averaging 33.8%. During September 2005 and September 2006, tree transpiration accounted for almost all of total plantation ET. These periods are at the end of the dry winter, and the dormant understory plants would have transpired at very low rates. The trees, however, undergo flushes of new leaf growth in the late dry season (September). The high sap flow rates recorded in the trees at this time suggest that the new leaves were transpiring at a relatively high rate, and it is likely that they were accessing ground water reserves as no significant rains had fallen by this stage. Between September 2005 and February 2006 transpiration rates never exceeded 2 mm day<sup>-1</sup> (50% of plantation ET), despite abundant available water (above-average rainfall), adequate solar radiation and high temperatures. This appears to be the maximum transpiration rate of these trees, and is evidence of their low water-use overall. Transpiration dropped off sharply from March onwards and remained consistently low throughout the dry season, averaging approximately 0.5 mm day<sup>-1</sup>.

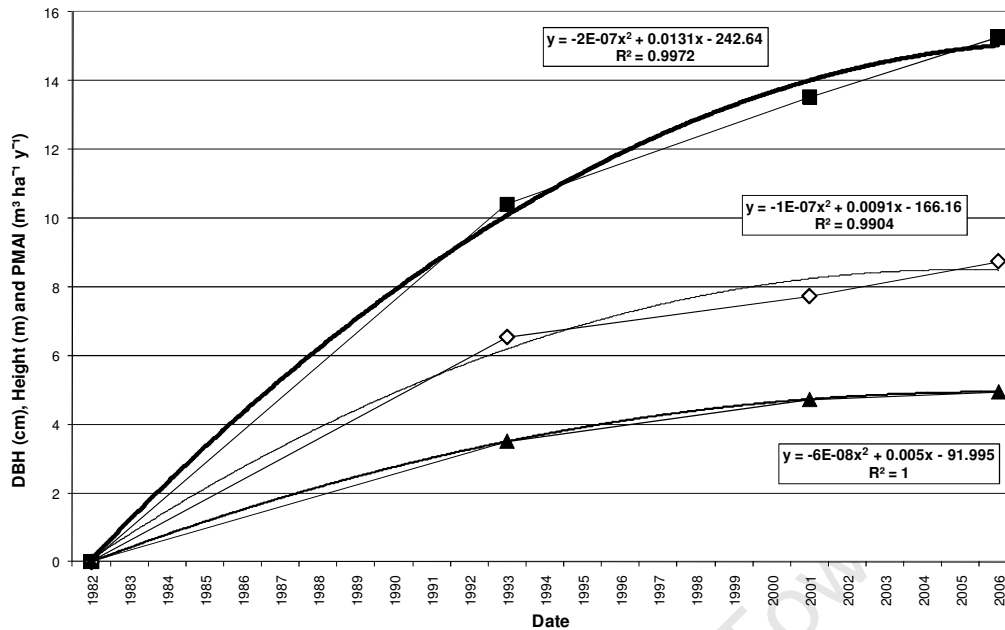
The average leaf area index (LAI) of the trees only was consistently between 2.0 and 2.5 m<sup>2</sup> m<sup>-2</sup> throughout the year, while the LAI of the under- and overstorey vegetation ranged from 2 m<sup>2</sup> m<sup>-2</sup> in the cold dry season to 4 m<sup>2</sup> m<sup>-2</sup> in the warm wet season. This emphasises the important contribution of the understorey to overall plantation leaf area and hence total evaporation. The noticeable difference between ET and T in this study is also likely to have been influenced by the high rainfall experienced (i.e. considerable evaporation of intercepted water) as well as the riparian nature of the site (i.e. considerable evaporation from the soil surface), both being sources of water that will have contributed to total evaporation but not to transpiration.

### **Tree growth and water-use efficiency**

Average tree and stand stem volumes were calculated for consecutive survey dates, together with the resultant estimates of growth rates based on the Periodic Mean Annual Increment (PMAI) of the plantation (Table 6.5). The PMAI data indicate that between 2001 and 2006 the average growth rate of the plantation was higher than between 1993 and 2001, however the trends in average tree height and DBH suggest that the growth rate of the plantation is slowing (Fig. 6.11).

**Table 6.5** Tree size data and stem volume increment estimates for respective sampling dates.

Sample Date	Tree Age (yrs)	Ave. Tree Height (m)	Ave. Tree DBH (cm)	Ave. Tree Stem Volume (m <sup>3</sup> )	Stand Stem Volume (m <sup>3</sup> ha <sup>-1</sup> )	Stand Volume Increment (m <sup>3</sup> ha <sup>-1</sup> )	PMAI (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )
Oct-82	0.0	0.00	0.0	0.000	0.00	0.00	0.00
Oct-93	11.0	6.53	10.4	0.035	38.60	38.60	3.51
May-01	18.6	7.72	13.5	0.067	74.42	35.82	4.72
Aug-06	23.9	8.73	15.3	0.091	100.69	26.27	4.94



**Figure 6.11 Relationship between observed stem diameter at breast height (■), tree height (◇) and calculated Periodic Mean Annual Increment (▲) for respective sampling periods of the *P. falcatus* plantation.**

Annual total evaporation values for the plantation modelled between September 2005 and October 2006 (743 mm) were converted to volumetric ( $7433 \text{ m}^3 \text{ ha}^{-1}$ ) and mass-based ( $7432900 \text{ kg ha}^{-1}$ ) units of water-use. These were compared against the PMAI of the plantation calculated for 2006 ( $4.94 \text{ m}^3 \text{ ha}^{-1}$ ) which was also converted to appropriate mass-based units ( $2224319 \text{ g ha}^{-1}$ ) using a wood density of  $0.45 \text{ g cm}^{-3}$ , being an average wood density value of samples from the 5 HPV trees. The resultant water-use efficiency (g stem wood produced per kg water used) of 0.299 was calculated for the plantation as a whole (trees and undergrowth). The observed annual transpiration total for the trees (255.3 mm) was then used to calculate the WUE of the trees only and was found to be 0.871 (Table 6.6).

**Table 6.6** Calculation of water-use efficiency for a *Podocarpus falcatus* plantation based on modelled total evaporation, observed transpiration and tree growth estimates between September 2005 and October 2006.

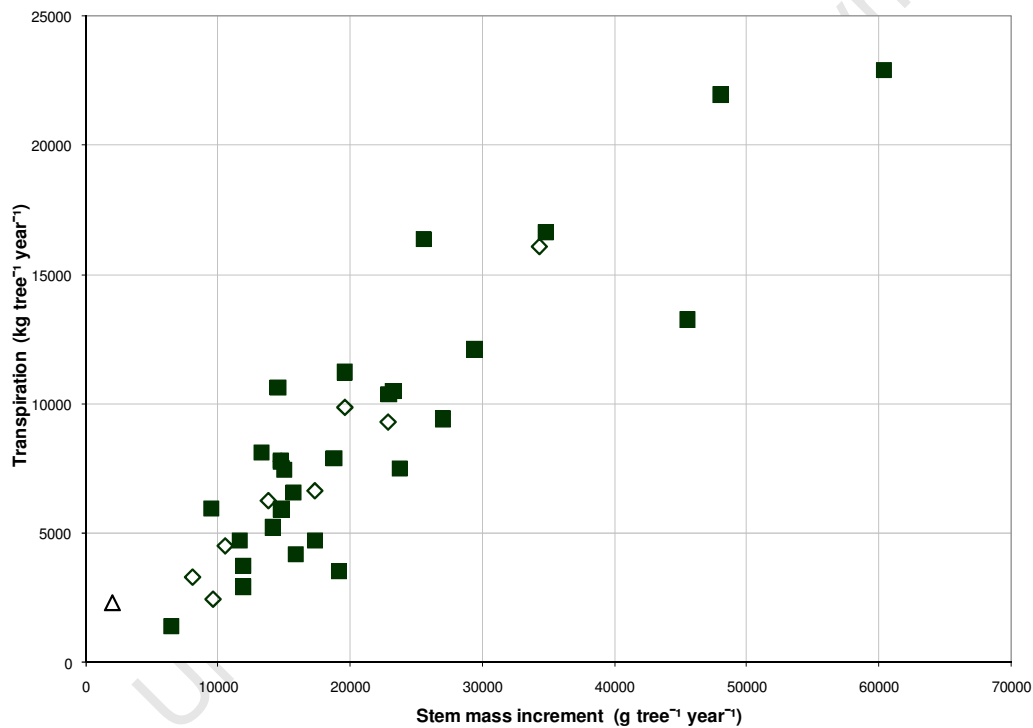
Cover	Annual Precipitation (mm)	Annual Water-use (kg.ha <sup>-1</sup> )	Periodic Mean Annual Increment (m <sup>3</sup> .ha <sup>-1</sup> )	Ave. Wood Density (g.cm <sup>-3</sup> )	Stem Mass Increment (g.ha <sup>-1</sup> )	Water-use Efficiency (g stem wood) / (kg water)
Trees & undergrowth	1848	7432900	4.94	0.45	2224319	0.299
Trees only	1848	2553000	4.94	0.45	2224319	0.871

### Discussion

The primary objective of this chapter was to test the hypothesis that an indigenous tree plantation uses less water than an introduced tree plantation. A secondary objective was to test how efficiently an indigenous tree plantation uses water (in terms of stem growth). The only comparable study found was one conducted by Fetene and Beck (2004) who compared the water-use (transpiration) of five *Podocarpus falcatus* and five *Eucalyptus globulus* (Labill.) (Tasmanian Blue Gum) trees growing in the tropical montane Munessa State Forest in Ethiopia (MAP 1250 mm). They found that *E. globulus* trees used 4-5 times more water (35 L day<sup>-1</sup>) than similarly sized (DBH 19.3 cm) *P. falcatus* trees (6 L day<sup>-1</sup>) on a particular day. These findings were confirmed in a related study by Fritzsche *et al* (2006) in the same forest. In South Africa data from several previous studies using sap flow and growth measurements on introduced *Eucalyptus* and *Pinus* spp. have been reported (Olbrich *et al.*, 1993; Olbrich *et al.*, 1996 and Dye *et al.*, 2001).

The Olbrich *et al.* (1993) study was conducted for less than a year, and emphasised the importance of a minimum measurement period of 12 months to cover all seasonal growth and water-use cycles in the year (i.e. the methodology applied in this study). Consequently only South African studies that report on actual sap flow and stem growth data collected from introduced tree species over 12-months are compared to this study. Results from three

such studies (Dye, 1996; Dye *et al.*, 1997a and Dye *et al.*, 1997b) on annual sap flow (transpiration) and annual growth increments measured in plantation-grown *Eucalyptus* and *Pinus* trees are summarised by Dye *et al.* (2001). Olbrich *et al.* (1996) report on additional data for *Pinus patula* (Schiede Schltld. & Cham.) (Mexican Weeping Pine). Observed daily transpiration rates (and growth rates) from the *P. falcatus* trees in this study are low compared to the results from Olbrich *et al.*, (1996) and Dye *et al.*, (2001), clearly illustrating that firstly, their water-use is less than that of most introduced trees sampled, but so is their growth (Fig. 6.12).



**Figure 6.12 Relationship between 1-year transpiration totals ( $\text{kg tree}^{-1} \text{ year}^{-1}$ ) and stem mass increments ( $\text{g tree}^{-1} \text{ year}^{-1}$ ) for plantation-grown Eucalypts (■) (after Dye *et al.*, 2001), Pines (◇) (Olbrich *et al.*, 1996) and *P. falcatus* (△ - this study).**

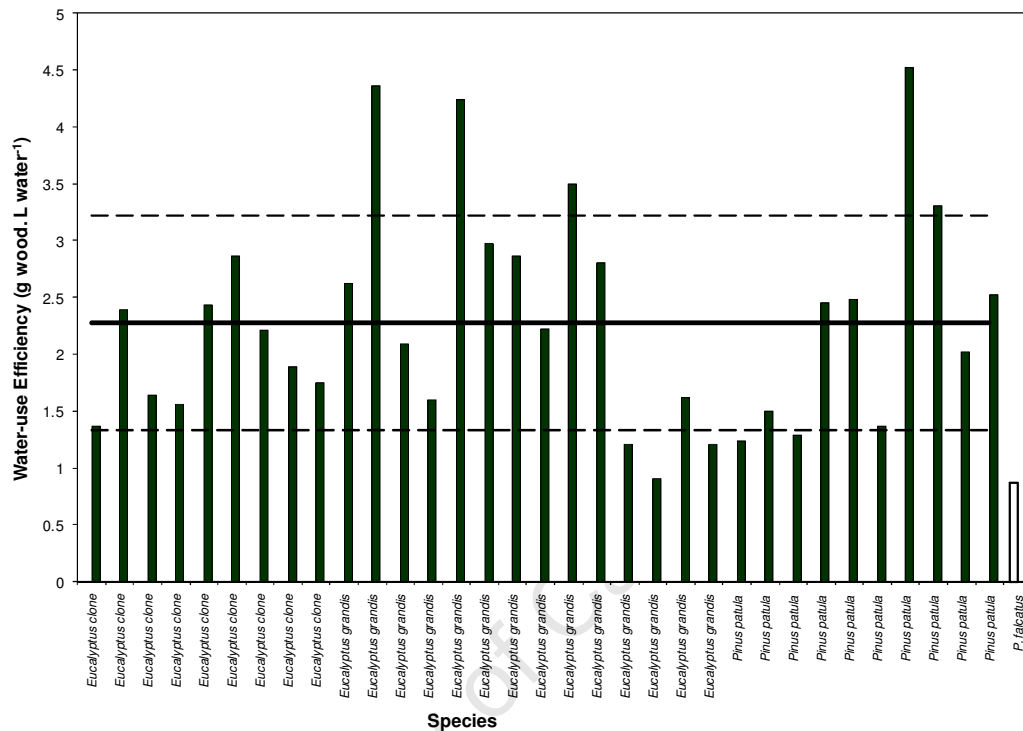
Of the data reported by Olbrich *et al.* (1996) and Dye *et al.*, (2001), 98% of the trees studied had annual water-use values exceeding those of the *P. falcatus* trees in this study, some using as much as 22 900 L  $\text{tree}^{-1} \text{ year}^{-1}$ . Wullschleger *et al.* (1998) reviewed data from 52 studies published between 1970 and 1998 that provided estimates of maximum daily whole-plant water-

use for trees growing in stands or plantations. They showed that the maximum rates of water used by several introduced plantation species of tree similar in size to the ones in this study ranged from 13 L tree<sup>-1</sup> day<sup>-1</sup> to 150 L tree<sup>-1</sup> day<sup>-1</sup>, significantly more than the average 6 L tree<sup>-1</sup> day<sup>-1</sup> for these *P. falcatus* trees.

A possible explanation for the conservative water-use of these *P. falcatus* trees compared to Eucalyptus species is that the tracheids, which conduct water in gymnosperms (e.g. *P. falcatus*), are believed to conduct at slower velocities than vessel elements, which are characteristic of angiosperms (e.g. Eucalyptus) (Tyree and Zimmerman, 2002; Becker, 1999). This is because gymnosperm tracheids and pit pores are much smaller in diameter than angiosperm vessels with bordered pits, and water flowing from tracheid to tracheid must also pass through pit membranes. Based on the sap flow data from Olbrich *et al.* (1996) and Dye *et al.*, (2001) this appears to hold true as the angiosperm Eucalypts show considerably higher water-use rates compared to the gymnosperm Pines (Fig. 6.12). The question then arises, how does the water-use of indigenous gymnosperms compare against an introduced gymnosperm? In this regard the data show that water-use is higher for the introduced gymnosperm pines. This finding is corroborated by similar results obtained by Licata *et al.* (2008) amongst gymnosperms in Patagonia, Argentina. They found that introduced *Pinus ponderosa* (Doug. ex. Laws) (Ponderosa Pine) used significantly more water than indigenous *Austrocedrus chilensis* (D. Don) Pic. Serm. et Bizzarri (Cordilleran Cypress).

The data from Olbrich *et al.*, (1996) and Dye *et al.*, (2001) may also be represented in terms of WUE. The calculated water-use efficiency of the *P. falcatus* plantation (trees only) is low compared to the results for introduced plantations (Fig. 6.13). The total evaporation measurements in the *P. falcatus* plantation, and subsequent modelling exercise showed that the increased water used by the undergrowth lowered the WUE of this indigenous plantation even further (see Table 6.6). This highlights the need for adequate control of understorey vegetation within plantations in order to improve WUE. Kagawa *et al.* (2009) also found that, while overall water-use of a native tropical forest in

Hawaii was considerably (three to nine times) lower than neighbouring introduced timber plantations, the understorey ferns in the native forest accounted for 70% of the water used by that forest.



**Figure 6.13** Water-use efficiency (g utilizable stem mass per kg of water transpired) recorded in a variety of introduced *E. grandis* and *P. patula* plantations in South Africa (■) (Olbrich et al., 1996; Dye et al., 2001) and an indigenous *P. falcatus* plantation (□ – this study). The mean (—) and standard deviation (---) for the introduced trees are indicated.

In conclusion, the hypothesis that the water-use of *P. falcatus* trees in a plantation is less than that of introduced tree species (Pines or Eucalypts) of similar size is supported by the results. However, indigenous *P. falcatus* trees do not use water more efficiently than introduced tree species because, while their water-use is less, their growth rates are proportionally even lower.

# Chapter 7

## **THE WATER-USE EFFICIENCY OF SELECTED INDIVIDUAL INDIGENOUS TREE SPECIES**

### **Introduction**

It has been proposed that the efficiency of resource use within forests (including water-use efficiency) tends to increase as forests increase their productivity and rate of resource use (Binkley *et al.*, 2004). This hypothesis has been tested and supported by various studies including Gyenge *et al.* (2008), who showed that the water-use efficiency (WUE) of a mixed species native forest (less productive system) was below that of an introduced *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) plantation (more productive system), both growing in the same area in Patagonia, Argentina. So while more productive systems (introduced plantations) appear to use water more efficiently than less productive systems (indigenous trees and natural forests), a number of recent studies have supported the notion that the former also use more water than the latter (Fetene and Beck, 2004; McJannet *et al.*, 2007; Licata *et al.*, 2008; Whitley *et al.*, 2008; Dierick and Hölscher, 2009; Kagawa *et al.*, 2009; Little *et al.*, 2009). Binkley *et al.* (2004) showed that an increase in water-use could also increase the efficiency of water use by increasing the “return on investment” of growing the canopy. In other words, more productive forest systems tend to use more water, but they also tend to use water more efficiently.

Water yield from catchments is a major ecosystem service for human activities but has been dramatically altered by landscape changes (van Wilgen *et al.*, 2008). This is of particular relevance in South Africa, where introduced plantation forestry is an extensive and profitable land use in many of the high-rainfall regions of the country (Chamberlain *et al.*, 2005; FSA, 2010), but is now restricted in certain areas because of the high water-use of commercial

plantations and their detrimental impact on catchment water yields (Farley *et al.*, 2005; Dye and Versfeld, 2007). The importance of further research on the water-use of indigenous tree species is supported by observations that increases in introduced tree plantations with simultaneous decreases in indigenous vegetation result in overall decreases in streamflow (Little *et al.*, 2009). This is well documented for scrubland in subhumid conditions (Huber *et al.*, 2008); however, comparative data on the water use of introduced and indigenous trees is scarce, particularly in South Africa. There is a largely unsubstantiated belief that they use less water than introduced plantation species and therefore have significantly less impact on catchment water yields (Wilson, 1982; Cooper, 1985; Cawe and McKenzie, 1989).

Indigenous trees also generally exhibit much slower growth rates than introduced plantation species which are selected and bred for fast above-ground growth (Keet, 1962; Coates-Palgrave, 1984; Geldenhuys and von dem Bussche, 1997). Average growth rates within plantations of introduced tree species (Pines and Eucalyptus) in South Africa are currently in the order of 15 m<sup>3</sup>/ha/yr (FSA, 2010), while growth rates of indigenous tree species in evergreen forest are typically in the region of 2 m<sup>3</sup>/ha/yr (van Daalen, 1991), increasing to 4.34 m<sup>3</sup>/ha/yr within a formal *Podocarpus falcatus* (Thunb.) R.Br. ex Mirb. plantation (Geldenhuys and von dem Bussche, 1997). Measurements on indigenous tree species report annual radial increments of just 3 mm for *Colophospermum mopani* Kirk ex J. Léonhard (Kirk ex Benth) (February *et al.*, 2007), 3.2 mm for *Widdringtonia cedarbergensis* Marsh (February *et al.*, 2007), and mean annual diameter increments of 4.5 mm for *Pterocarpus angolensis* D.C. (Shackleton, 2002).

Land-use and forest cover change play important roles in socio-economic processes and are closely linked with water supply and other ecosystem services (Little *et al.*, 2009). Improved information on the growth, water-use and WUE of indigenous trees consequently has the potential to inform policy and decision-making regarding forest and land-use planning. In this chapter I use the argument of Binkley *et al.* (2004), i.e. that more productive sites (plantations of introduced trees) tend to have higher efficiencies of resource

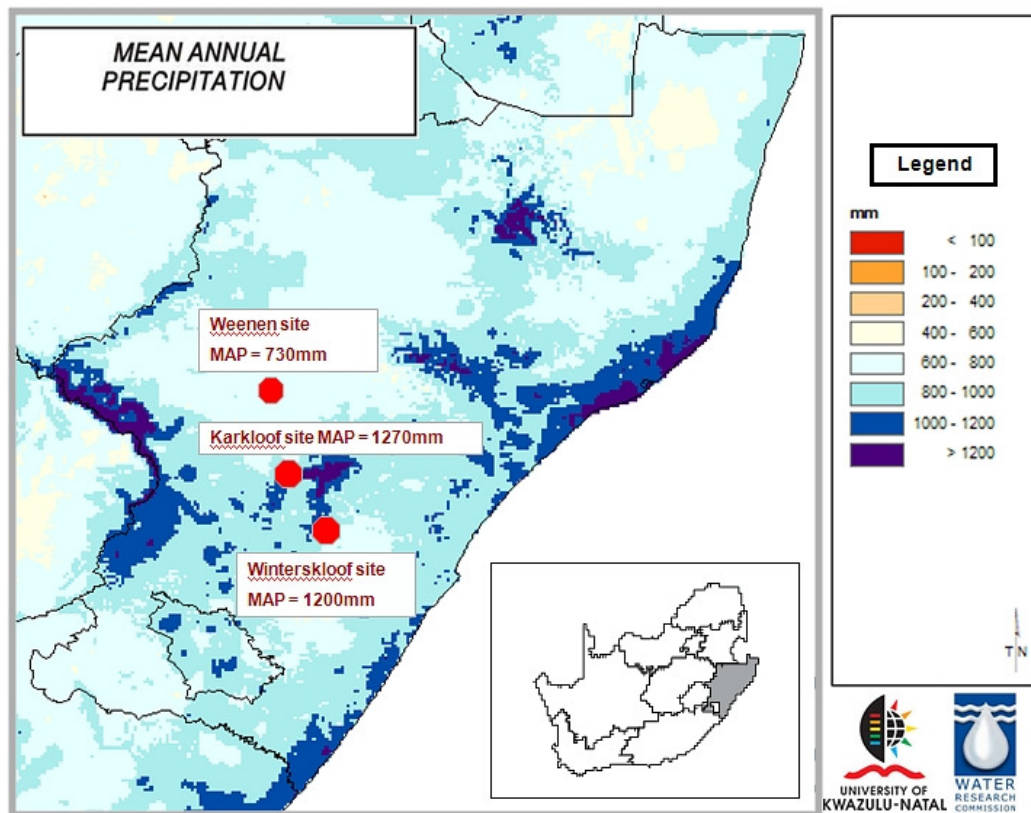
use than less productive sites (single indigenous trees), to suggest that the WUE of indigenous tree species is below that of introduced tree species. I test this hypothesis through measurements of the water-use, growth and resultant WUE of a selection of individual indigenous tree species in South Africa, and compare the results to data available on introduced plantation species (Olbrich *et al.*, 1996; Dye *et al.*, 2001). There is a great diversity of indigenous tree species in South Africa, whose potential, particularly in terms of low water-using alternatives to introduced tree plantations, has not been investigated. In this exploratory study I sample a diverse variety of indigenous tree species, to improve understanding of the potential range of water-use, growth and resultant WUE.

## **Methods**

### **Site and species selection**

The sampling procedure was to select indigenous tree species that showed a wide range of characteristics i.e. that were fast and slow growing, evergreen and deciduous, pioneer vs. late succession species, while also having some commercial potential (e.g. valuable timber). Due to the scarcity of monoculture plantations of indigenous trees in South Africa, the work was conducted on single specimens of various indigenous tree species that possessed well-formed canopies and were well exposed to sunlight. Naturally occurring trees of similar size to mid-rotation (4-6 year old) trees in an introduced plantation were selected under what could be considered optimum conditions (i.e. limited competition for water and light). The rationale behind this was to determine their water-use under non-limiting conditions in order to explore the upper limits of indigenous tree water-use and growth. In addition, indigenous species were selected from a range of climatic zones (from wet to dry), again to explore the range of WUE possible across species and sites. Trees were subsequently monitored at three sites in the KwaZulu-Natal province of eastern South Africa, in the summer-rainfall region of the country

(Fig. 7.1). The sites were Winterskloof, Karkloof and two sites at Weenen, namely a valley site and a higher-altitude plateau site.



**Figure 7.1** Locations of the single-tree study sites relative to the distribution of Mean Annual Precipitation across South Africa (from Lynch and Schulze, 2006).

The Winterskloof site ( $29^{\circ} 35.0' S$ ;  $30^{\circ} 17.926' E$ ", alt. 1051 m.a.m.s.l) is classified by Mucina and Rutherford (2006) as transitional between Southern Mistbelt Forest within a broader landscape of Midlands Mistbelt Grassland. It is within a suburban residential area and is consequently largely transformed, being dominated by a wide variety of planted indigenous and introduced tree species. However naturally occurring indigenous trees species are still common and include *Celtis africana* (Burm.) F. (White Stinkwood), *Halleria lucida* (L.) (Tree Fuchsia), *Cussonia spicata* (Thunb.) (Common Cabbage Tree) and *Ficus natalensis* (Hochst.) (Natal Fig). It is an area experiencing frequent wet season mists, with a Mean Annual Precipitation (MAP) of 1 207 mm (Lynch and Schulze, 2006) and a Mean Maximum Temperature of  $24^{\circ} C$

(Schulze and Maharaj, 2007). The tree chosen for analysis here was a single indigenous *Trema orientalis* (L.) Blume (Pigeonwood).

The Karkloof site (29° 18.230' S; 30° 13.699' E, alt. 1253 m.a.m.s.l), originally described by Rycroft (1944), is classified by Mucina and Rutherford (2006) as Southern Mistbelt Forest. The dominant woody species include *Podocarpus falcatus* (Outeniqua Yellowwood), *Celtis africana*, *Ptaeroxylon obliquum* (Thunb.) Radlk. (Sneezewood) and *Calodendrum capense* (L.f.) Thunb. (Cape Chestnut). Mean Annual Precipitation for this site is 1 273 mm (Lynch and Schulze, 2006), with a mean maximum temperature of 23 °C (Schulze and Maharaj, 2007). The site experiences a strong orographic effect, caused by the lifting (and convective cooling) of the south-east winds over the Karkloof mountain range during the wet season and, as it lies within the mist belt, is subject to heavy soaking mists during this season. By virtue of its south-easterly aspect, the forest is sheltered from the hot, dry “bergwinds” of the dry winter period (Taylor, 1961). Measurements at this site were conducted on three indigenous trees, namely *Celtis africana*, *Podocarpus falcatus* and *Ptaeroxylon obliquum*. The trees were approximately 20 m apart from each other, in line, on a gently sloping valley-bottom site. The site was non-riparian although there was a stream approximately 70 m away. The site appeared to have been cleared of alien invasive plants within the last few years as there was evidence of *Eucalyptus* stumps and logs still evident at the time that monitoring commenced. The site was consequently in the process of being re-colonised by indigenous species as a result of the removal of the eucalypts.

At Weenen, the valley-bottom site (28° 50.842' S; 30° 01.549' E, alt. 1010 m.a.m.s.l) is classified by Mucina and Rutherford (2006) as Thukela Thornveld, and is situated on a steep, warm, north-facing slope, with shallow and extremely rocky soils of the Mispah<sup>1</sup> form, approximately 50 m upslope from an ephemeral stream. Trees are abundant and the dominant species are *Acacia karroo* (Hayne) (Sweet Thorn), *Cussonia paniculata* (Eckl. & Zeyh.) (Mountain Cabbage Tree), *Euphorbia ingens* (E.Mey. ex Boiss.) (Common

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<sup>1</sup> According to Fey (2010) USDA classification of this South African soil forms is Orthic (Mispah).

Tree Euphorbia), *Olea europaea* (L.) subsp. *africana* (Mill.) P.S.Green (Wild Olive) and *Ziziphus mucronata* (Willd.) (Buffalo Thorn). The higher-altitude plateau site (28° 52.613' S; 30° 01.857' E, alt. 1241 m.a.m.s.l) is classified by Mucina and Rutherford (2006) as KwaZulu-Natal Highland Thornveld. It is characterized by open grassland savanna dominated by *Acacia sieberiana* (DC.) var. *woodii* (Burt Davy) Keay & Brenan (Paperbark Thorn) growing on shallow and stony Mispah (Orthic) soils. The MAP for the Weenen area is 730 mm (Lynch and Schulze, 2006) and Mean Maximum Temperature is 27.3 °C (Schulze and Maharaj, 2007). The trees chosen for analysis were an indigenous *Olea europaea* subsp. *africana* at the valley site and an indigenous *Berchemia zeyheri* (Sond.) Grubov. (Red Ivory) tree at the plateau site. Measurements at all the sites were conducted for a minimum of 12 months (14 Feb 2007 to 13 Feb 2008) to incorporate seasonal variations in, and responses to, climate.

### **Tree characteristics**

Tree heights and stem diameters (Table 7.1) were measured at the start and end of the monitoring period using extendable height rods and a tape measure. Canopy dimensions were determined by measuring canopy height and diameter, and calculating the resultant canopy cross-sectional areas for the individual trees. Leaf area index (LAI) fluctuations in the sample trees were recorded with a LI-COR LAI2000 Plant Canopy Analyser (LI-COR, Lincoln, Nebraska) using procedures similar to those reported by Cutini *et al.* (1998). Essentially, the monthly LAI readings were obtained from measurements above and below the canopies of the respective sample trees. The above canopy readings were taken in large clearings or open areas in the vicinity of the sample trees, while the below canopy readings were recorded at four positions around the base of each sample tree. The lens of the LAI2000 was covered by a cap with a 90° opening, to limit interference from surrounding areas and the operator (Li-Cor, 1991). All below-canopy measurements were taken at a standard height (0.5m above ground) so that the instrument was positioned below the leaves of the canopy but above any undergrowth

beneath the trees. Efforts were taken to conduct measurements under condition of diffuse light (early morning or late afternoon or during overcast days). Final LAI estimates were computed by the software within the instrument (Li-Cor, 1991). Monthly variation in total canopy tree leaf area ( $m^2$ ) was estimated by multiplying the monthly LAI value for each sample trees by the canopy cross-sectional area of that tree.

Bark thickness of the sample trees was determined by excising small sections of bark from the tree stems using a sharp knife, and measuring the cross-sectional depth to the nearest mm. Measurements of sapwood depth, required to determine the insertion depths of thermocouple probes for water-use measurements, were obtained using an 8 mm inside-diameter increment corer (Haglöf, Sweden). Cores were subsequently analysed for sapwood depth using the visual distinction between lighter coloured sapwood and darker coloured heartwood and /or by staining with Methyl Orange. However, despite staining, the sapwood of certain species (*Trema orientalis*, *Celtis africana* and *Podocarpus falcatus*) was still not readily discernable from the heartwood and was assumed to extend to within 10mm of the centre of the stem. Subsequent heat pulse velocity data obtained from the deepest insertion depths confirmed this assumption.

Basic wood density for the different tree species was determined according to TAPPI Test Method T258-om-94 (TAPPI, 1994). In accordance with this method the basic density of each segment was determined on the basis of its green volume as determined by water displacement and its oven-dry mass. Two small stem-wood samples chiselled from the trees were used for determining the basic wood density of each species. After soaking the samples in water for an hour to allow rehydration, the samples were impaled with a needle and fully submerged in a beaker of water placed on a previously zeroed electronic balance. The measured weight of displaced water, being equal to the volume of the sample (i.e.  $1\text{ g} = 1\text{ cm}^3$ ), was recorded as the green volume. The samples were subsequently oven-dried at  $105\text{ }^\circ\text{C}$  for 24 hours to determine dry mass. Basic density ( $\text{g}\cdot\text{cm}^{-3}$ ) was calculated by dividing dry mass by green volume (Table 7.1).

**Table 7.1** Sample tree details.

Tree Species	Site	Tree Height (m)	Crown diameter (m)	Max (wet season) leaf area (m <sup>2</sup> )	Diameter at breast height (cm)	Bark thickness (mm)	Sapwood depth (mm)	TC insertion depths (mm, below surface)	Wood Density (g cm <sup>-3</sup> )
<i>Trema orientalis</i>	W'kloof	5.65	5.41	32.2	15.92	6	65	8, 20, 30 and 40	0.422
<i>Celtis africana</i>	Karkloof	6.45	4.77	39.4	19.48	4	79	6, 27, 48 and 65	0.605
<i>Podocarpus falcatus</i>	Karkloof	6.10	3.50	35.9	21.04	7	95	15, 28, 48 and 70	0.468
<i>Ptaeroxylon obliquum</i>	Karkloof	5.16	2.71	19.0	13.34	3	35	8, 20, 30 and 40	0.716
<i>Olea europaea</i> subsp. <i>africana</i>	Weenen	5.00	3.82	14.9	13.37	3	40	8, 20, 33 and 45	0.916
<i>Berchemia zeyheri</i>	Weenen	5.43	5.09	59.1	21.31	5	30	10, 16, 22 and 23	0.807

### **Sap flow measurements**

The heat ratio method (HRM) of the heat pulse velocity (HPV) technique (Burgess *et al.*, 2001) was selected for sap flow measurements because of its ability to accurately measure low rates of sap flow, expected to be the case in indigenous tree species. I provide a detailed explanation of this method in Chapter 5, but in brief the HRM requires a line-heater to be inserted in the xylem at the midpoint (commonly 5 mm) between two temperature sensors (thermocouples). Heat pulses are used as a tracer, carried by the flow of sap up the stem. This allows the velocity of individual heat pulses to be determined by recording the ratio of the increase in temperature measured by the thermocouples, following the release of a pulse of heat by the line heater.

For these measurements thermocouple (TC) pairs and heater probes were positioned 80 cm up the main stem of each tree, below the first branches. TCs were inserted to four different depths within the sapwood (Table 7.1), to determine radial variations in sap flow. Insertion depths of the TCs were calculated after first determining the total sapwood depth for each species, and then spacing the probes evenly throughout. To account for radial growth in stems the TCs were completely removed and repositioned to their correct depths at the start of the growing season (October), and then rechecked periodically during the course of the monitoring period. CR10X data loggers connected to AM16/32 multiplexers (Campbell Scientific, Logan, UT) were programmed to initiate the heat pulses and record hourly data from the respective TC pairs. Cellular phone modems connected to the loggers allowed remote downloading of data.

Heat pulse velocities derived using the HRM were corrected for sapwood wounding caused by the drilling procedure, using wound correction coefficients described by Swanson and Whitfield (1981). The corrected heat pulse velocities were then converted to sap flux densities by accounting for wood density and sapwood moisture content (Marshall, 1958). Finally, the sap flux densities were converted to whole-tree total sap flow by calculating the

sum of the products of sap flux density and cross-sectional area for individual tree stem annuli (determined by below-bark TC insertion depths and sapwood depth). Hourly sap flow values were recorded from all the trees. Periods of missing data were patched and the complete record was aggregated into daily, monthly and annual totals of transpiration (water-use). Simultaneous measurements of certain meteorological variables (rainfall, solar radiation, air temperature and relative humidity) and soil water content in the top 10 cm of the soil profile, took place hourly at all sites for the corresponding period.

**Tree growth measurements and water-use efficiency**

Stem and branch biomass increment surveys were conducted on all the sample trees in conjunction with sap flow measurements. Initial biomass determination was carried out shortly after the individual trees had been instrumented with the HPV systems, and the final surveys were performed one year thereafter to incorporate seasonal variation in both water-use and growth. Stem diameters at increasing heights up the tree, as well as branch lengths and diameters (at their base) were measured. These measurements were converted to volumes by assuming that the stem consisted of a series of truncated cones with a complete cone at the top, while the branches consisted of individual elongated cones. The volumes of individual cones  $V$  (m<sup>3</sup>) were calculated using (Eq. 7.1):

$$V = (\pi r^2 h) / 3. \tag{7.1}$$

where  $r$  is radius of the base of the cone (m), and  $h$  is height of the cone (m). The volumes of the truncated cones were calculated using (Eq. 7.2):

$$V = (\pi h (r_1^2 + r_1 r_2 + r_2^2)) / 3 \tag{7.2}$$

where  $r_1$  is radius of the base of the truncated cone (m),  $r_2$  is radius of the top of the truncated cone (m), and  $h$  is height of the truncated cone (m).

The individual stem section volumes and branch volumes were totalled for each tree. This allowed for the calculation of stem, branch and total above-ground volume growth increase in the year. In conjunction with the sap flow (water-use) results this allowed the calculation of WUE, defined as amount of woody biomass produced ( $\text{m}^3$ ) per unit of water transpired ( $\text{m}^3$ ). Two separate calculations of WUE were conducted, firstly utilising stem volume increments only, and secondly utilising stem plus branch volume increments, both being relative to whole tree water-use. Biomass increments were converted from volume to mass using wood densities determined for each species (Table 7.1), and results were compared against data for introduced plantation species available from previous studies (Olbrich *et al.*, 1996; Dye *et al.*, 2001).

## **Results**

### **Weather**

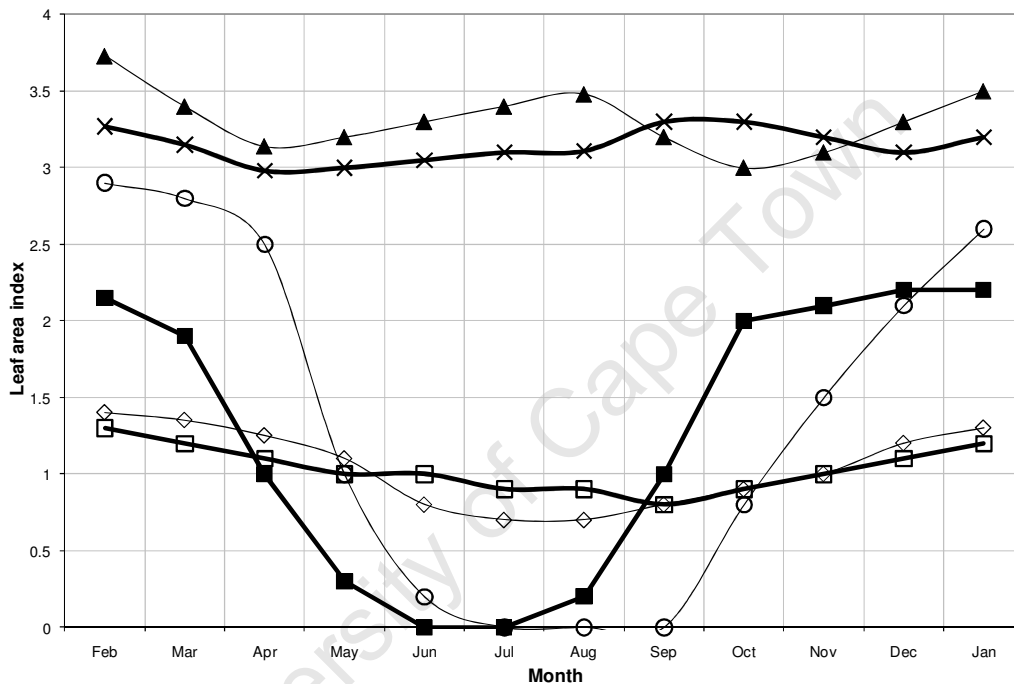
In general, the weather conditions at the three sites exhibited the seasonal patterns typical of the respective areas (Table 7.2). Total rainfall for the monitoring year (14 Feb 2007 to 13 Feb 2008) was 23% above the long-term mean at Winterskloof (1 481 mm), 11.2% below the mean at Karkloof (1 130 mm) and 13% below the mean at Weenen (637 mm). Temperatures were typical of long-term averages. Compared to the other two sites, the significantly hotter and drier climate experienced at the Weenen site is evident from the weather data for the respective sites (Table 7.2). The mean daily maximum temperature at Weenen (27.3 °C) was 3.6 °C warmer than Winterskloof and 4.5 °C warmer than Karkloof, however the mean daily minimum temperatures were similar at all sites (within 2 °C). Compared to Winterskloof and Karkloof, Weenen exhibited greater extremes in weather conditions with mean daily temperatures dropping from a peak of 33.6 °C in February to 4.7 °C in July (a range of 28.9 °C). Summers to winter temperature ranges at the other sites were 19.4 °C at Winterskloof and 20.8 °C at Karkloof.

**Table 7.2 Monthly values of meteorological variables, recorded between February 2007 and January 2008, at the respective study sites.**

Month	Winterskloof Site					Karkloof Site					Weenen Site			
	Total monthly rainfall (mm)	Mean daily max temp. (°C)	Mean daily min temp. (°C)	Mean daily solar rad. (MJ m <sup>-2</sup> day <sup>-1</sup> )		Total monthly rainfall (mm)	Mean daily max temp. (°C)	Mean daily min temp. (°C)	Mean daily solar rad. (MJ m <sup>-2</sup> day <sup>-1</sup> )		Total monthly rainfall (mm)	Mean daily max temp. (°C)	Mean daily min temp. (°C)	Mean daily solar rad. (MJ m <sup>-2</sup> day <sup>-1</sup> )
Feb'07	64.0	28.3	17.0	16.0		64.0	27.1	15.5	20.1		41.0	33.6	17.0	23.2
Mar'07	193.5	25.1	15.2	15.0		193.5	24.4	13.4	15.5		61.4	29.9	15.4	17.7
Apr'07	82.5	23.6	12.9	13.5		18.0	22.3	11.1	12.0		26.9	27.5	12.5	14.9
May'07	5.0	24.3	11.8	13.4		1.2	21.9	6.7	12.5		0.0	25.7	7.1	14.7
Jun'07	40.0	20.6	9.0	10.5		42.9	19.3	6.9	10.2		28.0	21.6	5.6	12.1
July'07	0.0	22.1	8.9	12.7		0.1	21.1	6.3	12.0		0.1	22.7	4.7	14.2
Aug'07	23.0	23.4	9.6	12.6		18.9	21.7	6.3	11.1		1.3	25.5	7.0	15.9
Sep'07	68.0	24.3	12.8	11.8		60.6	24.3	10.9	11.8		13.0	29.5	12.9	16.6
Oct'07	256.5	21.0	12.2	11.0		237.6	20.5	10.8	10.8		125.9	24.7	12.9	14.8
Nov'07	285.5	22.5	13.4	13.6		160.8	22.7	12.4	14.0		92.2	27.7	14.4	19.3
Dec'07	175.0	24.0	14.7	16.2		136.6	23.8	13.4	15.7		100.5	29.1	15.1	22.6
Jan'08	287.5	25.1	16.1	14.6		196.1	24.3	14.6	11.8		146.6	29.9	16.4	21.9
<b>Tot / Ave</b>	<b>1480.5</b>	<b>23.69</b>	<b>12.8</b>	<b>13.41</b>		<b>1130.3</b>	<b>22.78</b>	<b>10.69</b>	<b>13.13</b>		<b>636.9</b>	<b>27.28</b>	<b>11.75</b>	<b>17.33</b>

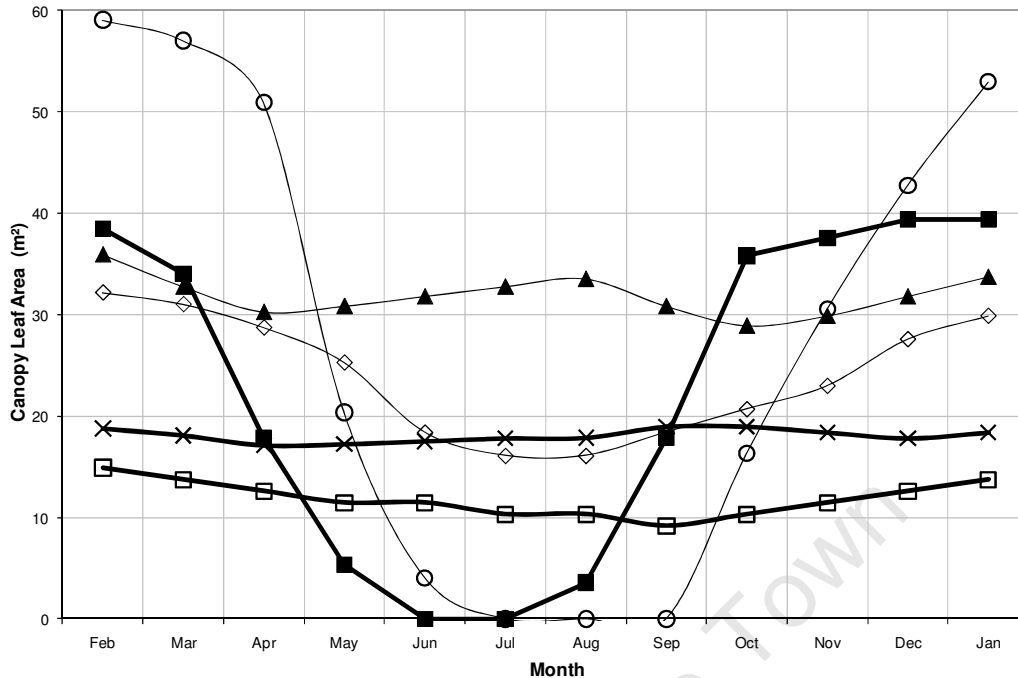
### Canopy leaf area and leaf area index

Monthly changes in leaf area index (LAI) of the sample trees (Fig. 7.2) illustrate the evergreen nature of some species (*P. falcatus*; *P. obliquum*; *O. europaea* subsp. *africana*; *T. orientalis*) and the deciduous nature of others (*C. africana*; *B. zeyheri*).



**Figure 7.2** Monthly leaf area index (LAI) changes recorded in a *Trema orientalis* (◇), a *Celtis africana* (■), a *Podocarpus falcatus* (▲), a *Ptaeroxylon obliquum* (X), an *Olea europaea* subsp. *africana* (□) and a *Berchemia zeyheri* (○) tree.

Consistently high leaf densities in the canopies of the *Podocarpus* and *Ptaeroxylon* trees resulted in maximum LAI values of between 3 and 3.5. These were more than double those recorded in the *Olea* and *Trema* trees. Multiplying monthly LAI values by observed canopy cross-sectional areas, provided rough estimates of changes in total canopy leaf area for the respective sample trees over the study period (Fig. 7.3).

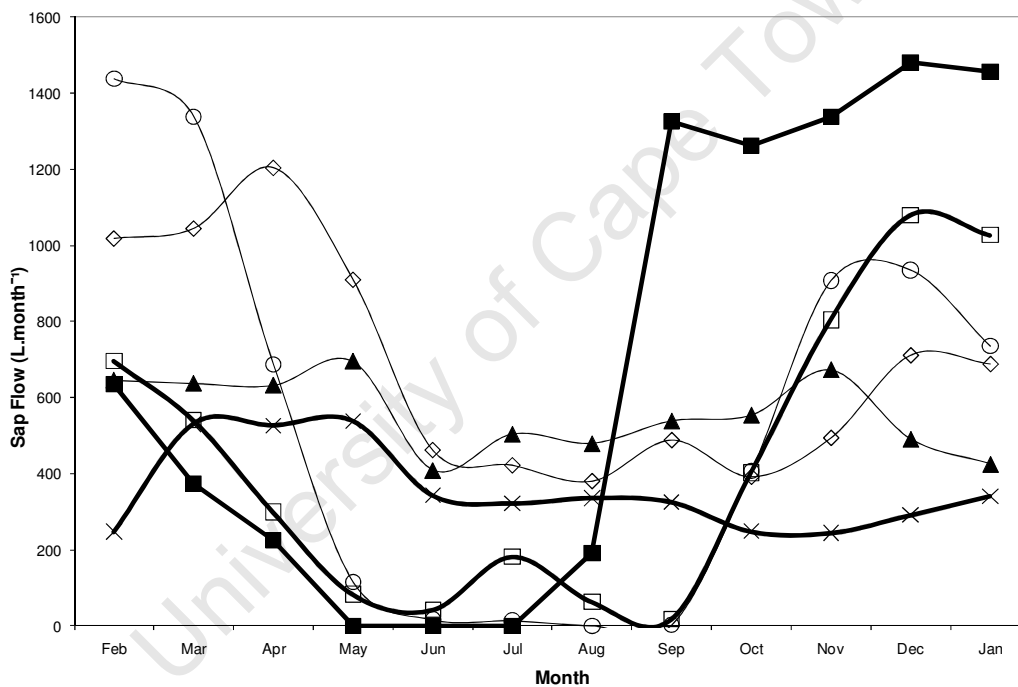


**Figure 7.3** Monthly changes in canopy leaf area calculated from leaf area index and canopy dimensions in a *Trema orientalis* (◇), a *Celtis africana* (■), a *Podocarpus falcatus* (▲), a *Ptaeroxylon obliquum* (X), an *Olea europaea subsp. africana* (□) and a *Berchemia zeyheri* (○) tree.

### Observed transpiration

Sap flow (water-use) volumes for most of the species peaked during the warm wet summer months, and declined in the cool, dry winter months (Fig. 7.4). This is intuitive considering seasonal fluctuations in available moisture and energy. Seasonal water-use trends were most distinct in the fully-deciduous species (*C. africana* and *B. zeyheri*). Of all the trees sampled, the highest sap flow volumes (approximately 100 L day<sup>-1</sup>) were recorded during the wet summer season in these two species, dropping to zero during the leafless dry winter months (Fig. 7.5 and 7.6). Over the common monitoring period (14 February 2007 to 13 February 2008) the *C. africana* averaged 23.0 ± 25.91 L day<sup>-1</sup> and totalled 8396 L annum<sup>-1</sup>, while the *B. zeyheri* averaged 16.72 ± 17.79 L day<sup>-1</sup> and totalled 6103 L annum<sup>-1</sup>. The onset of sap flow at the end of

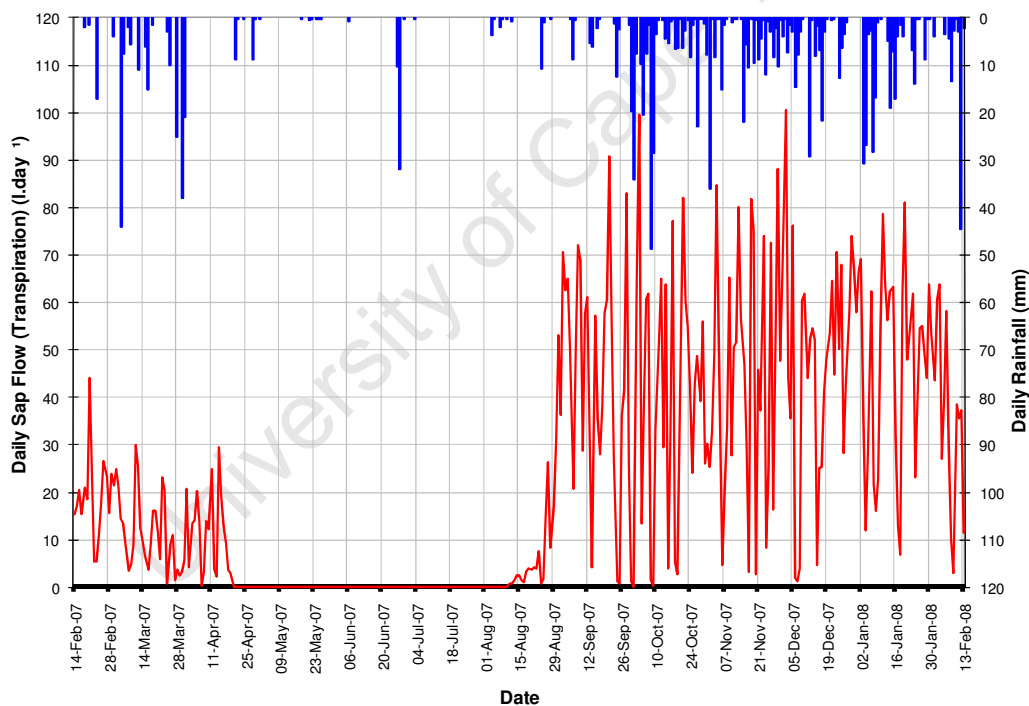
the dry season was a month and a half later for the *B. zeyheri* than for the *C. africana* due to the fact that the first rains fell later (end of September) at the Weenen site compared to early August at the Karkloof site. Interestingly, although *C. africana* is a deciduous species, it had the highest 1-year sap flow total of all the sample trees (Table 7.3). The *P. falcatus* and *P. obliquum* trees, on the other hand, showed far more conservative and consistent sap flow volumes throughout the year, with far less seasonal variation (Fig. 7.7 and 7.8). *P. falcatus* water-use averaged  $18.0 \pm 12.04 \text{ L day}^{-1}$  and totalled  $6571 \text{ L annum}^{-1}$ , while the *P. obliquum* had the lowest water-use of all trees sampled at an average of  $12.11 \pm 7.07 \text{ L day}^{-1}$  and a total of  $4407 \text{ L annum}^{-1}$ .



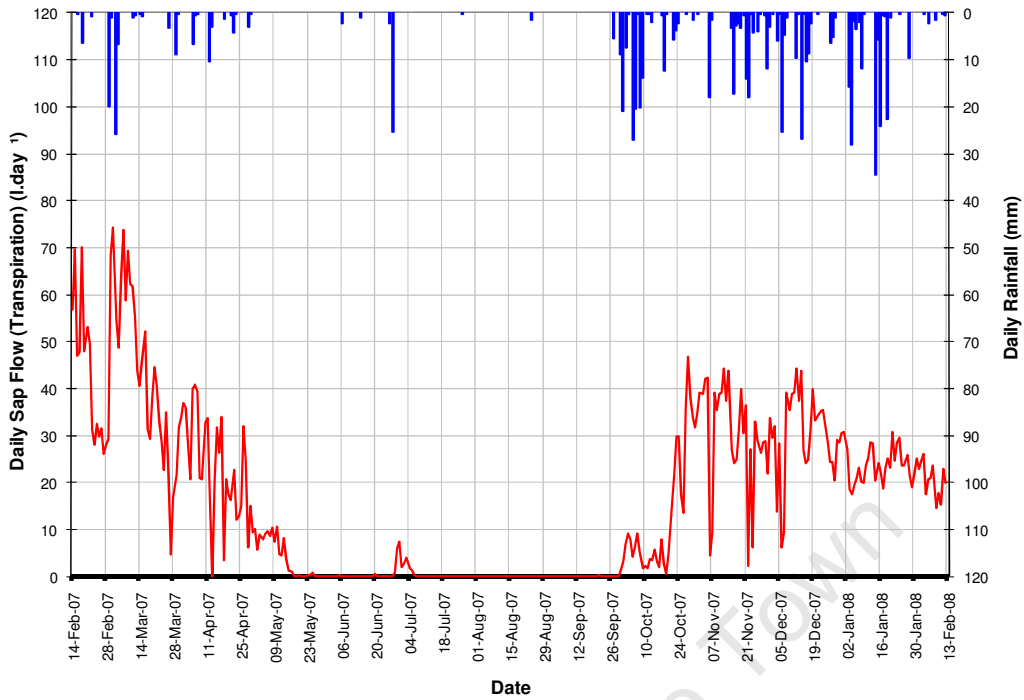
**Figure 7.4** Monthly sap flow volumes (water-use) of a *Trema orientalis* (◇), a *Celtis africana* (■), a *Podocarpus falcatus* (▲), a *Ptaeroxylon obliquum* (×), an *Olea europaea* subsp. *africana* (□) and a *Berchemia zeyheri* (○) tree.

Being a semi-deciduous species *T. orientalis* did not drop its leaves during the dry season, presumably due to sufficient available moisture and / or the relatively mild winter temperatures (minimum 9 °C) experienced at the Winterskloof site. Sap flow in this species continued throughout the dry

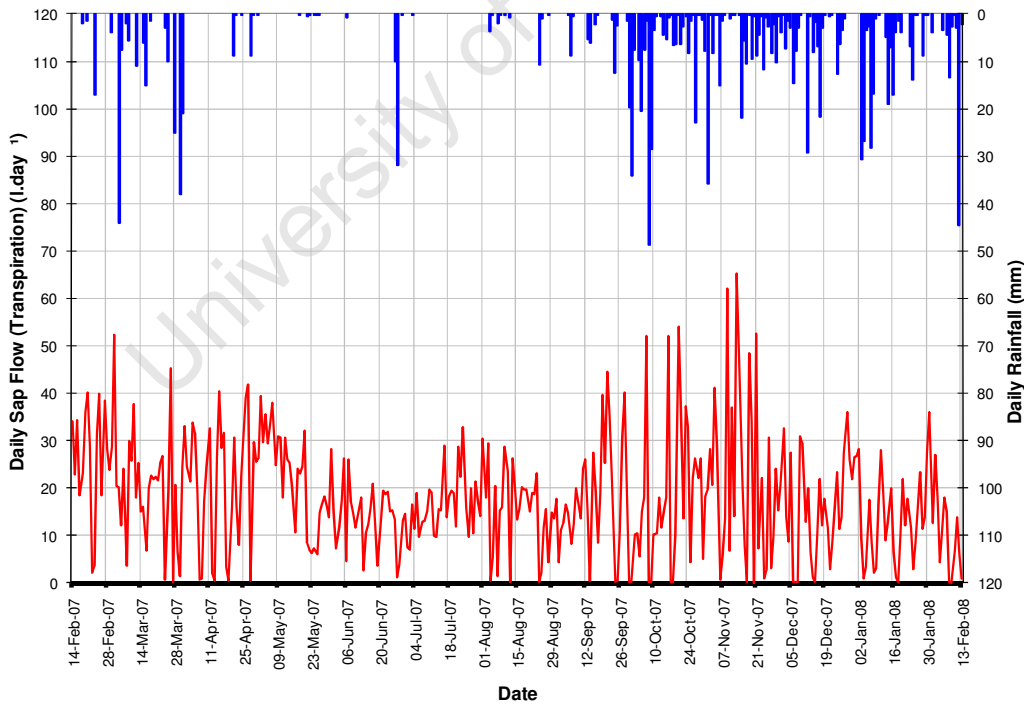
season, averaging  $15 \text{ L day}^{-1}$  in June/July, and peaked in the late wet season (March/April) when water-use rose to an average of  $40 \text{ L day}^{-1}$  (Fig. 7.9). Over the common monitoring period water-use for the *T. orientalis* averaged  $22.16 \pm 17.36 \text{ L day}^{-1}$  and totalled  $8089 \text{ L annum}^{-1}$ . In the case of the evergreen species at Weenen (*O. europaea* subsp. *africana*), water-use was a conservative  $14.31 \pm 14.83 \text{ L day}^{-1}$  and totalled  $5223 \text{ L annum}^{-1}$ . Average dry season sap flow volumes in the evergreen species at the Karkloof site ( $11\text{-}15 \text{ L day}^{-1}$ ) were 3-4 times higher than those recorded in the evergreen *O. europaea* subsp. *africana* at Weenen ( $3.5 \text{ L day}^{-1}$ ), reflecting the extremely dry winter conditions at the latter site. There was a slightly lagged sap flow response (July) in the *O. europaea* subsp. *africana*, due to an unseasonal rainfall event of 28 mm in June at the Weenen site (Fig. 7.10).



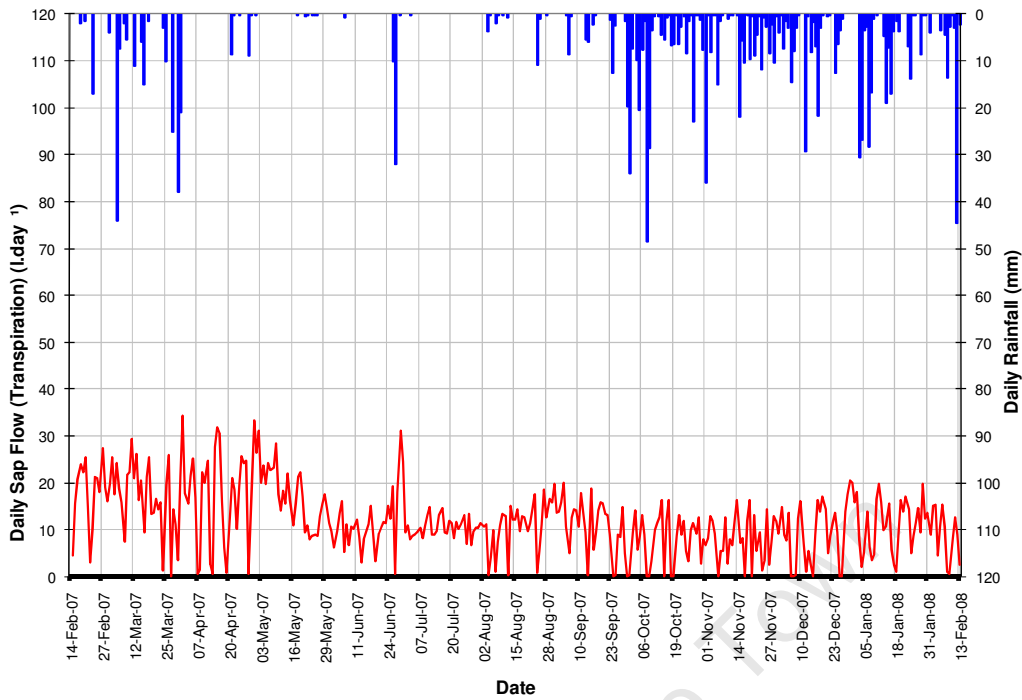
**Figure 7.5** Daily transpiration (—) (litres) observed in a *Celtis africana* tree using sap flow measurements, with daily rainfall (■) (mm) at the Karkloof site.



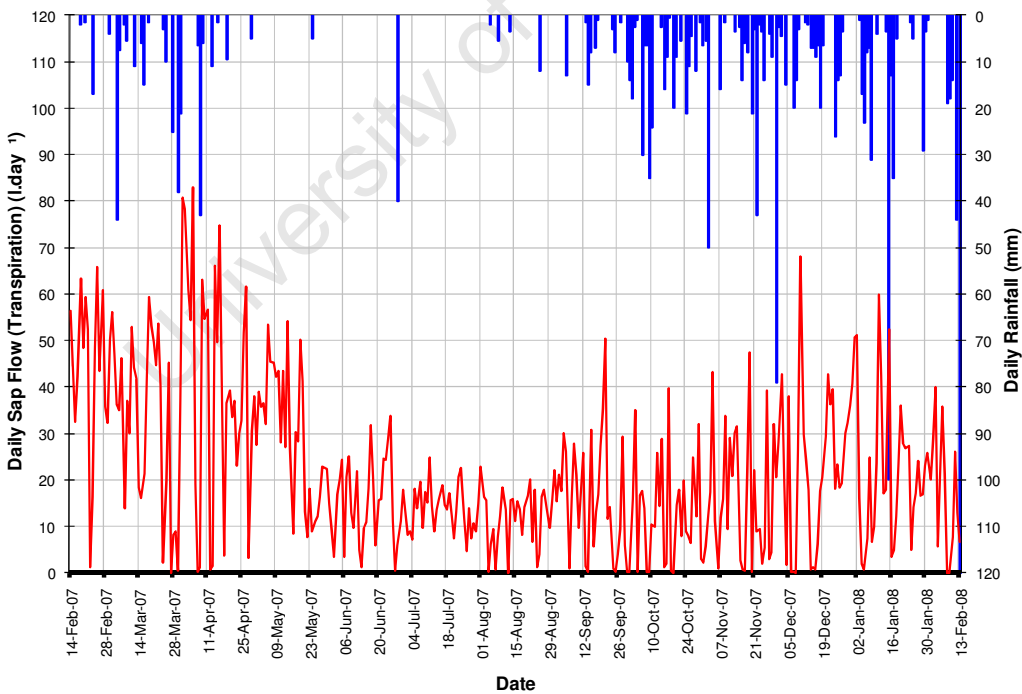
**Figure 7.6** Daily transpiration (—) (litres) observed in a *Berchemia zeyheri* tree using sap flow measurements, with daily rainfall (■) (mm) at the Weenen site.



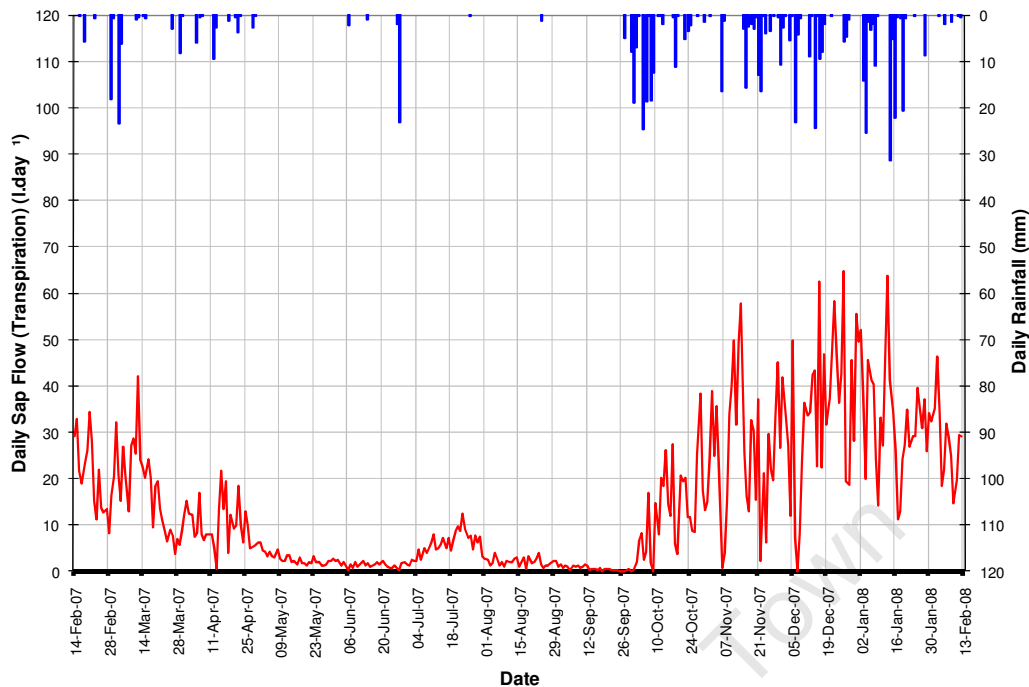
**Figure 7.7** Daily transpiration (—) (litres) observed in a *Podocarpus falcatus* tree using sap flow measurements, with daily rainfall (■) (mm) at the Karkloof site.



**Figure 7.8** Daily transpiration (—) (litres) observed in a *Ptaeroxylon obliquum* tree using sap flow measurements, with daily rainfall (■) (mm) at the Karkloof site.

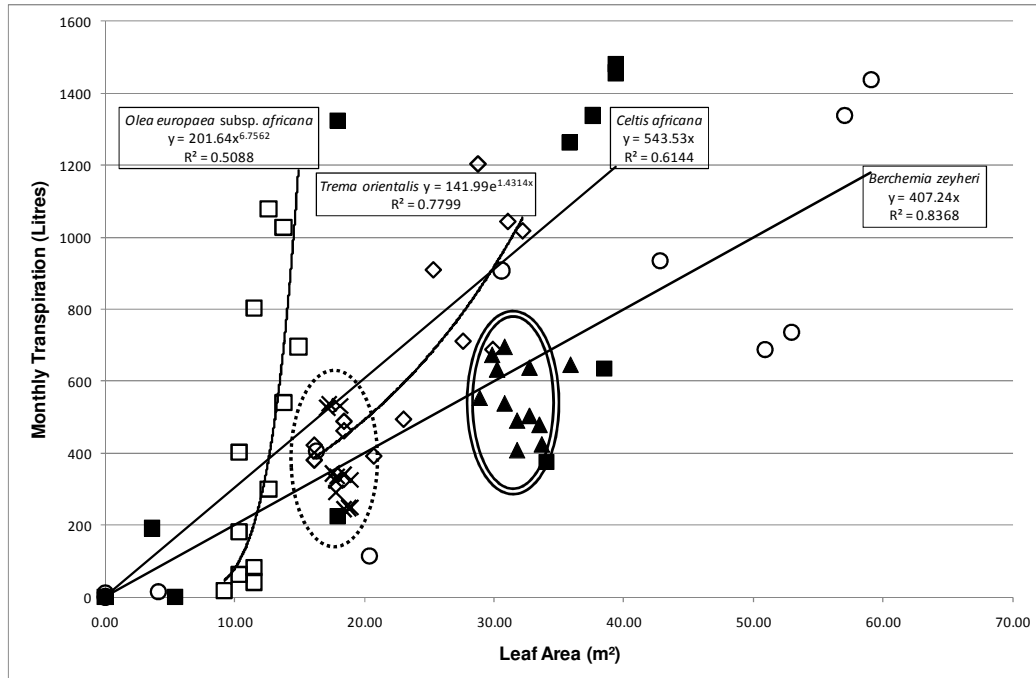


**Figure 7.9** Daily transpiration (—) (litres) observed in a *Trema orientalis* tree using sap flow measurements, with daily rainfall (■) (mm) at the Winterskloof site.



**Figure 7.10** Daily transpiration (—) (litres) observed in an *Olea europaea* subsp. *africana* tree using sap flow measurements, with daily rainfall (■) (mm) at the Weenen site.

Monthly variability in water-use of the indigenous trees studied was the result of seasonal (i.e. climatic) and phenological influences, particularly within the deciduous species. There were reasonably good correlations between monthly transpiration volumes and total tree leaf area for the deciduous species (*Trema orientalis*, *Celtis africana* and *Berchemia zeyheri*) (Fig. 7.11). However, within the evergreen species (*Olea europaea* subsp. *africana*, *Podocarpus falcatus* and *Ptaeroxylon obliquum*) there were either weak or no correlations between transpiration rates and leaf area. In those species transpiration was governed mostly by ambient weather conditions.



**Figure 7.11 Correlations between observed monthly transpiration totals and changes in total tree leaf area (estimated from monthly Leaf Area Index variation and canopy dimensions) for indigenous *Trema orientalis* (◇), *Celtis africana* (■), *Podocarpus falcatus* (▲), *Ptaeroxylon obliquum* (X), *Olea europaea* subsp. *africana* (□) and *Berchemia zeyheri* (○) trees. Species exhibiting little correlation are circled, namely *Ptaeroxylon obliquum* (dotted circle) and *Podocarpus falcatus* (double circle).**

### **Tree growth and water-use efficiency**

Utilising the stem growth increments and water-use data collected from the respective trees, resultant WUE calculations (t stem wood produced per t of water transpired) showed *B. zeyheri*, *C. africana* and *P. obliquum* to be the most water-use efficient of the species studied (Table 7.3). The results were similar when accounting for total above-ground woody biomass increment (t stem plus branch wood produced per t of water transpired), except that *C. africana* emerged as the most water-use efficient species in this case. The least water-use efficient species in both cases was *Olea europaea* subsp. *africana*. This was primarily a result of its very slow growth rate and limited stem growth increment.

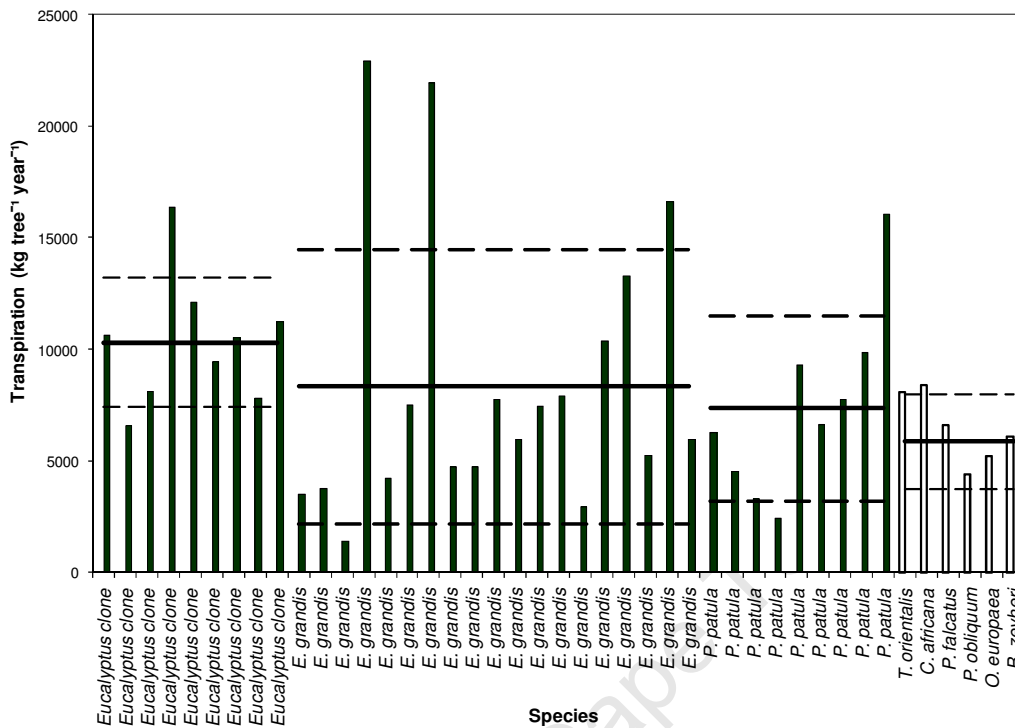
**Table 7.3 Summary of WUE data for selected South African indigenous tree species, as calculated from a mass-based ratio of biomass increment (stem wood or stem plus branch wood) over water-use.**

Tree Species	1-yr Rainfall (mm)	1-yr Water-use (L)	Stem Volume Increment (cm <sup>3</sup> )	Total Volume Increment (cm <sup>3</sup> )	Ave. Wood Density (g cm <sup>-3</sup> )	Stem Mass Increment (g)	Total Mass Increment (g)	WUE (g stem wood / L water transpired)	WUE (g total wood / L water transpired)
<i>Trema orientalis</i>	1 481	8089	18426	25246	0.422	7776	10654	0.9612	1.3170
<i>Celtis africana</i>	1 130	8396	21855	37894	0.605	13222	22926	1.5748	2.7306
<i>Podocarpus falcatus</i>	1 130	6571	14659	18114	0.468	6861	8477	1.0441	1.2901
<i>Ptaeroxylon obliquum</i>	1 130	4407	8117	12011	0.716	5812	8600	1.3188	1.9514
<i>Olea europaea</i> subsp. <i>africana</i>	637	5223	1784	5875	0.916	1634	5382	0.3129	1.0304
<i>Berchemia zeyheri</i>	637	6103	12659	15200	0.807	10216	12267	1.6739	2.0099

## **Discussion**

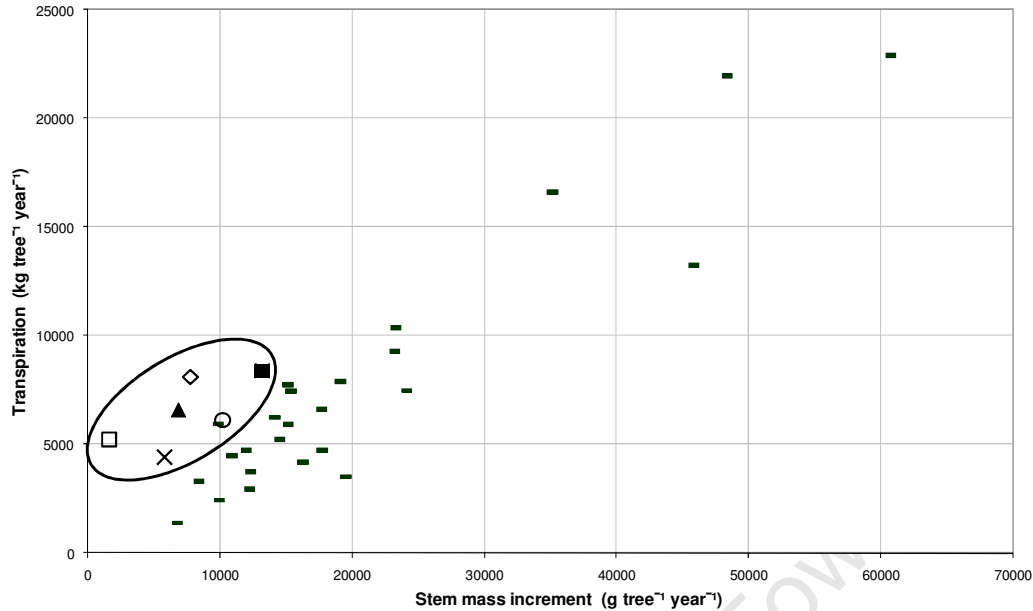
The primary objective of this study was to explore whether indigenous tree species use less water than introduced plantation species. Based on the slow growth rates observed in the indigenous tree species sampled I also determined whether the WUE of those indigenous trees was below that of introduced plantation species. Consequently, the results may be considered from the individual perspectives of growth, water-use and water-use efficiency (WUE), and assessed against similar data for introduced plantation species. Comparable WUE data for introduced plantation tree species (stem growth and transpiration measurements) are available from Olbrich *et al.* (1996) and Dye *et al.* (2001). WUE is a product of both growth and water-use, and compared to the indigenous tree species studied here, introduced plantation species generally exhibit similar or higher rates of both these variables.

The overall water-use of the indigenous trees studied averaged  $5870 \pm 2128$  kg tree<sup>-1</sup> year<sup>-1</sup>; which was also lower than for introduced plantation species (Fig. 7.12), which averaged  $8307 \pm 5054$  kg tree<sup>-1</sup> year<sup>-1</sup>. Maximum water-use was lower in the indigenous species studied compared to introduced plantation species, despite growing conditions that could be considered ideal for most of the indigenous species sampled (readily available water, energy and nutrients, and limited competition). The indigenous tree annual cumulative sap flows were all less than 8500 kg tree<sup>-1</sup> year<sup>-1</sup>, whereas sap flows in the more productive introduced plantation trees exceeded 20 000 kg tree<sup>-1</sup> year<sup>-1</sup>. This suggests that there is a genetically determined maximum threshold to water-use by indigenous tree species that is substantially lower than that for introduced plantation species. Similar findings have been reported by Kagawa *et al.* (2009) and Little *et al.* (2009), who found that the water-use of native tree species, in Hawaii and Chile respectively, was considerably lower than that of introduced timber species. However, my study must be considered to be exploratory, and was by no means exhaustive. There is consequently the possibility that certain indigenous tree species may still show higher water-use than the trees measured here.



**Figure 7.12 A comparison 1-year total sap flow (transpiration) for introduced plantation trees (■) (Olbrich et al., 1996; Dye et al., 2001) and selected South African indigenous trees (□ – this study). The mean (—) and standard deviation (----) for the two data sets are indicated.**

Rates of stem growth in the indigenous trees studied averaged  $6789 \pm 4174 \text{ g tree}^{-1} \text{ year}^{-1}$ ; significantly less than the average of  $19906 \pm 11713 \text{ g tree}^{-1} \text{ year}^{-1}$  for the introduced plantation species (Fig. 7.13). As has been the experience with introduced plantation species, genetic breeding for fast growth rates and the application of silvicultural practices employed in commercial plantations (e.g. pruning and thinning) could increase growth rates and influence the efficiencies of resource use among indigenous tree species. While some preliminary studies have been conducted in this regard (Geldenhuys and von dem Bussche, 1997), this remains to be more thoroughly tested.



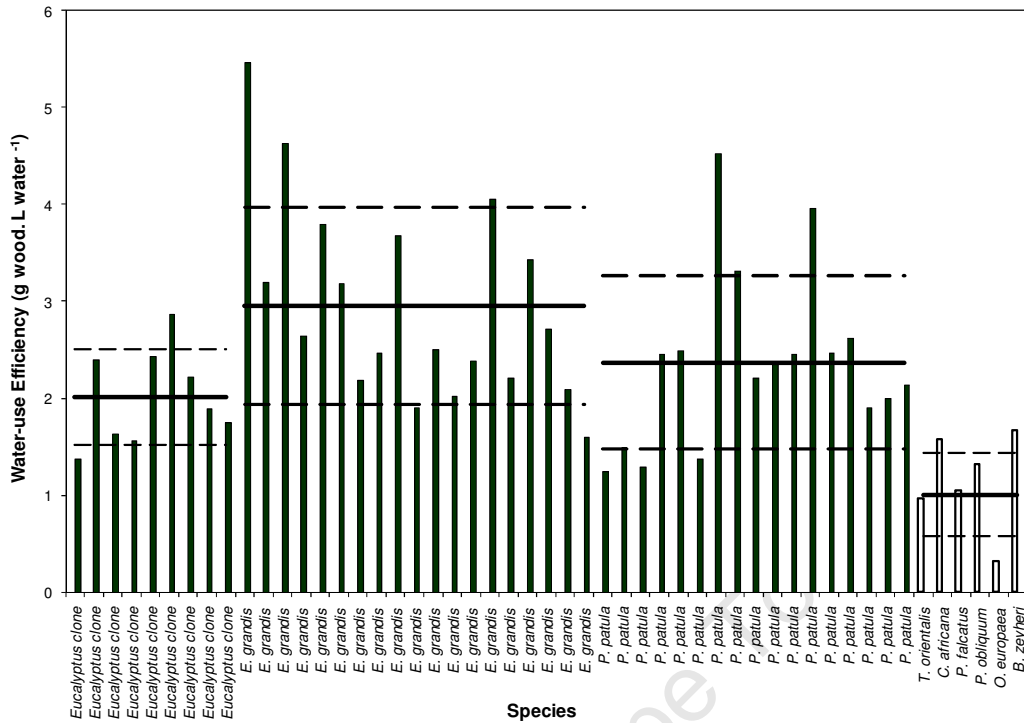
**Figure 7.13** A comparison between 1-yr stem mass increment and 1-yr total sap flow, for introduced commercial plantation trees (—) (Olbrich et al., 1996; Dye *et al.*, 2001) and indigenous *Trema orientalis* (◇), *Celtis africana* (■), *Podocarpus falcatus* (▲), *Ptaeroxylon obliquum* (X), *Olea europaea* subsp. *africana* (□) and *Berchemia zeyheri* (○) trees (circled).

In terms of growth and water-use it can therefore be concluded that while biomass production was much lower for the indigenous tree species, these trees also used much less water than introduced plantation species. The relatively lower water-use of the indigenous trees used in this study compared to introduced plantation species has some important implications. One potential application of this benefit could be the planting of indigenous tree species in riparian zones within commercially afforested areas. These zones are difficult to manage from a grassland conservation perspective as they are often narrow riparian corridors, in which it is dangerous to perform bi-annual burning regimes due to fire-risk within the plantations, and which are thus often heavily infested with alien invasive plants. The reforestation of these areas with suitable indigenous trees (climatically suited, riparian-adapted, pioneer species) could perform useful services of biodiversity augmentation, weed suppression and erosion control, without unduly negative impacts on streamflow. Furthermore, even when rainfall is high, indigenous tree species

do not appear to increase their water-use or biomass production. From a catchment water-yield perspective this suggests that natural indigenous forests growing in high-rainfall upper catchment areas will be less likely to reduce streamflow compared to introduced plantations.

Additional motivation for establishing indigenous tree species within invaded riparian zones is provided by Vanclay (2009). He suggests that the water-use of introduced tree plantations may be reduced by limiting the air turbulence induced by abrupt plantation edges and fire breaks (Zhang *et al.*, 2007), and by managing canopy roughness. He cites evidence (Forrester, 2007) that mixed species plantings may have a canopy structure that is less coupled to the atmosphere, and which may thus reduce transpiration. He concludes that legislation requiring riparian zones to remain unplanted may be counterproductive because of the possibility that turbulence induced by plantation edges may lead to greater water losses than if water courses were planted with selected native species.

WUE in the indigenous species studied averaged  $1.1 \pm 0.46$  g (stem wood)  $\text{kg}^{-1}$  (water), and was generally lower than for introduced plantation species (Fig. 7.14), which averaged  $2.6 \pm 0.91$  g (stem wood)  $\text{kg}^{-1}$  (water). It was concluded that the relatively lower WUE of the indigenous species was more a consequence of slow growth rates as opposed to high water-use rates – a finding supported by other studies (Binkley *et al.*, 2004; Gyenge *et al.*, 2008).



**Figure 7.14** A comparison of water-use efficiency (stem mass increment per mass of water transpired) for introduced plantation trees (■) (Olbrich et al., 1996; Dye et al., 2001) and selected South African indigenous trees (□ – this study). The mean (—) and standard deviation (---) for the two data sets are indicated.

The potential for significant year-to-year variation in WUE of a particular tree species or even an individual tree is uncertain. WUE in any given year may be dependent upon the climatic conditions experienced, although it is possible that a year of above-average rainfall would result in above-average water-use and growth (similarly with a below-average year), rendering the overall effect on WUE insignificant unless certain thresholds in water-use or growth were reached. However, longer-term WUE studies would be required to verify this. Although only exploratory at this stage, this study has provided the first direct comparison between the WUE of indigenous and introduced tree species in South Africa. Additional WUE studies on a greater variety of indigenous tree species growing under diverse conditions would be beneficial in their evaluation as alternative forestry systems, particularly in water-constrained catchments.

## Chapter 8

### **SYNTHESIS**

Anticipated world population increases and rising demands for food, fibre and fuel mean increasing water requirements globally (Rockström *et al.*, 2002; Rijsberman, 2006). However, supplies of renewable fresh water are finite, and while some countries have plentiful water, others such as South Africa do not (Berndes, 2002). In countries experiencing water scarcity this requires intervention, either in the form of reducing demand (unlikely), augmenting existing water supplies (expensive), and/or improving efficiencies of use wherever possible. Over half of South Africa's available water is estimated to be utilised by agriculture and forestry (van der Stoep *et al.*, 2005; Middleton and Bailey, 2008). Consequently, it is in this sector that the greatest potential exists for improvements in water-use efficiency (WUE) (Feres and Evans, 2006).

Past studies with improvements in agricultural WUE as an objective have focussed largely on improving irrigation efficiencies along the supply chain, by limiting water-loss, revising irrigation schedules and implementing new technologies such as drip irrigation systems (Reinders *et al.*, 2005; Hsiao *et al.*, 2007). While numerous studies have been conducted on the efficiencies of water-use within trees and forests (e.g. Forrester *et al.*, 2010; Maseyk *et al.*, 2011), limited work has been done on the potential for improvements in WUE (genetic or otherwise) within the forestry sector (Dye, 2000). The potential benefits of improved WUE within plantation forestry have been suggested by Stape *et al.* (2004) to be significant, with reductions in rotation length, land requirements and water-use impacts all being possible under conditions of more efficient resource use.

Catchment Management Agencies (CMAs) have been established in certain Water Management Areas (WMAs) in South Africa, and more are to follow (Nomqupu *et al.*, 2007). These agencies are mandated to ensure that water

resources at regional or catchment level are conserved, used and managed in an environmentally, socially and economically beneficial manner (Schreiner and van Koppen, 2002). To do this CMAs require accurate information on the water use and associated economic benefit of all relevant land uses to make water-allocation decisions (Woyessa *et al.*, 2006). While this information is available for introduced plantation species (Crafford *et al.*, 2007), prior to this study no water-use information was available for indigenous South African tree species. Here four individual studies were conducted to determine the water-use, growth rates and resultant WUE of indigenous tree species. The primary objectives were:

1. To determine whether indigenous tree species use less water than introduced tree species, and
2. To determine whether indigenous tree species use water more efficiently than introduced tree species.

In addressing these questions it should be remembered that two methods were applied. In the first method, estimates of water-use and water-use efficiency (WUE) for an entire forest (trees and undergrowth) were obtained using above-canopy total evaporation (ET) data from Scintillometry and Eddy Covariance measurements, combined with long-term growth data (utilisable above-ground woody biomass increments). In the second method estimates of water-use and WUE for individual trees only were determined using measurements of transpiration (sap flow) and above-ground woody biomass increments.

My results show that mixed species / mixed age indigenous forests of the southern Cape (Chap. 4), and mixed species / mixed age savanna woodlands of Mpumalanga (Chap. 5) are not particularly conservative in terms of their overall water-use, generally utilising all the water supplied by rainfall at their respective study sites. However, a single species / even-aged plantation of indigenous *Podocarpus falcatus* trees (Chap. 6) used less than half of the available water supplied by rainfall. By combining the use of above- and

below-canopy methods for determining water-use in this indigenous plantation it was possible to distinguish between tree-only water-use (transpiration) and plantation total evaporation (evaporation from trees, soil and understorey vegetation). The resultant water-use of the undergrowth or understorey vegetation, determined by subtraction, was substantial, accounting for up to 66% of the water used by this indigenous tree system. This highlighted the importance of rigorous management of the understorey vegetation under plantation conditions, to minimise water-use.

Measurements of water-use in several indigenous *Podocarpus falcatus* trees growing in a single species / even aged plantation (Chap. 6) were made. My results showed that the water-use (transpiration component) of these trees was low compared to data for introduced plantation tree species (Olbrich *et al.*, 1996; Dye *et al.*, 2001). Further sap flow (transpiration) measurements in individual specimens of several indigenous tree species growing in different environments (Chap. 7) support the results for *Podocarpus*. The range of observed 1-year water-use totals for indigenous species was noticeably less than for introduced plantation species. The highest 1-year water-use total from all the indigenous tree species tested was less than half that of the higher water-using clonal *Eucalyptus* varieties. These results strongly support the suggestion of a relatively low maximum water-use threshold for indigenous species, compared to introduced plantation tree species.

In conclusion, I believe that the indigenous tree species tested used less water than introduced species (particularly clonal *Eucalyptus* varieties). Similar findings have been reported by Kagawa *et al.* (2009) and Little *et al.* (2009), who found that the water-use of native tree species, in Hawaii and Chile respectively, were considerably lower than that of introduced timber species. The question then is, to what extent do growth rates correspond with water-use rates within indigenous and introduced species, and what is the net result in terms of their respective water-use efficiency values?

My results from scintillometry and eddy covariance studies on the water-use (total evaporation), growth and resultant WUE of a mixed species / mixed age indigenous Afro-temperate forest (Chap. 4) and a single species / even-aged plantation of indigenous *Podocarpus falcatus* trees (Chap. 6) show that the *P. falcatus* plantation was only marginally more efficient, in terms of utilisable above-ground biomass production, than the Afrotemperate forest. This was attributed to the lower total evaporation rates from the *Podocarpus falcatus* plantation. In the case of WUE estimates obtained on individual trees using transpiration measurements and above-ground (stem and branch) annual biomass increments (Chap. 7), my results show that the WUE of indigenous tree species was lower than that of introduced tree species.

I attribute the lower WUE of the indigenous tree species to slow growth rates as opposed to high water-use rates. These findings are supported by a number of studies, which show that light-use efficiency (and consequently WUE under non-limiting conditions) was greater for younger trees, suggesting larger photosynthetic rates at canopy scale than for older trees (Lamaud *et al.*, 1997). Almeida *et al.* (2007) and Forrester *et al.* (2010) also demonstrated that WUE declines with increasing tree age. Plantations of introduced tree species may be grown under short rotation periods for maximum productivity (e.g. 6-8 years for pulp-wood production), while indigenous trees within a natural forest are generally of a much older age. This would also tend to lower the WUE of indigenous trees relative to introduced species. It follows, therefore, that indigenous tree species established under controlled (plantation) conditions designed to maximise resource use, will show increases in productivity and also WUE, particularly if combined with tree improvement programmes to maximise growth rates.

Plantations of introduced tree species established in the higher rainfall regions of the country exhibit high water-use rates, but they have also been genetically selected and bred for higher growth rates over a long time (Verry, 2000). Based on findings by Binkley *et al.*, (2004) and Stape *et al.*, (2004) this is likely to have improved their WUE. On the other hand, efforts at tree

improvement and silvicultural enhancement of growth rates in indigenous tree species have been limited in extent. Measures that have been taken have primarily been associated with the sustainable management of the southern Cape indigenous forests, and have included the use of nurse stands to provide shade and cover for newly planted indigenous trees (Stapleton, 1955, Geldenhuys, 1997); reduction of competition through slashing of competing undergrowth, cutting of strangling climbers and selective reduction of coppice shoots (von Breitenbach, 1974); and enrichment and replacement planting in gaps in the forest left by fallen or removed trees (von dem Bussche, 1975). Some pioneering progeny trials on the growth of *Podocarpus falcatus* (Yellowwood) seedlings have been conducted (Geldenhuys and von dem Bussche, 1997), as well as experimental plantings (including silvicultural treatments such as thinning and pruning) of *Trema orientalis* (L.) Blume (Pigeonwood) (Keet, 1962). These were established with a view to exploring the potential for plantations of indigenous tree species.

Much evidence suggests that indigenous forests cannot compete with plantations of introduced tree species for wood production. Mature indigenous forests are close to a point of ecological equilibrium, in which standing biomass is high, but the rate of biomass increase is very low. Plantations of several indigenous species of trees have been established over the years to evaluate growth rates and wood properties against existing commercial forest plantations. These have generally shown slow growth rates, although rapid growth rates have been demonstrated in some pioneer species such as *Virgilia oroboides* (P.J.Bergius) Salter (Blossom Tree) (van Wyk, 1982) and *Trema orientalis* (Keet, 1962). From a wood production point of view, it appears unlikely that, in the foreseeable future, indigenous species will offer an economically competitive land use option to plantations of exotic species. However, the possibility that an indigenous tree improvement programme could genetically improve growth rates should be explored. Some progress has already been made in the domestication of indigenous fruit tree species in southern Africa (Akinnifesi *et al.*, 2006), and the same could apply in terms of their growth rates.

Results therefore indicate that hypothesis two has not been proven, i.e. that indigenous tree species do not use water more efficiently than introduced plantation tree species. Again, this result should be seen as exploratory, and a need exists to test a wider selection of indigenous tree species.

### ***Implications of findings***

Amongst other things, this study has demonstrated the relatively low water-use characteristics of indigenous tree species, particularly compared to introduced eucalyptus plantations. One of the practical applications of this research could be to help identify which indigenous tree species are most promising for expanding natural and plantation tree production systems in South Africa, maximising benefits (goods and services) and minimising negative impacts (water-use). To achieve this potential indigenous tree species could be considered from environmental, social and economic perspectives. An environmental perspective would be likely to focus on hydrological aspects (Dye *et al.*, 2008), the potential for suppression of alien invasive plants (Geldenhuys, 2004), biodiversity conservation (Armstrong and van Hensbergen, 1996; Ratsirarson *et al.*, 2002) and the provision of ecosystem services (Turpie *et al.*, 2008). A social perspective might focus primarily on rural livelihoods (Lawes *et al.*, 2004; Shackleton and Shackleton, 2004; Shackleton *et al.*, 2007), but may also consider ecotourism and the use of street trees for urban greening (Stoffberg *et al.*, 2008). An economic perspective would need to consider appropriate means of valuing forests and the goods and services they provide, and then assess markets, product values and total economic value (Hassan and Haveman, 1997). Recommendations could be made as to the species considered to be the most beneficial from these individual perspectives.

Another potential application of these results could be the planting of indigenous tree species in riparian zones within commercially afforested areas. These zones are difficult to manage from grassland conservation and weed control perspectives as they are often narrow riparian corridors, in which

It is dangerous to perform bi-annual burning regimes due to fire-risk within the plantations, and which are thus often heavily infested with alien invasive plants. If riparian zones are continuously weed-infested and have limited biodiversity value then an indigenous tree cover could be considered preferable. It has also been shown locally (Seagrief, 1965; Geldenhuys, 1997) and internationally (Feyera *et al.* 2002, Kasenene, 2007; Farwig *et al.*, 2009) that, under suitable conditions, commercial plantations of introduced trees may act as “nurse” stands, enabling the regeneration of indigenous trees and shrubs under the protection of their canopies, to eventually form forests.

The observed low water-use rates of indigenous tree species relative to introduced timber species make them a viable alternative land-use (in appropriate areas) from a hydrological perspective, but also from an economic perspective. Preliminary economic assessments on indigenous tree systems in South Africa found that certain indigenous tree systems (e.g. *Podocarpus falcatus* plantations and Afro-temperate forest) may be able to compete with introduced plantation systems, despite longer rotation lengths, based on favourable economic criteria (Wise *et al.*, 2011). This was attributed to relatively low input costs (not intensively managed) and higher product prices. The study went on to suggest that financing mechanisms such as the UN Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) programmes, as well as tax breaks for superannuation funds, could stimulate investment in long-term projects such as indigenous plantations.

The question remains, is it possible (and expedient) to expand areas under indigenous trees? In addressing this question it may be helpful to consider the southern Cape indigenous forests. Those forests cover a small area of South Africa, but are an excellent example of a sustainable, multiple use system that offers a wide range of benefits to society. Research over many years has culminated in a sustainable system of management, in which timber extraction of high-value logs generates significant income without compromising the sustainability and species composition of the forest. On the other hand, heavy utilisation of Indigenous forests by people in rural communal areas has been

reported in several different parts of the country (Lawes *et al.*, 2004). There is danger of over-utilisation in such situations (Obiri *et al.*, 2002), and a potential solution is for alternative tree-production systems to be established as a way of alleviating harvesting pressure on indigenous forests. Similarly, woodlands occupy a large proportion of South Africa, and yield a very wide range of products to a large proportion of the population (Shackleton *et al.*, 2007). Multi-use species such as Marula and Kiaat, for example, have great economic potential (Leakey *et al.* 2005a/b; Lumbile *et al.*, 2007), especially in rural areas with high population densities of people heavily dependent on local natural resources. In such situations, new indigenous tree production systems may offer a viable alternative to introduced plantation forests exhibiting marginal profitability under conditions of low rainfall and poor soil.

Given the wide range of climatic and site conditions around South Africa, the large number of multiple-use indigenous tree species that are found in this country, and increasing pressure on water resources, it is important to identify new and sustainable indigenous forest and woodland production systems. Considering that on the one hand further afforestation with commercial forest species is now severely restricted due to concerns about reductions in catchment water yields, while on the other hand significant potential exists to expand indigenous tree systems, the possibility of this low water-use form of forestry is an attractive proposition.

### ***Future research needs***

A number of studies have shown that under conditions of increased productivity growth rates increase faster than rates of water-use improving WUE as a result (Binkley *et al.*, 2004; Stape *et al.*, 2004; Almeida *et al.*, 2007; Forrester *et al.*, 2010). Indigenous tree species, with slower growth rates and no management interventions to increase productivity are likely to exhibit lower WUE. The question is, to what extent can the WUE of indigenous tree species be improved through more intensive management; how will the ratio's of growth to water-use change under conditions of increased productivity, and

what will be the associated environmental and socio-economic costs and benefits? Silvicultural aspects such as use of “nurse” stands, planting densities, thinning and pruning regimes, weed control measures and species choices are potential areas for future indigenous tree stand management research.

A highly successful tree improvement programme has already been conducted on introduced plantation tree species (Verryn, 2000), resulting in substantial increases in productivity, disease resistance, wood-quality and, seemingly, WUE. With increasing attention being given to environmental issues, particularly threats to water resources and bio-diversity, there is a need to invest in a similar programme for indigenous tree species. Preliminary results from Geldenhuys and von dem Bussche (1997) already suggest that provenance trials and genotype selection can significantly influence production in indigenous tree plantations. Another South African example is how the mean fruit yield of marula (*Sclerocarya birrea* subsp. *caffra*) trees has been shown to be significantly higher in village trees than from those in protected areas, suggesting some degree of tree improvement through historical selection of trees (Shackleton *et al.* 2003, Leakey *et al.* 2005a/b). Results from a more extensive research programme along these lines could guide species selection, direct land cover choices and inform catchment management decisions; balancing the water needs of society, environment and industry, against the need to maximise products and services from indigenous tree systems, and thereby contribute to economic growth and poverty alleviation.

A century ago the South African Government was first motivated to promote the establishment of fast growing introduced plantations in response to a specific need at the time; namely a shortage of utilizable timber in the country. South Africa now faces a new forestry challenge, namely that of reconciling a growing need for timber products against the constraints of shortages in suitable land, and the potential environmental impacts (specifically in terms of impacts on water resources) that meeting that need may pose. A century ago the private sector was reluctant to venture into such a long-term investment

and the Government had to lead the way in establishing the forestry industry of South Africa. From that initiative a successful and self-sufficient sector was formed. Indigenous forestry requires a new mindset change to an even longer investment, with not only socio-economic considerations, but now more than ever, environmental benefits to weigh up. The question, to Government and the private sector alike, is will they rise to the new challenge?

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## **REFERENCES**

- Acocks, J.P.H. 1988. 'Veld types of South Africa'. In: Botanical survey of South Africa Memoirs, 57. Botanical Research Institute, Pretoria, RSA.
- Akinnifesi, F.K., Kwesiga, F., Mhango, J., Chilanga, T., Mkonda, A., Kadu, C.A.C., Kadzere, I., Mithofer, D., Saka, J.D.K., Sileshi, G., Ramadhani, T. and Dhlwayo, P. 2006. Towards the development of Miombo fruit trees as commercial tree crops in southern Africa. *Forests, Trees and Livelihoods*, 16: 103–121.
- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. pp 300.
- Almeida, A.C., Soares, J.V., Landsberg, J.J. and Rezende, G.D. 2007. Growth and water balance of Eucalyptus grandis hybrid plantations in Brazil during a rotation for pulp production. *Forest Ecology and Management*, 251: 10–21.
- Archibald, S. and Scholes, R. J. 2007. Leaf green-up in a semi-arid African savanna – separating 10 tree and grass responses to environmental cues. *Journal of Vegetation Science*, 18: 583-594.
- Archibald, S., Kirton, A., van der Merwe, M., Scholes, R. J., Williams, C. A. and Hanan, N. 2008. Drivers of interannual variability in Net Ecosystem Exchange in a semi-arid savanna ecosystem, South Africa. *Biogeosciences Discussions*, 5: 3221-3266.
- Armstrong, A.J. & van Hensbergen, H.J. 1996. Impacts of afforestation with pines on assemblages of native biota in South Africa. *South African Forestry Journal*, 175: 35–42.
- Asbjornsen, H., Goldsmith, G.R., Alvarado-Barrientos, M.S., *et al.* 2011. Ecohydrological advances and applications in plant-water relations research: a review. *Journal of Plant Ecology*, 4: 3-22.
- Baldocchi, D., 1997. Measuring and modelling carbon dioxide and water vapour exchange over a temperate broad-leaved forest during the 1995 summer drought, *Plant Cell Environment*, 20: 1108–1122.
- Becker, P., Tyree, M.T. and TSUDA, M. 1999. Hydraulic conductances of

- angiosperms versus conifers: Similar transport sufficiency at the whole-plant level. *Tree Physiology*, 19: 445-452.
- Berndes, G. 2002. Bioenergy and water - the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, 12: 253-271.
- Binkley, D., Stape, J.L., and Ryan, M.G. 2004. Thinking about efficiency of resource use in forests. *Forest Ecology and Management*, 193: 5-16.
- Bosch, J.M. and Hewlett, J.D. 1982. A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55: 3-23.
- Bosch, J.M. and Smith, R.E. 1989. The effect of afforestation of indigenous scrub forest with *Eucalyptus* on streamflow from a small catchment in the Transvaal, South Africa. *South African Forestry Journal*, 150: 7-17.
- Bosch, J.M. and Versfeld, D.B. 1984. A vegetation survey of catchment D, Westfalia Estate. Department of Water Affairs and Forestry, South African Forestry Research Institute Centre, Private Bag X313, Pretoria, South Africa. Rep. No. JFRC 84/20.
- Bosch, J.M. and von Gadow, K. 1990. Regulating afforestation for water conservation in South Africa. *South African Forestry Journal*, 153: 41-54.
- Bovard, B.D., Curtis, P.S., Vogel, C.S., Su, H.-B. and Schmid, H.P. 2005. Environmental controls on sap flow in a northern hardwood forest. *Tree Physiology*, 25: 31-38.
- Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W. and Vertessy, R. A. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, 310: 28-61.
- Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment*, 104: 185-228.
- Bruijnzeel, L.A., Mulligan, M. and Scatena, F.N. 2011. Hydrometeorology of tropical montane cloud forests: Emerging patterns. *Hydrological Processes*, 25: 465-498.

- Burgess, S.S.O., Adams, M.A., Turner, N.C., Beverly, C.R., Ong, C.K., Khan, A.A.H. and Bleby, T.M.. 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology*, 21: 589-598.
- Calder, I.R. 2005 *Blue Revolution II, Integrated Land & Water Resources Management*. London: Earthscan.
- Cavaleri, M.A. and Sack, L., 2010. Comparative water use of native and invasive plants at multiple scales: a global meta-analysis. *Ecology*, 91(9): 2705-2715.
- Cawe, S.G. and McKenzie, B., 1989. The afro-montane forests of Transkei. IV. Aspects of their exploitation potential. *South African Journal of Botany*, 55: 45-55.
- Cernusak, L.A., Aranda, J., Marshall, J.D. and Winter, K., 2007. Large variation in whole-plant water-use efficiency among tropical tree species. *New Phytologist*, 173: 294–305.
- Chamberlain D, Essop H, Hougaard C, Malherbe S and Walker R (2005) *The GENESIS Report, Part I: The contribution, costs and development opportunities of the Forestry, Timber, Pulp and Paper industries in South Africa*. Report to the Department of Trade and Industry and the Pulp and Paper Manufacturers Association, South Africa. Genesis Analytics.
- Clulow, A.D., Everson, C.S. and Gush, M.B. 2010. The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow and ground water resources. WRC Report TT468/10, Water Research Commission, Pretoria, South Africa.
- Coates-Palgrave, K., 1984. *Trees of southern Africa*. Struik, Cape Town.
- Cooper, K.H. 1985. The conservation status of indigenous forests in Transvaal, Natal and O.F.S., South Africa. *Wildlife Society of SA*. Pp 108.
- Cowan, I.R. 1977. Stomatal behaviour and environment. *Advances in Botanical Research*, 4: 117-228.
- Crafford, J.G., Hassan, R.M., King, N.A., Damon, M.C., de Wit, M.P., Bekker, S., Rapholo, B.M. and Olbrich, B.W. 2007. An analysis of the social, economic, and environmental direct and indirect costs and benefits of

- water use in irrigated agriculture and forestry. WRC Research Report, No.1048/1/04. Water Research Commission, Pretoria, South Africa.
- Cutini, A., Matteucci, G. and Mugnozza, G.S. 1998. Estimation of leaf area index with the Li-Cor LAI 2000 in deciduous forests. *Forest Ecology and Management*, 105: 55-65.
- DAFF, 2009. Forest maps. < <http://forestry.daff.gov.za/webapp/Maps.aspx> >. [accessed 23 July 2011].
- Dawson, T.E., Mambelli, S., Plamboeck, A.H., Templer, P.H. and Tu, K.P. 2002. Stable Isotopes in Plant Ecology. *Annual Review of Ecology and Systematics*, 33: 507-559.
- DeBano, L.F., and Schmidt, L.J. 1990. Potential for enhancing riparian habitats in the southwestern United States with watershed practices. *Forest Ecology and Management*, 33/34: 385-403.
- Dierick, D. and Hölscher, D. 2009. Species-specific tree water use characteristics in reforestation stands in the Philippines. *Agricultural and Forest Meteorology*, 149: 1317-1326.
- DWAF. 2004. Stream Flow Reduction Allocations: History. Department of Water Affairs and Forestry, Pretoria, South Africa. Available from: < [http://www.dwaf.gov.za/sfra/sfra\\_lic\\_history.asp](http://www.dwaf.gov.za/sfra/sfra_lic_history.asp) > [Last Update Used: 18 March 2004].
- Dye P.J., 1996. Response of *Eucalyptus grandis* trees to soil water deficits. *Tree Physiology*, 16: 233-238.
- Dye, P.J., 2000. Water-use efficiency in South African Eucalyptus plantations: a review. *South African Forestry Journal*, 189: 17-25.
- Dye, P.J. and Bosch, J.M. 2000. Sustained water yield in afforested catchments – the South African experience. *In*: von Gadow, K., Pukkala, T. and Tomé, M. (Eds.) *Sustainable Forest Management*, Dordrecht, Netherlands. Kluwer Academic Publishers. 99-120.
- Dye, P.J. and Jarman, C. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. *South African Journal of Science*, 100: 40-45.
- Dye PJ and Olbrich BW 1993 Estimating transpiration from 6-year-old *Eucalyptus grandis* trees: development of a canopy conductance model

- and comparison with independent sap flux measurements. *Plant Cell Environment*, 16: 45-53.
- Dye, P.J. and Versfeld, D. 2007. Managing the hydrological impacts of South African plantation forests: An overview. *Forest Ecology and Management*, 251: 121-158.
- Dye, P.J., Gush, M.B., Everson, C.S., Jarman, C., Clulow, A., Mengistu, M., Geldenhuys, C.J., Wise, R., Scholes, R.J., Archibald, S. and Savage, M.J. 2008. Water-use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions. WRC Report 1462/1/08, Water Research Commission, Pretoria, South Africa.
- Dye, P.J., Poulter, A.G., Hudson, K.E. and Soko, S. 1996. A comparison of the water-use of common riparian forests and grasslands. Report FOR-DEA 962, Division of Forest Science and Technology, CSIR, Pretoria, South Africa.
- Dye, P.J., Poulter, A.G., Soko, S. and Maphanga, D. 1997a. The determination of the relationship between transpiration rate and declining available water for *Eucalyptus grandis*. Water Research Commission Report No. 441/1/97, pp103.
- Dye, P.J., Soko, S. and Maphanga, D. 1997b. Intra-annual variation in water use efficiency of three clones in kwaMbonambi, Zululand. CSIR Report ENV/P/C 97048.
- Dye PJ, Soko S and Poulter AG 1996 Evaluation of the heat pulse velocity method for measuring sap flow in *Pinus patula*. *Journal of Experimental Botany*, 47: 975-981.
- Dye, P.J., Vilakazi, P., Gush, M.B., Ndlela, R. and Royappen, M. 2001. Investigation of the feasibility of using trunk growth increments to estimate water use of *Eucalyptus grandis* and *Pinus patula* plantations. WRC Report 809/1/01, Water Research Commission, Pretoria, South Africa.
- Er-Raki, S., Chehbouni, A., Ezzahar, J., Khabba, S., Boulet, G., Hanich, L. and Williams, D., 2009. Evapotranspiration partitioning from sap flow and eddy covariance techniques for olive orchards in semi-arid region. *Acta Horticulturae*, 846: 201-208.

- Everard, D.A. and Hardy, S.D. 1993. Forest resource utilization by the local population in the Amatole region. *Report FOR-C 190*, Division of Forest Science and Technology, CSIR, Pretoria.
- Everson, C.S., Gush, M.B., Moodley, M., Jarman, C., Govender, M. and Dye, P.J., 2007. Effective management of the riparian zone vegetation to significantly reduce the cost of catchment management and enable greater productivity of land resources. Report to the Water Research Commission. *WRC Report No 1284/1/07* (ISBN: 978-1-77005-613-8).
- FAO. 2001. Global forest resources assessment 2000: Main report. FAO Forestry Paper, 140. 479 pp.
- Farley, K.A., Jobbágy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology*, 11: 1565-1576.
- Farquhar, G.D. and Richards, R.A. 1984. Isotopic composition of plant carbon correlates with water use efficiency of wheat genotypes. *Australian Journal of Plant Physiology*, 11: 539-552.
- Farquhar, G.D. and Sharkey, T.D. 1982. Stomatal conductance and photosynthesis. *Annual Review of Plant Physiology*, 33: 317-345.
- Farquhar, G.D., O'Leary, M.H. and Berry, J.A. 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Australian Journal of Plant Physiology*, 9: 121-137.
- Farwig, N., Sajita, N. and Böhning-Gaese, K., 2009. High seedling recruitment of indigenous tree species in forest plantations in Kakamega Forest, western Kenya. *Forest Ecology and Management*, 257: 143–150.
- February, E.C, Higgins, S.I., Newton, R. and West, A.G. 2007. Tree distribution on a steep environmental gradient in an arid savanna. *Journal of Biogeography*, 34: 270-278.
- February, E.C, West, A.G. and Newton, R.J. 2007. The relationship between rainfall water resource and growth for an endangered tree. *Austral Ecology*, 32: 397-402.
- Fereres, E. and Evans, R.G. 2006. Irrigation of fruit trees and vines: an introduction. *Irrigation Science*, 24: 55-57.
- Fetene, M. and Beck, E. 2004. Water relations of indigenous versus exotic

- tree species, growing at the same site in a tropical montane forest in southern Ethiopia. *Trees – Structure and Function*, Vol. 18 (4): 428-435.
- Fey, M.V. 2010. *Soils of South Africa*. Cambridge University Press. Pp. 287.
- Feyere, S., Beck, E. and Ulrich, L. 2002. Exotic trees as nurse-trees for the regeneration of natural tropical forests. *Trees – Structure and Function*, 16: 245-249.
- FIEC 1995. Guidelines for environmental conservation management in commercial forests in South Africa. Forestry Industry Environmental Committee, Forest Owners Association, Johannesburg.
- Forrester, D.I., 2007. Increasing water use efficiency using mixed species plantations of *Eucalyptus* and *Acacia*. *The Forester*, 50(1): 20-21.
- Forrester, D.I., Collopy, J.J. and Morris, J.D. 2010. Transpiration along an age series of *Eucalyptus globulus* plantations in southeastern Australia. *Forest Ecology and Management*, 259: 1754–1760.
- Fritzsche, F., Abate, A., Fetene, M., Beck, E., Weise, S. and Guggenberger, G. 2006. Soil-plant hydrology of indigenous and exotic trees in an Ethiopian montane forest. *Tree Physiology*, 26(8): 1043–1054.
- FSA, 2010. Abstract of South African Forestry Facts for the year 2007/2008. Forestry South Africa, report to Dept. Water Affairs and Forestry. Available from [<http://www.forestry.co.za>].
- Geldenhuys, C.J. 1980. The effect of management for timber production on floristics and growing stock in the Southern Cape indigenous forests, *South African Forestry Journal*, 113: 6 - 15.
- Geldenhuys, C.J. 1983. Plaaslike volumetabel vir inheemse boomsoorte in die Suid-Kaap. *South African Forestry Handbook*, South African Institute of Forestry, Pretoria.
- Geldenhuys, C.J. 1991. Distribution, size and ownership of forests in the southern Cape. *South African Forestry Journal*, 158: 51-66.
- Geldenhuys, C.J. 1993. Floristic composition of the southern Cape forests with an annotated check-list. *South African Journal of Botany*, 59 (1): 26-44.

- Geldenhuys, C.J. 1994a. Bergwind fires and the location pattern of forest patches in the southern Cape landscape, South Africa. *Journal of Biogeography*, 21: 49 - 62.
- Geldenhuys, C.J. 1994b. Review of studies of the fern *Rumohra adiantiformis* in the southern Cape forests: Implications for sustained management. CSIR Report FOR DEA-758.
- Geldenhuys, C.J. 1996. The Blackwood Group System: its relevance for sustainable forest management in the southern Cape. *South African Forestry Journal*, 177: 1 - 15.
- Geldenhuys, C.J. 1997. Native forest regeneration in pine and eucalypt plantations in Northern Province, South Africa. *Forest Ecology and Management*, 99: 101-115.
- Geldenhuys, C.J. 1998. Growth, ingrowth and mortality patterns over stands and species in the Groenkop forest study site, George. Report ENV/P/C 98001, Division of Water, Environment & Forestry Technology, CSIR, Pretoria. 58 pp.
- Geldenhuys, C.J. 1999. Requirements for improved and sustainable use of forest biodiversity: Examples of multiple use of forests in South Africa. In: Poker, J., Stein, I. & Werder, U. (eds). *Proceedings of Forum Biodiversity - Treasures in the World's Forests*, 3 - 7 July 1998, Alfred Toepfer Akademie für Naturschutz, Schneverdingen, Germany. p. 72-82.
- Geldenhuys, C.J. 2004. Concepts and process to control invader plants in and around natural evergreen forest in South Africa. *Weed Technology*, 18: 1386 - 1391.
- Geldenhuys, C.J. 2005. Estimated growth of Groenkop forest in the southern Cape. Unpublished report submitted to the CSIR.
- Geldenhuys, C.J. and Theron, J.M. 1994. Litterfall and nutrient cycling in mixed evergreen forest near George, South Africa. Report FOR-DEA 746, Division of Forest Science and Technology, CSIR, Pretoria. 28 pp.
- Geldenhuys, C.J. and von dem Bussche, G.H. 1997. Performance of *Podocarpus falcatus* provenances in South Africa. *Southern African Forestry Journal*, 178: 15-24.

- Goldsmith, B. and Carter, D.T. 1981. The indigenous timbers of Zimbabwe. The Zimbabwe Bulletin of Forestry Research, No. 9: Forestry Commission, Harare.
- Granier, A., Biron, P., Köstner, B., Gay, L.W. and Najjar, G. 1996. Comparisons of xylem sap flow and water vapor flux at the stand level and derivation of canopy conductance for Scots pine. *Theoretical and Applied Climatology*, 53: 115-122.
- Granier, A., Loustau, D. and Bréda, N. 2000. A generic model of forest canopy conductance dependent on climate, soil water availability and leaf area index. *Annals of Forest Science*, 57: 755-765.
- Gush, M.B. 2008. Measurement of water-use by *Jatropha curcas* L. using the heat pulse velocity technique. *Water SA*, Vol. 34 (5): 579-583.
- Gush, M.B. and Dye, P.J. 2009. Water-use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements. *Acta Hort. (ISHS)* 846: 323-330 [http://www.actahort.org/books/846/846\\_37.htm](http://www.actahort.org/books/846/846_37.htm).
- Gush, M.B., Dye, P.J., Wise, R.M., Everson, C.S., Jarman, C., Clulow, A. and Mengistu, M.G. 2009. Bio-physical and economic estimates of the water-use efficiency of an indigenous yellowwood plantation (*Podocarpus falcatus*). *In*: Proceedings of the 14<sup>th</sup> SANCIAHS Symposium, Pietermaritzburg, South Africa. 21-23 September.
- Gush, M.B., Scott, D.F., Jewitt, G.P.W., Schulze, R.E., Lumsden, T.G., Hallows, L.A. and Görgens, A.H.M. 2002. A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. *Southern African Forestry Journal*, 196: pp 27-36.
- Gyenge, J., Fernández, M.E., Sarasola, M. and Schlichter, T. 2008. Testing a hypothesis of the relationship between productivity and water use efficiency in Patagonian forests with native and exotic species. *Forest Ecology and Management*, 255: 3281-3287.
- Hassan, R. and Haveman, J. 1997. The values and rates of harvesting natural forest and woodland products for direct use by communities in the Eastern Cape Province. Unpubl. draft report. Development Bank of Southern Africa, Midrand.

- Hatton, T.J. and Wu, H.I. 1995. Scaling theory to extrapolate individual tree water use to stand water use. *Hydrological Processes*, 9: 527-540.
- Henrici, M., 1945. The transpiration of South African Plant Association – Part III: Indigenous and exotic trees in the Drakensberg area. Government Printer -S. 10961. Department of Agriculture, Pretoria, RSA. Pp 85.
- Hibbert, A.R., 1967. Forest treatment effects on water yield. *In*: Sopper, W.E. and Lul, H.W. (eds.). *International Symposium of Forest Hydrology*, Oxford, Pergamon Press. pp. 527-543.
- Hill, R. J., Clifford, S. F., and Lawrence, R. S. 1980. Refractive Index and Absorption Fluctuations in the Infrared Caused by Temperature, Humidity and Pressure Fluctuations. *J. Opt. Soc. Amer.* 70(10): 1192–1205.
- Hill, R. J. 1992. Review of Optical Scintillation Methods of Measuring the Refractive-Index Spectrum, Inner Scale and Surface Fluxes. *Wave. Random Media*, 2: 179–201.
- Hsiao, T.C., P. Steduto and E. Fereres. 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. *Irrigation Science*. 25: 209-231.
- Hubbard, R.M., Stape, J., Ryan, M.G., Almeida, A.C. and Rojas, J. 2010. Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. *Forest Ecology and Management*, 259: 1714–1721.
- Huber, B. 1927. Zur methodik der transpirations bestimmung am standort. *Ber. dt. bot. Ges.* 45: 611-18.
- Huber, A., Iroume, A. and Bathurst, J., 2008. Effect of *Pinus radiata* plantations on water balance in Chile. *Hydrological Processes* 22 (1), 142–148.
- Hutrya, L.R., Munger, J.W., Saleska, S.R., Gottlieb, E., Daube, B.C., Dunn, A.L., Amaral, D.F., de Camargo, P.B. and Wofsy, S.C. 2007. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. *J. Geophys. Res.*, 112: G03008.
- Huxman, T.E., Wilcox, B.P., Breshears, D.D. *et al.* 2005. Ecohydrological implications of woody plant encroachment. *Ecology*, 86: 308-319.

- Jackson, R.B., Jobbágy, E.G., Avissar, R., Baidya Roy, S., Barrett, D., Cook, C.W., Farley, K.S., le Maitre, D.C., McCarl, B.A., Murray, B., 2005. Trading water for carbon with biological carbon sequestration. *Science*, 310: 1944-1947.
- Jarmain, C. and Everson, C.S. 2002. Comparative evaporation measurements above commercial forestry and sugarcane canopies in the KwaZulu-Natal Midlands. Report to Dept. Water Affairs & Forestry, CSIR report ENV-C-S 2002/005.
- Jarmain, C., Everson, C.S., Savage, M.J., Mengistu, M.G., Clulow, A.D. and Gush, M.B. 2008. Refining tools for evaporation monitoring in support of water resources management. WRC Report No. 1567/1/08, Water Research Commission, Pretoria.
- Jarvis, P.G. 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society, London, Series B*, 273: 593-610.
- Jarvis, P.G. 1981. Stomatal conductance, gaseous exchange and transpiration. *In*: Grace, J., Ford, E.D. and Jarvis, P.G. (Eds), *Plants and their atmospheric environment*. Blackwell, Oxford.
- Jones, H. 2004. What is water use efficiency? *In*: Bacon, M.A. (Ed), *Water use efficiency in plant biology*. Blackwell, Oxford, pp 27–41.
- Kagawa, A. Sack, L. Duarte, K. and James, S. 2009. Hawaiian native forest conserves water relative to timber plantation: Species and stand traits influence water use. *Ecological Applications*, 19 (6): 1429-1443.
- Kasenene, J.M. 2007. Impact of exotic plantations and harvesting methods on the regeneration of indigenous tree species in Kibale forest, Uganda. *African Journal of Ecology*, 45 (s1): 41-47.
- Keet, J.D.M. 1962. The *Trema* plantations of Westfalia Estate. *South African Forestry Journal*, 41: 15-26.
- Krishnan, P., Black, T.A., Grant, N.J., Barr, A.G., Hogg, E.H., Jassal, R.S. and Morgenstern, K. 2006. Impact of changing soil moisture distribution on net ecosystem productivity of a boreal aspen forest during and following drought. *Agricultural and Forest Meteorology*, 139: 208-223.
- Lamaud, E., Brunet, Y. and Berbigier, P., 1997. Radiation and water use efficiencies of two coniferous forest canopies. *Physics and Chemistry*

of the Earth, 21: 361-365.

- Laughton, F.S. 1937. The silviculture of the indigenous forests of the Union of South Africa with special reference to the forests of the Knysna Region. Science Bulletin 157: Forestry Series 7, Government Printer, Pretoria. 168 pp.
- Law, B.E., Falge, E., Gu, L., Baldocchi, D.D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A.J., Falk, M., Fuentes, J.D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I.A., Jarvis, P., Jensen, N.O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Muner, W., Oechel, W., Olson, R., Pilegaard, K.P., U.K.T., Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S. 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, Agricultural and Forestry Meteorology, 113: 97–120.
- Lawes, M.J., Obiri, J.A.F. and Eeley, H.A.C. 2004. The uses and value of indigenous forest resources in South Africa. In: Lawes, M.J., Eeley, H.A.C, Shackleton, C.M. and Geach, B.G.S. (eds). Indigenous forests and woodlands in South Africa: Policy, people and practice. University of KwaZulu-Natal Press, Scottsville, South Africa. P. 227-273.
- Le Maitre, D.C., Versfeld, D.B. and Chapman, R.A. 2000. The impact of invading alien plants on surface water resources in South Africa: a preliminary assessment. Water SA, 26: 397-408.
- Le Roux, D., Stock, W.D., Bond, W.J. and Maphanga, D. 1996. Dry mass allocation, water use efficiency and  $\delta^{13}\text{C}$  in clones of *Eucalyptus grandis*, *E. grandis* x *camaldulensis* and *E. grandis* x *nitens* grown under two irrigation regimes. Tree Physiology, 16: 497—502.
- Leakey, R., Pate, K. and Lombard, C. 2005a. Domestication potential of Marula (*Sclerocarya birrea* subsp *caffra*) in South Africa and Namibia: 2. Phenotypic variation in nut and kernel traits. Agroforestry Systems, 64: 37–49.
- Leakey, R., Shackleton, S. and du Plessis, P. 2005b. Domestication potential of Marula (*Sclerocarya birrea* subsp *caffra*) in South Africa and Namibia: 1. Phenotypic variation in fruit traits. Agroforestry Systems, 64: 25–35.

- Licata, J.A., Gyenge, J.E., Fernández, M.E., Schlichter, T.M. and Bond, B.J. 2008. Increased water use by ponderosa pine plantations in northwestern Patagonia, Argentina compared with native forest vegetation. *Forest Ecology and Management*, 255: 753–764.
- Li-Cor, 1991. LAI-2000 Plant Canopy Analyser Operating Manual. Lincoln, Nebraska, USA.
- Lieth, H., 1972. Modeling the primary productivity of the world. *Tropical Ecology*, 13: 125–130.
- Lindroth, A. and Cienciala, E. 1996. Water use efficiency of short-rotation *Salix viminalis* at leaf, tree and stand scales. *Tree Physiology*, 16: 257-262.
- Little, C., Lara, A., McPhee, J. and Urrutia, R. 2009. Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile. *Journal of Hydrology*, 374: 162–170.
- Lohammer, T., Larsson, S, Linder, S. and Falk, S.O. 1980. FAST – Simulation models of gaseous exchange in Scots Pine. *Ecological Bulletin*, 32: 505-523.
- Low, A.B. and Rebelo, T.G., 1996. *Vegetation of South Africa, Lesotho and Swaziland*. Department of Environmental Affairs and Tourism Press, Pretoria.
- Lu, X. and Zhuang, Q. 2010. Evaluating evapotranspiration and water-use efficiency of terrestrial ecosystems in the conterminous United States using MODIS and AmeriFlux data. *Remote Sensing of Environment*, 114: 1924–1939.
- Lumbile, A.U., Kwerepe, B.C. and Kelatlhilwe, M. 2007. The characteristics and economic importance of *Pterocarpus angolensis* in D.C. Botswana. *Pakistan journal of biological sciences*, 10 (4): 627-631.
- Lynch, S. D. and Schulze, R. E., 2006. Rainfall Database. In: Schulze, R. E. (Ed). 2006. *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, South Africa, WRC Report 1489/1/06, Section 2.2.
- Malmer, A. and Nyberg, G. 2008. Forest and water relations in miombo woodlands: need for understanding of complex stand management. In: Varmola, M., Valkonen, S. and Taipanen, S. (eds), *Research and*

development for sustainable management of semiarid / miombo woodlands in East Africa. Working Papers of the Finnish Forest Research Institute, 98: 70-86.  
<http://www.metla.fi/julkaisut/workingpapers/2008/mwp098.htm>.

- Marshall, D.C. 1958. Measurement of sap flow in conifers by heat transport. *Plant Physiology*, 33: 385-396.
- Marshall, J.D. and Zhang, J. 1994. Carbon isotope discrimination and water-use efficiency in native plants of the north-central Rockies. *Ecology*, 75: 1887-1895
- Maseyk, K., Hemming, D., Angert, A., Leavitt, S.W. and Yakir, D. 2011. Increase in water-use efficiency and underlying processes in pine forests across a precipitation gradient in the dry Mediterranean region over the past 30 years. *Oecologia*, DOI: 10.1007/s00442-011-2010-4.
- McJannet, D., Fitch, P., Disher, M., Wallace, J., 2007. Measurements of transpiration in four tropical rainforest types of north Queensland. *Aust. Hydrological Processes*, 21: 3549-3564.
- McKenzie, B. 1988. Guidelines for the sustained use of forests and forest products. Ecosystem Programmes Occasional Report 35. CSIR, Pretoria. 69 pp.
- Meijninger, W. M. L., Hartogensis, O. K., Kohsiek, W., Hoedjes, J. C. B., Zuurbier, R. M. and de Bruin, H. A. R. 2002. Determination of area-averaged sensible heat fluxes with a large aperture scintillometer over a heterogeneous surface – Flevoland field experiment. *Boundary-Layer Meteorology*, 105: 37–62.
- Middleton, B.J. and Bailey, A.K. 2008. Water Resources of South Africa, 2005 Study (WR2005). WRC Report No. TT 381/08. Water Research Commission, Pretoria, South Africa.
- Monteith, J.L. 1965. Evaporation and environment. In: G.E. Fogg (ed.) *Symposium of the Society for Experimental Biology, The State and Movement of Water in Living Organisms*, Vol. 19: 205-224, Academic press, Inc., NY.
- Mucina, L. and Geldenhuys, C.J. 2006. Afrotropical, subtropical and azonal forests. In: Mucina, L. and Rutherford, M.C. (Eds) *The vegetation of South Africa, Lesotho and Swaziland*. *Strelitzia*, 19: 584-614.

- Mucina, L. and Rutherford, M.C. (eds.) 2006. The vegetation of South Africa, Lesotho and Swaziland. *Strelitzia* 19. South African National Biodiversity Institute, Pretoria.
- Nänni, U.W. 1970. Trees, water and perspective. *South African Forestry Journal*. 75: 9-17.
- Newman, B.D., Wilcox, B.P., Archer, S.R., Breshears, D.D., Dahm, C.N., *et al.* 2006. Ecohydrology of water-limited environments: a scientific vision. *Water Resources Research*, 42: W06302
- NFA, 1998. National Forests Act of the Republic of South Africa (No. 84. of 1998). Government Gazette Volume 400, No. 19408. Cape Town, South Africa.
- Nogueira, A., Martinez, C.A., Ferreira, L.L. and Prado, C.H.B.A., 2004. Photosynthesis and water use efficiency in twenty tropical tree species of differing succession status in a Brazilian reforestation, *Photosynthetica*, 42 (3): 351-356.
- Nomqophu, W., Braune, E. and Mitchell, S. 2007. The changing water resources monitoring environment in South Africa. *South African Journal of Science*, 103: 306-310.
- NWA. 1998. National Water Act of the Republic of South Africa, (No. 36 of 1998): *RSA Government Gazette* No. 19182. Cape Town, South Africa.
- O'Neill, R.V. and DeAngelis, D.L. 1981. Comparative productivity and biomass relations of forest ecosystems. *In*: D.E. Reichle (Ed). *Dynamic Properties of Forest Ecosystems*. Cambridge University Press, Cambridge, UK. pp. 411-449.
- Obiri, J.A.F., Lawes, M.J. and Mukolwe, M. 2002. The dynamics and sustainable use of high-value tree species of the coastal Pondoland forests of the Eastern Cape Province, South Africa. *Forest Ecology and Management*, 166: 131-148.
- Olbrich, B.W. and Olbrich, K.A. 1996. Testing the screening and sampling procedures for water use efficiency on a selection of *Eucalyptus* clonal hybrids in Zululand, kwaZulu-Natal. Report FOR-DEA 955, Forestek, CSIR.

- Olbrich, B.W., Le Roux, D., Poulter, A.G., Bond, W.J. and Stock, W.D. 1993. Variation in water use efficiency and  $\delta^{13}\text{C}$  levels in *Eucalyptus grandis* clones. *Journal of Hydrology*, 150: 615-633.
- Olbrich, B., Olbrich, K., Dye, P. and Soko, S. 1996. A year-long comparison of water use efficiency of stressed and non-stressed *E. grandis* and *P. patula*: findings and management recommendations. CSIR report FOR-DEA 958.
- Olivier, W., 2009. There is honey in the forest: The history of South African forestry. Southern African Institute of Forestry, Pretoria.
- Paço, T. A., David, T. S., Henriques, M. O., Pereira, J. S., Valente, F., Banza, J., Pereira, F. L., Pinto, C. and David, J. S. 2009. Evapotranspiration from a Mediterranean evergreen oak savannah: The role of trees and pasture. *Journal of Hydrology*, 369: 98-106.
- Pallett, R.N. and Sale, G. 2004. The relative contributions of tree improvement and cultural practice toward productivity gains in *Eucalyptus* pulpwood stands. *Forest Ecology and Management*, 193: 33-43.
- Parton, W.J., Stewart, J.W.B. and Cole, C.V. 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry*, 5: 109-131.
- Phillips, J.F.V., 1931. Forest succession and ecology in the Knysna region. Botanical Survey Memoirs: 14. Government Printer, Pretoria, South Africa.
- Phillips, J.F.V. 1963. The forests of George, Knysna and the Zitzikama. A brief history of their management: 1778 - 1939. *Bulletin 40*, Government Printer, Pretoria.
- Rana, G. and Katerji, N., 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *European Journal of Agronomy*, 13: 125–153.
- Ratsirarson, H., Robertson, H.G., Picker, M.D. and van Noort, S. 2002. Indigenous forests versus exotic eucalypt and pine plantations: a comparison of leaf-litter invertebrate communities. *African Entomology*, 10: 93–99.
- Reinders, F.B., Smal, H.S., Van Niekerk, A.S., Bunton, S. and Mdaka, B. 2005. Sub-surface drip irrigation: Factors affecting the efficiency and

- maintenance. Water Research Commission Report No 1189/1/05, Pretoria, South Africa.
- Rijsberman, F.R. 2006. Water scarcity: Fact or fiction? *Agricultural Water Management*, 80: 5–22.
- Rocha, A.V., Su, H.-B., Vogel, C.S., Schmid, H.P. and Curtis, P.S., 2004. Photosynthetic and water use efficiency responses to diffuse radiation by an aspen-dominated northern hardwood forest, *For. Sci.* 50: 793–801.
- Rockström, J., Barron, J. and Fox, P. 2002. Rainwater management for increased productivity among small-holder farmers in drought-prone environments. *Physical Chemistry of the Earth*, 27: 949-959.
- Rowe, P.B. 1963. Streamflow increases after removing woodland riparian vegetation from a southern California watershed. *Journal of Forestry*, 61: 365–370.
- Rycroft, H.B., 1944. The Karkloof Forest, Natal. *Journal of the S.A. Forestry Association*, No. 11.
- Sankaran, M., Hanan, N.P., Scholes, R.J., Ratnam, J., Augustine, D.J., Cade, B.S., Gignoux, J., Higgins, S.I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K.K., Coughenour, M.B., Diouf, A., Ekaya, W., Feral, C.J., February, E.C., Frost, P.G.H., Hiernaux, P., Hrabar, H., Metzger, K.L., Prins, H.H.T., Ringrose, S., Sea, W., Tews, J., Worden, J. & Zambatis, N. 2005. Determinants of woody cover in African Savannas. *Nature*, 438: 846-849.
- Sankaran, M., Ratnam, J. & Hanan, N. 2008. Woody cover in African savannas: the role of resources, fire and herbivory. *Global Ecology and Biogeography*, 17: 236–245.
- Savage, M.J., 2009. Estimation of evaporation using a dual-beam surface layer scintillometer and component energy balance measurements. *Agricultural and Forest Meteorology*, 149: 501-517.
- Savage, M.J., Everson, C.S. and Metelerkamp, B.R. 1997. Evaporation measurement above vegetated surfaces using micrometeorological techniques. WRC Report No. 349/1/97, Water Research Commission, Pretoria.
- Savage, M.J., Everson, C.S., Odhiambo, G.O., Mengistu, M.G. and Jarmain,

- C. 2004. Theory and practice of evaporation measurement, with special focus on surface layer scintillometry as an operational tool for the estimation of spatially averaged evaporation. Water Research Commission Report No. 1335/1/04, p204, ISBN No 1-77005-247-X.
- Savenije, H. H. G. 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrological Processes*, 18: 1507-1511.
- Scholes, R.J. and Archer, S.R. 1997. Tree–grass interactions in savannas, *Annu. Rev. Ecol. Syst.*, 28: 517–544.
- Scholes, R.J., Gureja, N., Giannecchini, M., Dovie, D., Wilson, B., Davidson, N., Piggott, K., McLoughlin, C., van Der Velde, K., Freeman, A., Bradley, S., Smart, R. and Ndala, S. 2001. The environment and vegetation of the flux measurement site near Skukuza, Kruger National Park. *Koedoe*, 44(1): 73-83.
- Schreiner, O. and van Koppen, B. 2002. Catchment management agencies for poverty eradication in South Africa. *Physics and Chemistry of the Earth*, 27: 969-976.
- Schulze, R.E. and Chapman, R.D. 2007. Estimation of Daily Solar Radiation over South Africa. *In: Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 5.2.*
- Schulze, R.E. and Maharaj, M. 2007. Temperature Database. *In: Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 2.1.*
- Schulze, R.E., Chapman, R.D. and Maharaj, M. 2007. Daily minimum, maximum and mean relative humidity. *In: Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 12.2.*
- Scott, D. F. 1993. The hydrological effects of fire in South African mountain catchments. *Journal of Hydrology*, 150: 409 – 432.
- Scott, D. F. 1999. Managing riparian zone vegetation to sustain streamflow: Results of paired catchment experiments in South Africa. *Canadian Journal of Forest Research*, 29: 1149 – 1157.

- Scott, D.F. and Lesch, W. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, Mpumalanga Province, South Africa. *Journal of Hydrology*, 199: 360-377.
- Scott, D.F. and Prinsloo, F.W. 2008. Longer-term effects of pine and eucalypt plantations on streamflow, *Water Resour. Res.*, 44: W00A08, doi:10.1029/2007WR006781.
- Scott, D.F. and Smith, R.E. 1997. Preliminary empirical models to predict reductions in total and low-flows resulting from afforestation. *Water SA*, 23: 135-140.
- Scott, D.F., Prinsloo, F.W., Moses, G., Mehlomakulu and Simmers, A.D.A. 2000. A re-analysis of the South African catchment afforestation experimental data. WRC report 810/1/00, Water Research Commission, Pretoria.
- Scott, R.L., Huxman, T.E., Williams, D.G. and Goodrich, D.C. 2006. Ecohydrological impacts of woody-plant encroachment: seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. *Global Change Biology*, 12: 311-324.
- Seagrief, S.C. 1965. Establishment of *Podocarpus latifolius* in Blackwood plantations at the Hogsback. *South African Journal of Science*, 61: 433-437.
- Seydack, A.H.W. 1995. An unconventional approach to timber yield regulation for multi-aged, multi-species forests. I. Fundamental considerations. *Forest Ecology and Management*, 77: 139 - 153.
- Seydack, A.H.W., van Daalen, J.C., van Dijk, D., Reynell, D., Heyns, H., Jooste, A., Ferguson, M., Pitchford, W., Durrheim, G., and Williams, D. 1990. Yield regulation in the Knysna forest, *South African Forestry Journal*, 152: 50 - 61.
- Seydack, A.H.W., Vermeulen, W.J., Heyns, H.E., Durrheim, G.P., Vermeulen, C., Willems, D., Ferguson, A., Huisamen, J. and Roth, J. 1995. An unconventional approach to timber yield regulation for multi-aged, multispecies forests. II. Application to a South African forest. *Forest Ecology and Management*, 77: 155-168.

- Shackleton, C.M. 2002. Growth patterns of *Pterocarpus angolensis* in savannas of the South African lowveld. *Forest Ecology and Management*, 166: 85-97.
- Shackleton, C.M. and Shackleton, S.E. 2000. Direct use values of savanna resources: a case study of the Bushbuckridge lowveld, South Africa, *Journal of Tropical Forest Products*, 6: 21 - 40.
- Shackleton, C. M. and Shackleton, S.E. 2004. The importance of non-timber forest products in rural livelihood security and as safety nets: a review of evidence from South Africa. *South African Journal of Science*, 100: 658 - 663.
- Shackleton, C.M., Botha, J. and Emanuel, P.L. 2003. Productivity and abundance of *Sclerocarya birrea* subsp. *caffra* in and around rural settlements and protected areas of the Bushbuckridge lowveld, South Africa. *Forests, Trees and Livelihoods*, 13: 217–232.
- Shackleton, C.M., Cawe, S.G. and Geldenhuys, C.J. 1999. Review of the definitions and classifications of South African forests and woodlands. *Report ENV-P-C 99007*, CSIR, Pretoria. 33 pp.
- Shackleton, C.M., Shackleton S.E, Buiten, E. and Bird, N. 2007. The importance of dry woodlands and forests in rural livelihoods and poverty alleviation in South Africa. *Forest Policy and Economics*, 9 (5): 558-577.
- Silveira, L. and Alonso, J., 2009. Runoff modifications due to the conversion of natural grasslands to forests in a large basin in Uruguay. *Hydrological Processes*, 23: 320–329.
- Sim, T.R. 1907. *The Forests and Forest Flora of the Colony of the Cape of Good Hope*. Taylor and Henderson, Aberdeen, Scotland.
- Smith, D.M. and Allan, S.J. 1996. Measurement of sap flow in plant stems. *Journal of Experimental Botany*, 47: 1833-1844.
- Stape, J.L., Binkley, D., and Ryan, M.G. 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil, *Forest Ecology and Management*, 193: 17-31.
- Stapleton, C.C., 1955. The cultivation of indigenous trees and shrubs. *Journal of the South African Forestry Association*, 26: 10-17.

- Stehle, T.C. 2007. The occurrence of indigenous forests in South Africa: Historical and current. Available from [http://www2.dwaf.gov.za/webapp/ResourceCentre/Documents/Scientific\\_And\\_Technical\\_Information/IndigenousForestsAug07.pdf](http://www2.dwaf.gov.za/webapp/ResourceCentre/Documents/Scientific_And_Technical_Information/IndigenousForestsAug07.pdf)
- Stewart, J.B. 1988. Modelling surface conductance of pine forest. *Agricultural and Forest meteorology*, 43: 19-35.
- Stoffberg, G.H., van Rooyen, M.W., van der Linde, M.J. and Groeneveld, H.T. 2008. Predicting the growth in tree height and crown size of three street tree species in the City of Tshwane, South Africa. *Urban Forestry & Urban Greening*, 7: 259–264.
- Swanson, R.H., 1994. Significant historical developments in thermal methods for measuring sap flow in trees. *Agricultural and Forest Meteorology*, 72: 113-132.
- Swanson, R.H. and Whitfield, D.W.A. 1981. A numerical analysis of heat pulse velocity theory and practice. *Journal of Experimental Botany*, 32: 221-239.
- TAPPI (Technical Association of the Pulp and Paper Industry), 1994. TAPPI Test Methods 1994-1995. TAPPI Press, Atlanta, Georgia, USA.
- Taylor, H.C., 1961. The Karkloof forest: A plea for its protection. *Forestry in South Africa*, No. 1 (July). pp 123-134.
- Taylor, H.C., 1962. A report on the Nxamalala Forest. *Forestry Surv. S. Afr.* No. 2, Dec.
- Thiermann, V. and Grassl, H. 1992. The Measurement of Turbulent Surface Layer Fluxes by Use of Bichromatic Scintillation. *Boundary-Layer Meteorology*, 58: 367–389.
- Thom, A.S., 1975. Momentum, mass and heat exchange of plant communities. In: J.L. Monteith (Ed.), *Vegetation and the atmosphere*, Vol. 1, Academic Press, London.
- Tu, K., Knohl, A., Mambelli, S., Ma, S., Baldocchi, D. and Dawson, T. 2008. Observations and scaling of water use efficiency from leaf to globe. *Geophysical Research Abstracts*, 10: EGU2008-A-07012.
- Turpie, J.K., Marais, C. and Blignaut, J.N. 2008. The working for water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service

- delivery in South Africa. *Ecological Economics*, 65: 788 – 798.
- Tyree, M.T. and Zimmerman, M.H., 2002. *Xylem Structure and the Ascent of Sap*. Springer Verlag, Berlin.
- van Daalen, J.C. 1991. Forest growth: A 35-year southern Cape case study. *South African Forestry Journal*, 159: 1-10.
- van der Schyff, H.P., 1963. A preliminary account of the vegetation of the Mariepskop complex. *Fauna and Flora*, No. 14, 42-53.
- van der Stoep, I., Benadé, N., Smal, H.S. & Reinders, F.B. 2005. Guidelines for Irrigation Water Measurement in Practice, Water Research Commission Report No TT248/05, Pretoria, South Africa.
- van der Waal, C., de Kroon, H., de Boer, W.F., Heitkönig, I.M.A., Skidmore, A.K., de Knecht, H.J., van Langevelde, F., van Wieren, S.E., Grant, R.C., Page, B.R., Slotow, R., Kohi, E.M., Mwakiwa, E. and Prins, H.H.T. 2009. Water and nutrients alter herbaceous competitive effects on tree seedlings in a semi-arid savanna. *Journal of Ecology*, 97: 430–439.
- van der Zel, D.W. 1987. Hydrological implications of the changing role of forestry in a catchment context. In: *Proc. 3rd South African National Hydrological Symposium, Vol. 2*: 671-679. Hydrological Research Unit, Dept. of Geography, Rhodes University, Grahamstown, September.
- van der Zel, D.W. 1995. Accomplishments and dynamics of the South African Afforestation Permit System. *South African Forestry Journal*. 172: 49-58.
- van Laar, A. and Geldenhuys, C.J. 1975. Tariff tables for indigenous tree species in the Southern Cape Province. *Forestry in South Africa*, 17: 29-36.
- van Laar, A. and Lewark, S. 1973. Sampling for forest inventories in the indigenous forests of the Southern Cape Province. *Forestry in South Africa*, 14: 35 - 43.
- van Wilgen, B.W., Le Maitre, D.C., Reyers, B., Richardson, D.M. and Schonegevel, L., 2008. Invasive alien plants and the delivery of services from South African ecosystems: A preliminary assessment. *Journal of Environmental Management*, 89: 336-349.

- van Wyk, B.E. 1982. Keur (*Virgilia oroboides*): a feasible indigenous hardwood for the South African Forestry Industry. South African Forestry Journal, 122: 49-51.
- van Wyk, D. B. 1987. Some effects of afforestation on streamflow in the Western Cape Province, South Africa, Water SA, 13: 31-36.
- van Wyk, G.F. Ham, C., Geldenhuys, C.J., Mander, M., Diederichs, N., Kirsten, J., Doyer, T and Robbertse, H., 2003. Commercial products from the wild: Sustainable utilisation, commercialisation and domestication of products from indigenous forest and woodland ecosystems. *Innovation Fund Project No. 31114 final report*. National Research Foundation, Pretoria.
- Vanclay, J.K., 2009. Managing water use from forest plantations. Forest Ecology and Management, 257 (2): 385-389.
- Venter, F.J., Scholes, R.J. and Eckhardt, H.C. 2003. The abiotic template and its associated vegetation pattern, pp. 83–129. In: du Toit, J.T., Rogers, K.H. and Biggs, H.C. (eds), The Kruger experience: ecology and management of savanna heterogeneity. Island Press, Washington.
- Vermeulen, W.J. 2000. Management of natural forests. In: Owen, D.L. & Vermeulen, W.J. (Eds). South African Forestry Handbook 2000, Vol 2, The Southern African Institute of Forestry, Pretoria. p. 601-612.
- Verryn, S. D. 2000. Eucalypt hybrid breeding in South Africa. In: Dungey, H. S., Dieters, M. J., and Nikles, D. G. Hybrid Breeding and Genetics of Forest Trees. pp. 191-199. QFRI/CRC-SPF, Noosa, Australia.
- von Breitenbach, F., 1968. Southern Cape Indigenous Forest management manual. *Unpublished manuscript*, Department of Forestry, Pretoria.
- von Breitenbach, F., 1974. Southern Cape Forests and Trees. *The Government Printer*, Pretoria, RSA. Pp 328.
- von Breitenbach, F. 1990. National list of indigenous trees. Dendrological Foundation, Pretoria.
- von dem Bussche, G.H. 1975. Indigenous forest conservation management. South African Forestry Journal, 93: 25-31.
- von dem Bussche, G.H. and Ellis, G.A. 1987. Establishment of *Khaya nyasica* Plantations. South African Forestry Journal, 141: 4.
- von Maltitz, G., Mucina, L., Geldenhuys, C.J., Lawes, M.J., Eeley, H., Aidie,

- H., Vink, D., Fleming, G. & Bailey, C. 2003. Classification system for South African Indigenous Forests. An objective classification for the Department of Water Affairs and Forestry Unpublished report, No. ENV-P-C 2003-017, Environmentek, CSIR, Pretoria. 275 pp.
- Walker, B.H., and Noy-Meir, I. 1982. Aspects of the stability and resilience of savanna ecosystems, p. 577-590. *In*: B.J. Huntley and B.H. Walker (eds), *Ecology of Tropical Savannas*. Springer. Berlin.
- Water Matters Committee., 1970. Report of the Commission of Enquiry into Water Matters. Report no. 34/1970. Government Printer, Pretoria.
- Webb, W., Szarek, S., Lauenroth, W., Kinerson, R. and Smith, M. 1978. Primary Productivity and Water Use in Native Forest, Grassland, and Desert Ecosystems. *Ecology*, 59 (6): 1239-1247.
- White, F. 1978. The Afromontane Region. *In*: Werger, M.J.A. (ed.) *Biogeography and Ecology of Southern Africa*. W. Junk, The Hague, pp 463-513.
- Whitehead, D. 1998. Regulation of stomatal conductance and transpiration in forest Canopies. *Tree Physiology*, 18: 633–644.
- Whitehead, D. and Beadle, C.L. 2004. Physiological regulation of productivity and water use in Eucalyptus: a review. *Forest Ecology and Management*, 193, 113–140.
- Whitley, R., Zeppel, M., Armstrong, N., Mcinnis-Ng, C., Yunusa, I., Eamus, D., 2008. A modified Jarvis–Stewart model for predicting stand-scale transpiration of an Australian native forest. *Plant Soil*, 305: 35-47.
- Wicht, C.L. 1941. Diurnal fluctuations in Jonkershoek streams due to evaporation and transpiration. *Journal of the S.A. Forestry Association*, 7: 34-49.
- Wicht, C.L., 1949. Forestry and water supplies in South Africa. *Government Printer*, Pretoria. Bulletin no. 33.
- Wigley, B.J., Bond, W.J. and Hoffman, M.T. 2010. Thicket expansion in a South African savanna under divergent land use: local vs. global drivers? *Global Change Biology*, 16: 964-976.
- Wilcox, B.P. 2002. Shrub control and streamflow on rangelands: A process based viewpoint. *Journal of Range Management*, 55: 318-326.

- Wilcox, B. P. 2010. Transformative ecosystem change and ecohydrology: Ushering in a new era for watershed management. *Ecohydrology*, 3: 126–130.
- Williams, D.G., Cable, W., Hultine, K., Hoedjes, J.C.B., Yopez, E.A., Simonneaux, V., Er-Raki, S., Boulet, G., de Bruin, H.A.R., Chehbouni, A., Hartogensis, O.K. and Timouk, F. 2004. Evapotranspiration components determined by stable isotope, sap flow and eddy covariance techniques. *Agricultural and Forest Meteorology*, 125: 241-254.
- Williams, M., Malhi, Y., Nobre, A., Rastetter, E.B., Grace, J. and Pereira, M.G.P., 1998. Seasonal variation in net carbon exchange and evapotranspiration in a Brazilian rain forest: a modelling analysis. *Plant Cell Environment*, 21: 953–968.
- Wilson, M. 1982. The re-establishment of yellowwood forest. *Veld and Flora*, 68: 111-112.
- Wilson, K.B., Hanson, P.J., Mulholland, P.J., Baldocchi, D.D. and Wullschleger, S.D. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agricultural and Forest Meteorology*, 106: 153-168.
- Wise, R.M., Dye, P.J. and Gush, M.B. 2011. A comparison of the biophysical and economic water use efficiencies of indigenous and introduced forests in South Africa. *Forest Ecology and Management*, 262: 906-915.
- Woyessa, Y.E., Hensley, M. and van Rensburg, L.D. 2006. Catchment management in semi-arid area of central South Africa: Strategy for improving water productivity. *Water SA*, 32 (5): 648-654.
- Wullschleger, S.D., Hanson, P.J. and Todd, D.E., 2001. Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques. *Forest Ecology and Management*, 143: 205-213.
- Wullschleger, S.D., Meinzer, F.C. and Vertessy, R.A., 1998. A review of whole-plant water use studies in trees. *Tree Physiology*, 18: 499-512.
- Yopez, E., Williams, D., Scott, R. and Lin, G. 2003. Partitioning overstory and understory evapotranspiration in a semi-arid savanna ecosystem from

the isotopic composition of water vapor. *Agricultural and Forest Meteorology*, 119: 53-68.

Zhang, L., Dawes, W.R. and Walker, G.R. 1999. Predicting the effect of vegetation changes on catchment average water balance. CSIRO Technical Report 99/12, CRC for Catchment Hydrology, CSIRO, Canberra, Australia.

Zhang, L., Dawes, W.R. and Walker, G.R. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, 37(3): 701–708.

Zhang, G., Thomas, C., Leclerc, M.Y., Karipot, A., Gholz, H.L., Binford, M., Foken, T., 2007. On the effect of clearcuts on turbulence structure above a forest canopy. *Theoretical and Applied Climatology*, 88(1-2): 133-137.

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